US Army Corps
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St. Paul District

Appendix E – Geology and Geotechnical Analysis

Riverbank Stabilization Project Feasibility Report and Integrated Environmental Assessment

Section 203 Tribal Partnership Program

Document Updated: 2 August 2023

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1 Glossary

Term	Definition
BOR	Bureau of Reclamation
C&S	Cost and Specifications Section
CEMVP	St. Paul District
G&G or ECG	Geotech and Geology
H&H	Hydraulics and Hydrology
O&M	Operations and maintenance
O&M	Operations and Maintenance
P&S	Plans and Specifications Design Stage (synonymous with PED in this appendix)
PED	Pre-Construction Engineering and Design
PDT	Project Delivery Team
USACE	U.S Army Corp of Engineers

2 Background

The purpose of this appendix is to explain the Geology and Geotechnical (G&G) findings, analysis, and results that lead to the selection of the TSP for riverbank stabilization. Some discussion is devoted to the geotechnical reasons behind eliminating alternative designs. The appendix is written to lead the reader through the development process in a linear fashion; however, the reader should note that the design process was iterative.

The main problem is erosion of the toe of the slope through normal channel meandering processes (e.g., scour of erodible material at the toe, ice and debris flow, uprooted vegetation and tree blowdowns, animal burrows). These processes created slope instability, so the geotechnical effort narrowed to a slope stability analysis without the need to perform a seepage or settlement analysis. Generally, Minnesota is not a tectonically active location, and the location has no infrastructure that could be put at risk; therefore, G&G did not perform a seismic analysis.

Scope was limited due to typical funding constraints typical of a feasibility study. No secondary modeling effort to confirm the findings of the GeoStudio models was performed. No peer review of the findings of this appendix was performed before DQC review. These efforts will have to be taken up during P&S stage.

2.1 Aerial Imagery and Erosion Rate

The reader should note that some aerial imagery present in some figures does not reflect the present status of the riverbank. The figure below illustrates this rapid erosion.

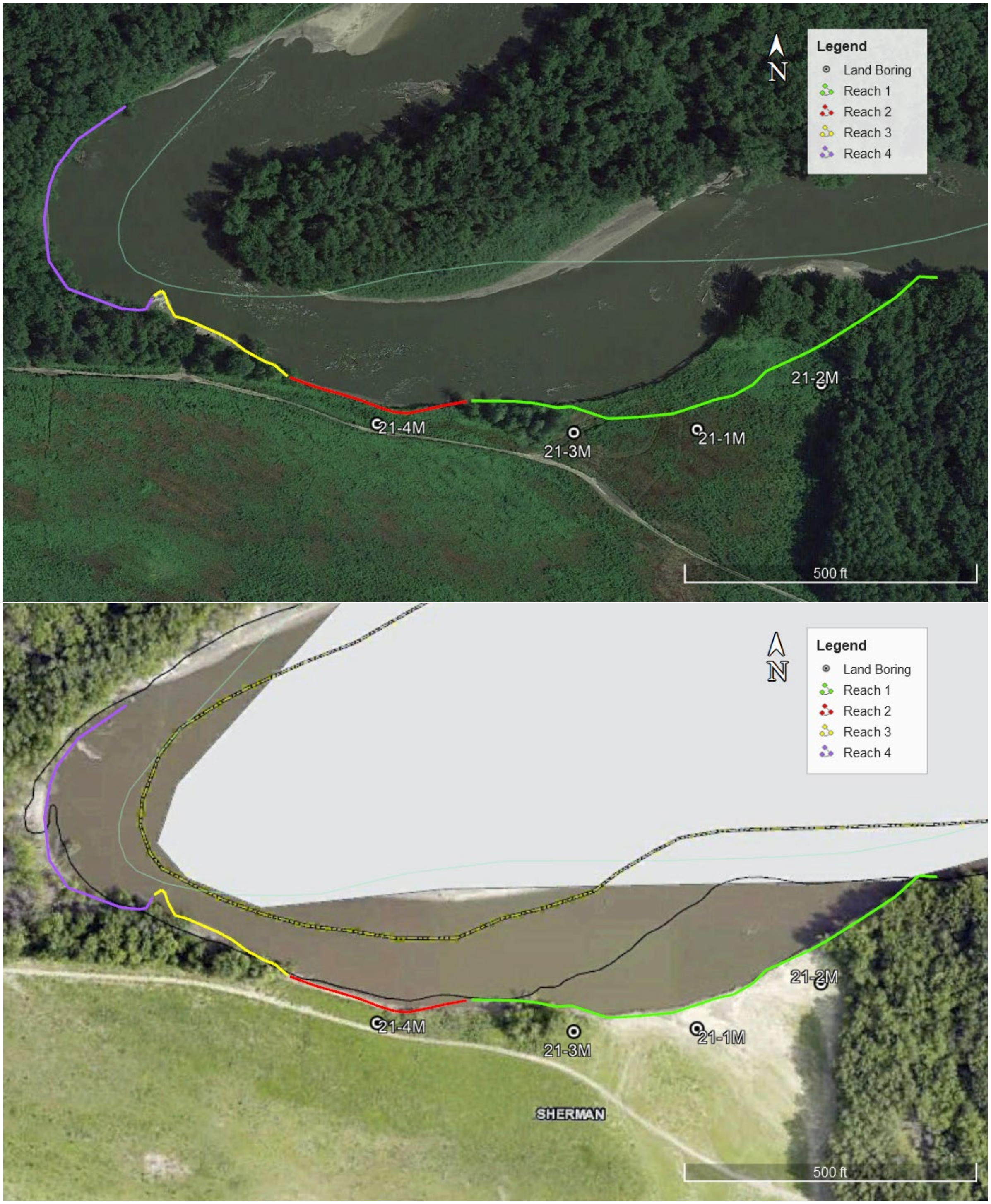


Figure 1 Aerial imagery comparison (2015 at top, 2020 at bottom)

One of the significant challenges of this project is the speed at which the erosion is occurring, especially in Reach 1, and that site conditions may have altered significantly during the plans and specifications stage of the project as well as immediately before construction.

2.2 Initial Reach Divisions

From a site visit on 30 Sept 2020, the PDT divided the bank into three reaches (eastern, central, and western), as shown in the figure below.

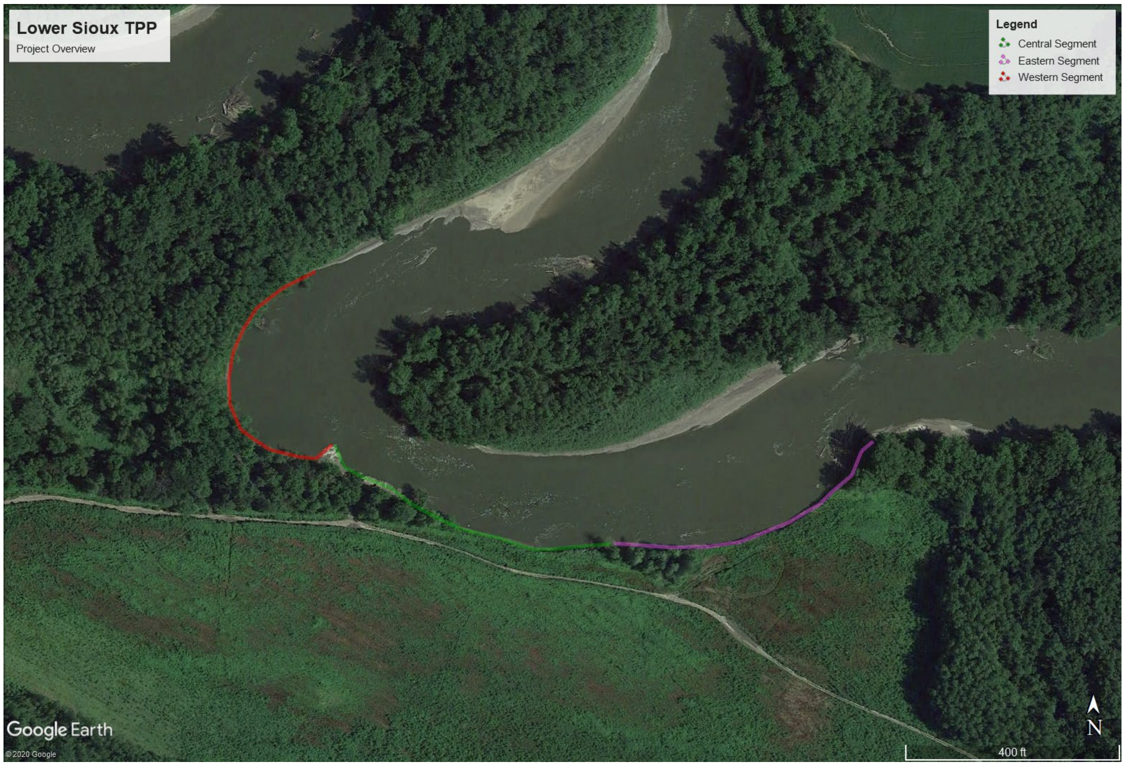


Figure 2 Former reach divisions (2015 aerial shown with bank lines based on 2015 aerial)

The PDT based this decision solely on the available ground surface information available at the time, and the PDT later changed to a different series of reaches. This information is presented here to make the reader aware that some figures developed in the preliminary stages of the iterative design process may reflect these early reach divisions and not the final reach divisions. Due to resource constraints, the authors of this document have not redeveloped some figures with the final reach divisions if that redevelopment is not pertinent.

2.3 Final Reach Divisions

The PDT later subdivided the riverbank into four reaches based on the geology and flow regime. The reaches are numbered from downstream to upstream. See the figure below for the final reach divisions (numbered 1 through 4). Note that the aerial photography in the figure below is from 2015 and does not match the existing bank line.

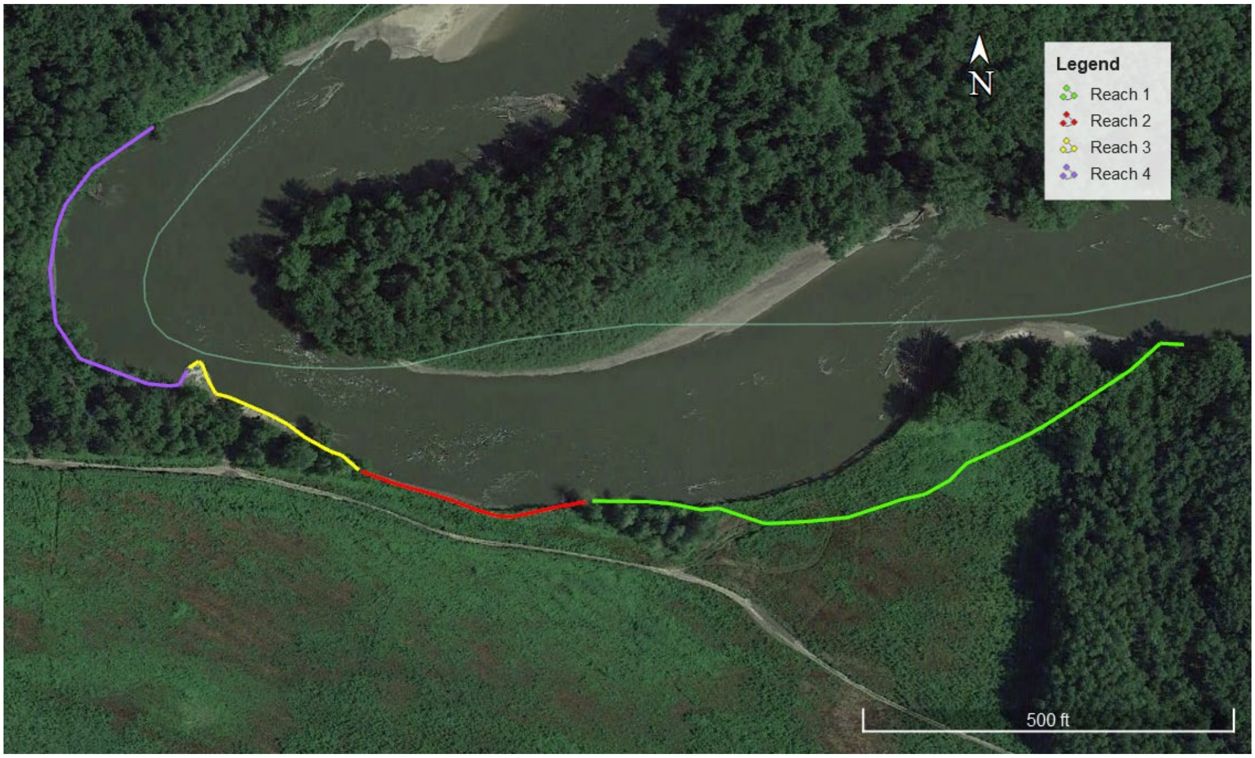


Figure 3 Final reach divisions (note 2015 aerial image versus existing bank lines)

3 Geology and Physiography

3.1 Physiography and Topography

As the last glaciers in the southern Minnesota area retreated northward above the continental divide at Browns Valley and into the Red River Valley, Lake Agassiz, headwaters of the glacial River Warren, was formed. The River Warren, flowing to the southeast, began cutting and shaping the Minnesota Valley to its present form. Eventually, the retreating ice margin uncovered lower outlets, and Lake Agassiz, now draining to the north, was reduced to such a low elevation that River Warren ceased to flow. In its place, the Minnesota River became established.

The 1347-square-mile Minnesota River-Granite Falls watershed is one of 13 major watersheds of the Minnesota River Basin. Situated within the Northern Glaciated Plains Ecoregion, the watershed can further be divided into three geomorphic settings: the headwaters flowing off the Coteau des Prairies, the lower basin-situated within the Blue Earth Till Plain, and the Minnesota River Valley-carved by the glacial River Warren.

The portion of the watershed within the Blue Earth Till Plain is represented by nearly level to gently sloping lands, ranging from 0% to 6% in steepness. Soils are predominantly loamy, with landscapes having a complex mixture of well and poorly drained soils. Drainage of depressional areas is often poor, and tile drainage is common. Water erosion potential is moderate on much of the land within this geomorphic setting.

The Coteau des Prairies or Highland of the Prairies is a morainal plateau that occupies the headwaters of the Upper Minnesota River and several other rivers. The Coteau acts as an important drainage divide. Its well-drained southwestern side sheds water into the Big Sioux River, while waters on the northeastern side flow into the Des Moines and Minnesota Rivers. The Coteau is characterized by landscapes with long northeast facing slopes which are undulating to rolling (2% to 18%). Soils are predominantly loamy and well drained. Tributaries draining the Coteau and entering the Upper Minnesota River from South Dakota include the Little Minnesota River, headwaters of Big Stone Lake and the Whetstone River. Alluvial deposits at the mouth of the Whetstone River formed a natural dam and originally impounding Big Stone Lake.

Below Ortonville, the Minnesota is a small but distinct river. It flows for fifteen miles, passing through the Big Stone-Whetstone Reservoir (constructed during the 1970's) and further down receives the waters of the Yellow Bank River whose headwaters are also in South Dakota. The Upper Minnesota River then meets Marsh Lake and Lac Qui Parle. Both Marsh and Lac Qui Parle lakes are natural impoundments, dammed by alluvial fans of sediment deposited at the mouths of two major tributaries, the Pomme De Terre and Lac Qui Parle rivers respectively. The Pomme De Terre River comes down from the hills of the lake country to the north. The Lac Qui Parle River originates in the Coteau des Prairies, flows northeast through the prairies of the southwest, then confluences with the Minnesota River by Watson. Although they are natural reservoirs, the lakes were subject to some natural fluctuation; dams were built at the outlets for greater water control. The outlet of the Upper Minnesota River Watershed is below the Lac Qui Parle Reservoir, 288 miles upstream from the mouth of the Minnesota River.

3.2 General Geology

The Lower Sioux Community is in the Minnesota River Valley. The pertinent geology and stratigraphy are related to the last glacier that retreated the area approximately 14,000 years ago.

As the glacier retreated north, the melting ice margin headed the ancestral Minnesota River. The glacier eventually retreated north of the topographic divide, near Browns Valley, and meltwater ponded behind the divide to form Glacial Lake Agassiz. When the meltwater raised the lake enough to overtop the drainage divide, a southern outlet stream, the River Warren, discharged from the lake. The River Warren carved the present oversized valley now occupied by the Minnesota River. Lake Agassiz ultimately drained to the northeast, allowing the Minnesota River to aggrade and adjust to the local conditions.

3.3 Site Hydrogeology

Currently, insufficient data exist for a detailed, site-specific, groundwater characterization at the Lower Sioux Community project site. Commonly, groundwater levels in the project area are high. Groundwater will be located within ten feet below the ground surface. Water levels fluctuate seasonally with fall and winter conditions exhibiting the lowest measured water levels as might be expected.

3.4 Seismic Risk and Earthquake History

According to Corps of Engineers Regulation ER 1110-2-1806, Earthquake Design Analysis for Corps of Engineers Projects, the entire state of Minnesota is located within earthquake Seismic Risk Zone 0. The Uniform Building Code of the International Conference of Building Officials assigns every location in the United States to a four-grade Seismic Risk Zone (0 = least risk, 3 = greatest risk). The absence of major or catastrophic earthquakes, coupled with the infrequency of these earthquakes in general, implies an extremely low risk level for seismic activity in the vicinity of the Lower Sioux Community.

3.5 Site Specific Geology

The site is in the Minnesota River Valley, which is a product of ancient glacial river flows incising bedrock and later geomorphological fluvial processes. The area has been developed since the 1880s and reflects the agricultural and mining use typical of the region.

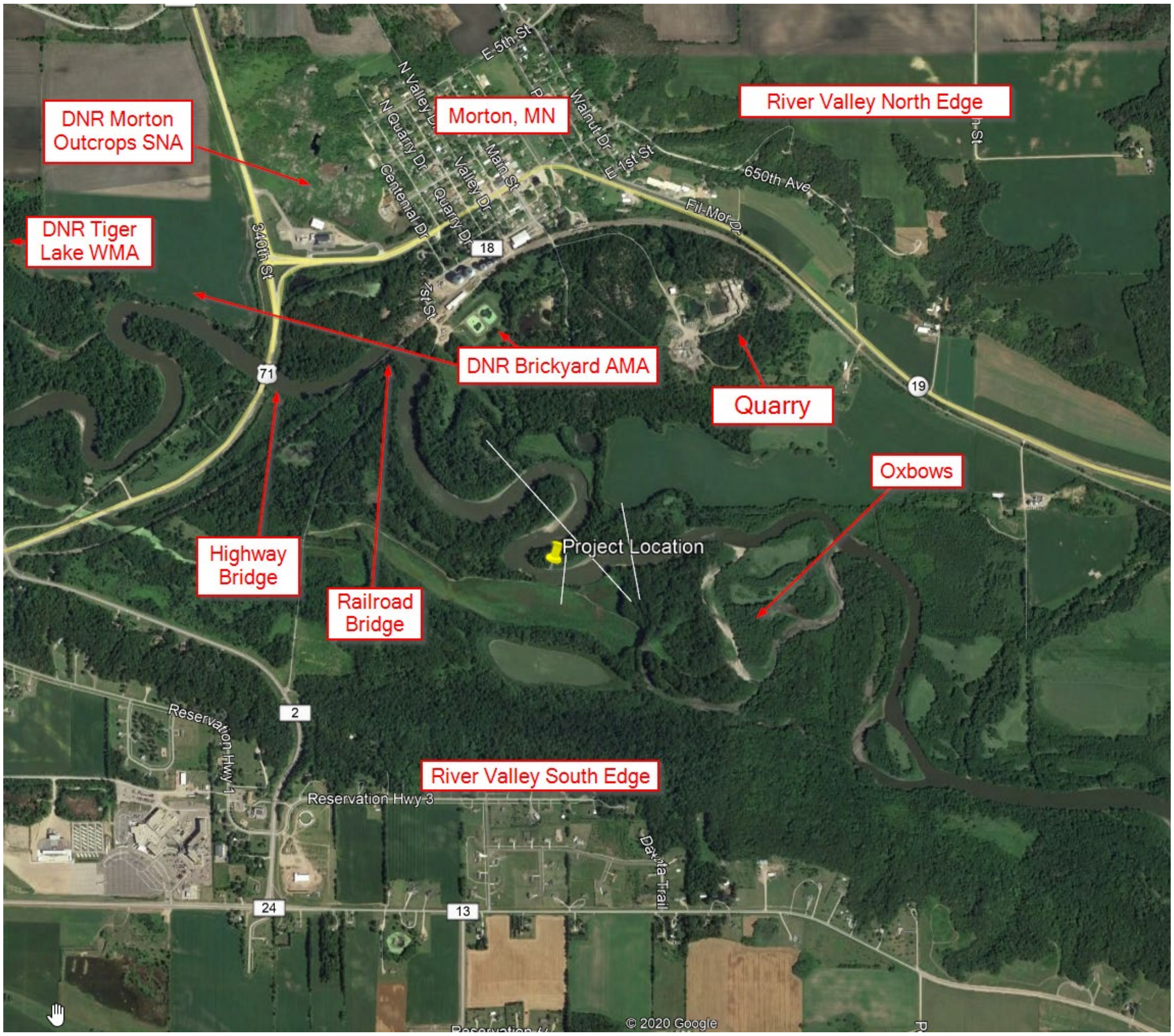


Figure 4 Nearby notable features

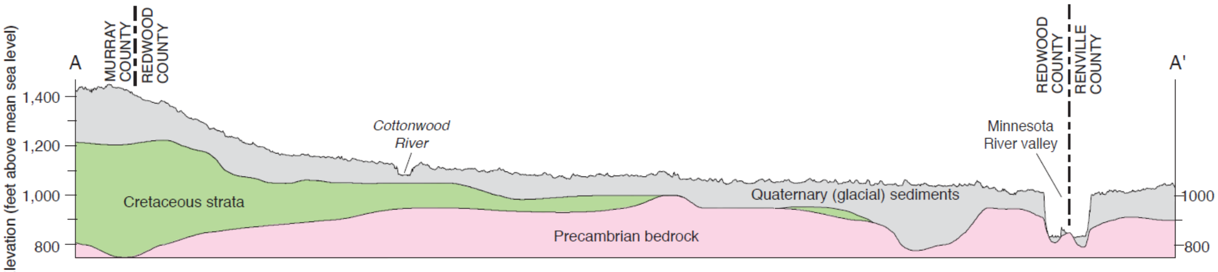


Figure 2. Schematic cross-section (A–A') derived from contoured and gridded surfaces showing elevation of the land surface, bedrock surface including Cretaceous bedrock, and Precambrian bedrock surface (Fig. 1). Note that the cross section is shown with 50x vertical exaggeration and it extends slightly beyond county boundaries; horizontal scale is the same as Figure 1.

Figure 5 Precambrian bedrock exposure and quaternary sediments exist in the Minnesota River Valley (Setterholm, 2016)

3.5.1 Bedrock

The oldest bedrock features in the Minnesota River Valley are Late Archean granite (3 to 2.5 billion years ago or bya) and Middle Archean gneiss (3.6–3 bya). Bedrock at the site is likely a combination of igneous granite (plutons and mafic dikes) and the metamorphosized form of granite called gneiss. The Minnesota Geologic Survey indicates that the bedrock is likely tonalitic to granodioritic orthogneiss from the Morton Block of the Archean (Precambrian) and likely between EL 751 to 800 (Setterholm, 2016). The Minnesota Geologic Survey's Bedrock Geology from State Map Series S-21 from 2011 indicates Granitoid gneiss with amphibolitic to dioritic enclaves, which is part of the Minnesota River Valley subprovince and dates to the Mesoarchean to Paleoarchean Eras.

Pertinent to the project, the site is south of Morton, MN, which is known for continuous gneiss and granite mining operations dating back to 1884 and the Morton Outcrops Scientific and Natural Area (SNA). As the MNDNR states about the SNA:

> *Classified as "Morton Quartz Monzonite Gneiss," this SNA features the oldest known bedrock in Minnesota and among the oldest in the world. Rosy-hued Morton gneiss is a type of crystalline granite, characterized by bands of white quartz, pink and grey feldspar, black biotite and amphibole. It was exposed when the torrent of glacial River Warren formed the Minnesota River Valley roughly 10,000 years ago, scouring through glacial drift of the Des Moines lobe and underlying cretaceous sediments to reveal the ancient bedrock. Today, the Minnesota River flows past to the south, a quarter mile away and 100 feet lower in elevation than the highest point of the SNA. But potholes in the rock here are testament to the time when all was submerged by the swirling waters of River Warren. (Minnesota Department of Natural Resources, n.d.)*

Due to this unique geology, granite and gneiss are often used as riprap in this area.

An outcrop of weathered rock is exposed on the western portion of the project site. Jointing is visibly present. Samples from this outcrop were field identified as granite, which is common for the area.

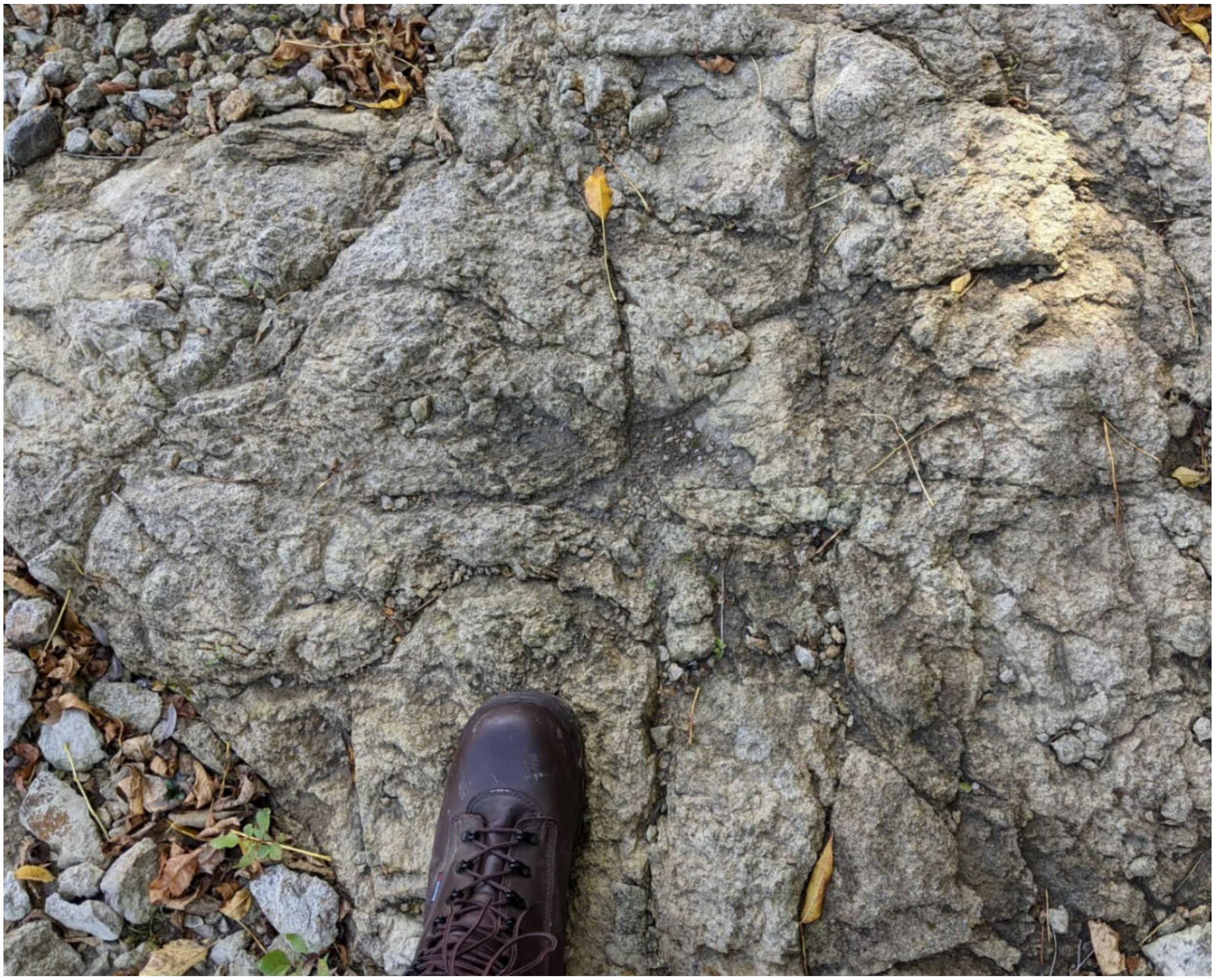


Figure 6 Jointing evident in the outcrop

Weathering along the outcrop varies. The rock is fragmented from freeze/thaw cycles and rounded by the erosive forces of flows. Some of the rock mass appears solid, yet other portions have experienced such significant erosion that portions can be popped off with multiple boot kicks.

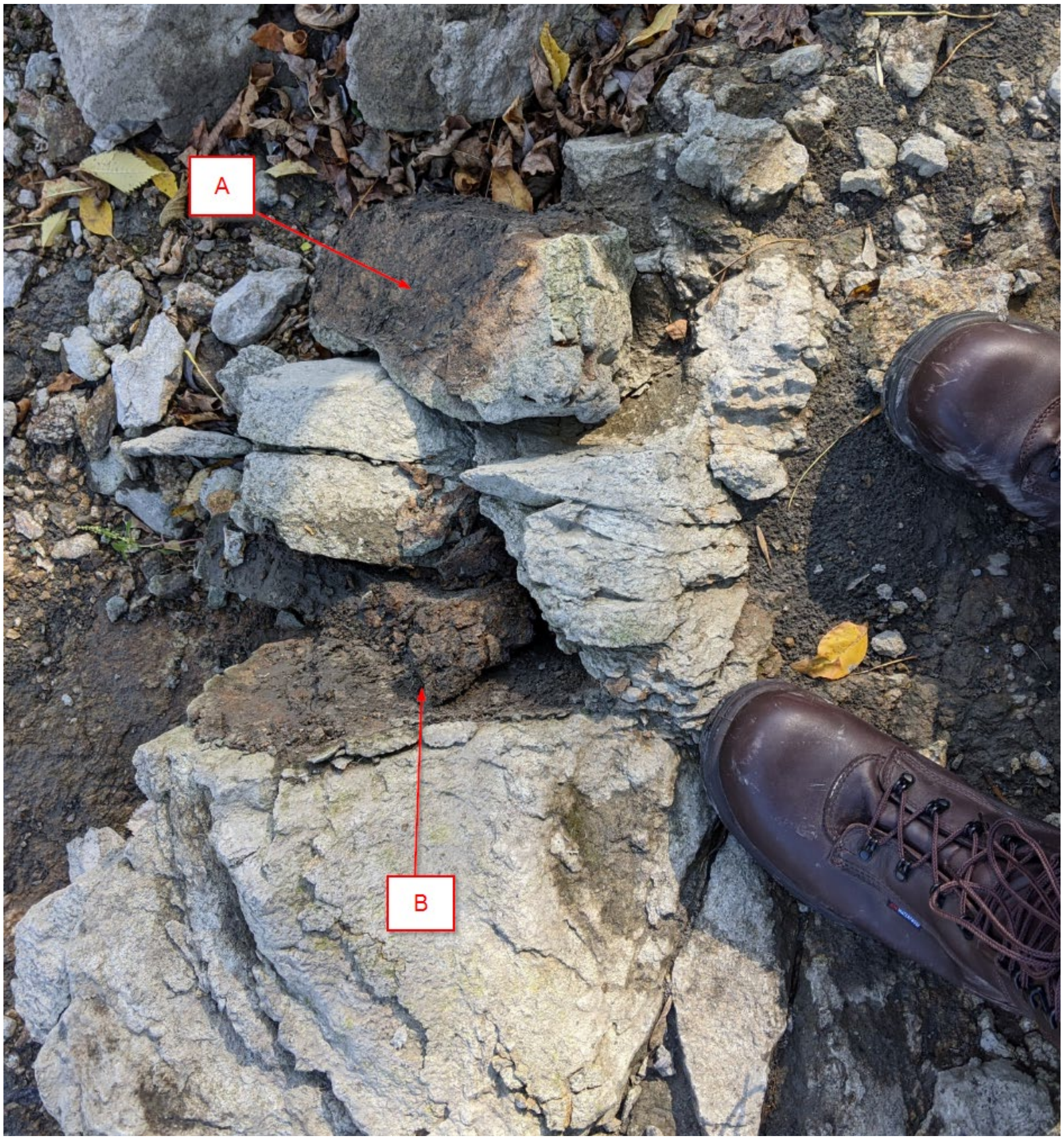


Figure 7 Rock at (A) dislodged with a few boot kicks from (B)

3.5.2 Saprolite

The bedrock is typically weathered as elevation increases, and nearby borings from MNDOT indicate the weathered layers can be between 5 and 20 feet thick. These layers can consist of relatively competent rock to a soil with small amounts of gravel indicating the parent rock. According to the MN Geological Survey, this weathered rock is referred to as saprolite: a residuum formed during extended periods of extensive chemical weathering that converted some to nearly all minerals in the near-surface Precambrian bedrock into clay minerals.

This saprolite has been a major source of commercial mining of kaolin clay in Redwood County, with two mining sites located south of the project site. Kaolin is a primary weathering product of granitoid bedrock (saprolite). Kaolin has a low shrink-swell capacity (Budhu, 2011, p. 54).

“Kaolinite, because it does not absorb water, does not expand when it comes in contact with water. Thus, kaolinite is the preferred type of clay for the ceramic industry” (Nelson, 2014). Recent research indicates that increases in kaolinite content decreases the soil’s friction angle while increasing cohesion (Charkley, Zhang, & Mei, 2019). G&G considered this research while developing the parameters for the clays used in the stability models, which is covered in more detail under Section 5.4.

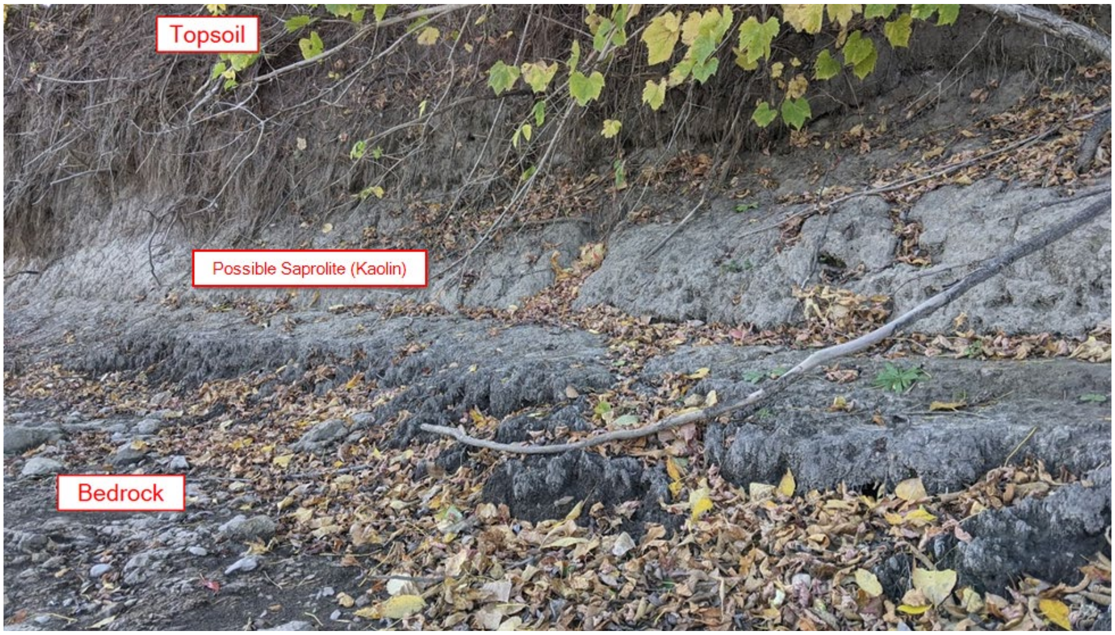


Figure 8 Potential saprolite above bedrock on Reach 3, a sign of possible high kaolin content

3.5.3 Glacial Till

Though no longer present at the project site in the river valley, glacial deposits were likely ultimately eroded from the bottom of the river valley during outwash events of the Lake Agassiz beach failures. Till deposits vary in thickness up to over 200 feet deep outside of the Minnesota River Valley near Redwood Falls, Minnesota.

3.5.4 Alluvial Channel Sediments (Alluvium)

After Lake Agassiz outwash events through the valley, alluvial sediments were deposited. Above the weathered rock and saprolite are alluvial sand deposits.

3.5.5 Recent Alluvium

Recent, upper-level soils consist of stream sediments of the Minnesota River, channel fill of clays, silts, and wetland sediments south of project site. Varying CL and ML are encountered in the 2021 USACE borings, and these fine sediments vary in thickness depending on the depositional mechanism, and the channel topography. The upper portion of the alluvium has organics and is very soft. The lower portion is sparsely organic and soft. It contains fine sands and is greyish brown.

4 Subsurface Investigation

4.1 Review of Existing Borings Nearby

The PDT reviewed publicly available sources for boring data and was only able to locate MNDOT borings nearby the project site. The closest MNDOT borings were performed in two clusters, one within 3500 feet of the project and the other within 6000 feet. The figure below shows these clusters relative to the project site.

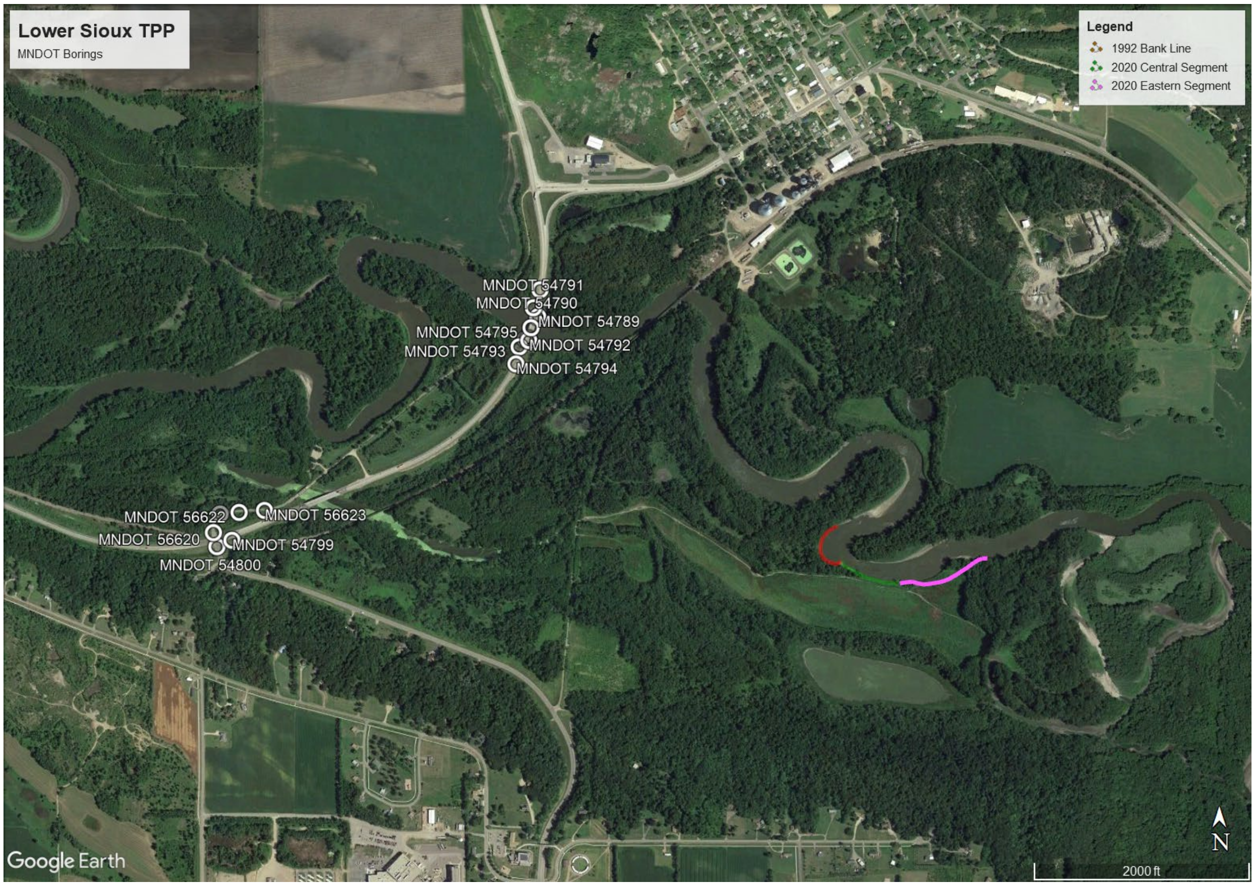


Figure 9 Closest MNDOT borings (locations estimated)

These MNDOT borings provided some insight into the typical alluvium above weathered granite and bedrock common for the area; however, their distance from the project site did not eliminate the need for a subsurface investigation at the project site due to the site's variability (e.g, varying elevations of weathered and exposed bedrock).

These MNDOT borings are present in the attachments to this report.

4.2 Exploration Planning and Execution

Based on the apparent variability present in the MNDOT borings and resource constraints, the PDT planned five machine borings for the project site if the drill crew found optimal conditions; however, the PDT did prioritize the borings based on the historic rates of erosion in case conditions during drilling were suboptimal. Resource constraints did not allow for additional borings, borings by access other than land, or more than one day of borings.

The PDT determined that a spacing of about 200 feet between borings would help characterize variability in the alluvium above the bedrock. From large-scale bedrock maps of the area and rudimentary field measurements, the PDT predicted the drillers would have to extend up to 30 to 40 feet deep to reach bedrock. The PDT requested that drilling be performed to at least below the thalweg or to refusal (e.g., at least 50 blows from SPT).

The PDT did not plan for obtaining rock cores due to the assumption that any exposed rock in the river along the project reaches would be competent enough to construct upon for any of the feasible designs and any unexposed rock would remain buried. The PDT also did not plan borings in any forested areas due to access issues (e.g., trees would need to be cleared, which could exacerbate the erosion).

The borings are displayed in the following figure at their approximate, planned locations and numbered in order of priority.

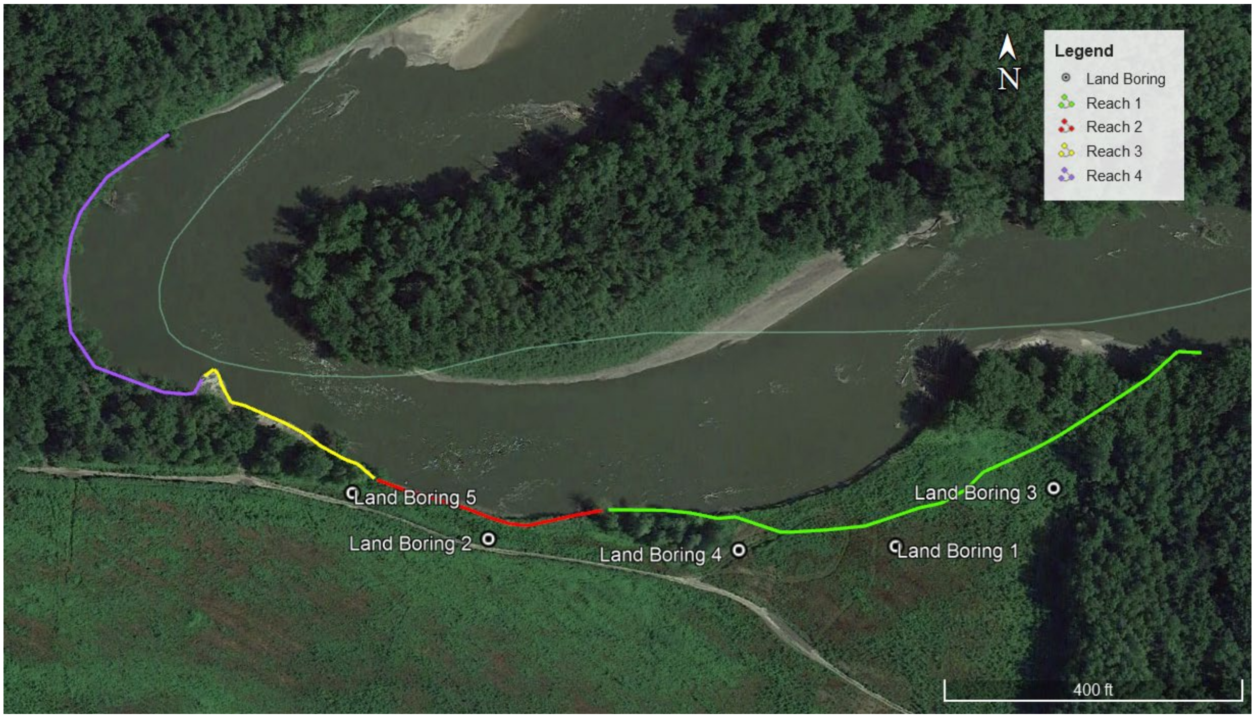


Figure 10 Proposed boring plan

The PDT determined that the first boring would have sampling performed roughly every 5 feet. If drillers encountered a new formation, another sample would be obtained for that new formation.

Additional samples would be obtained at the discretion of the geologist present to account for variability and confirm the underlying stratigraphy.

CEMVP's surveying crew marked the position of the proposed borings before the drillers traveled to the site.

4.3 Obtained Borings

Field conditions proved challenging due to snow and ice, so the drillers were only able to obtain machine borings at the four locations shown in the figure below. Borings were number 21-1M through 21-4M.

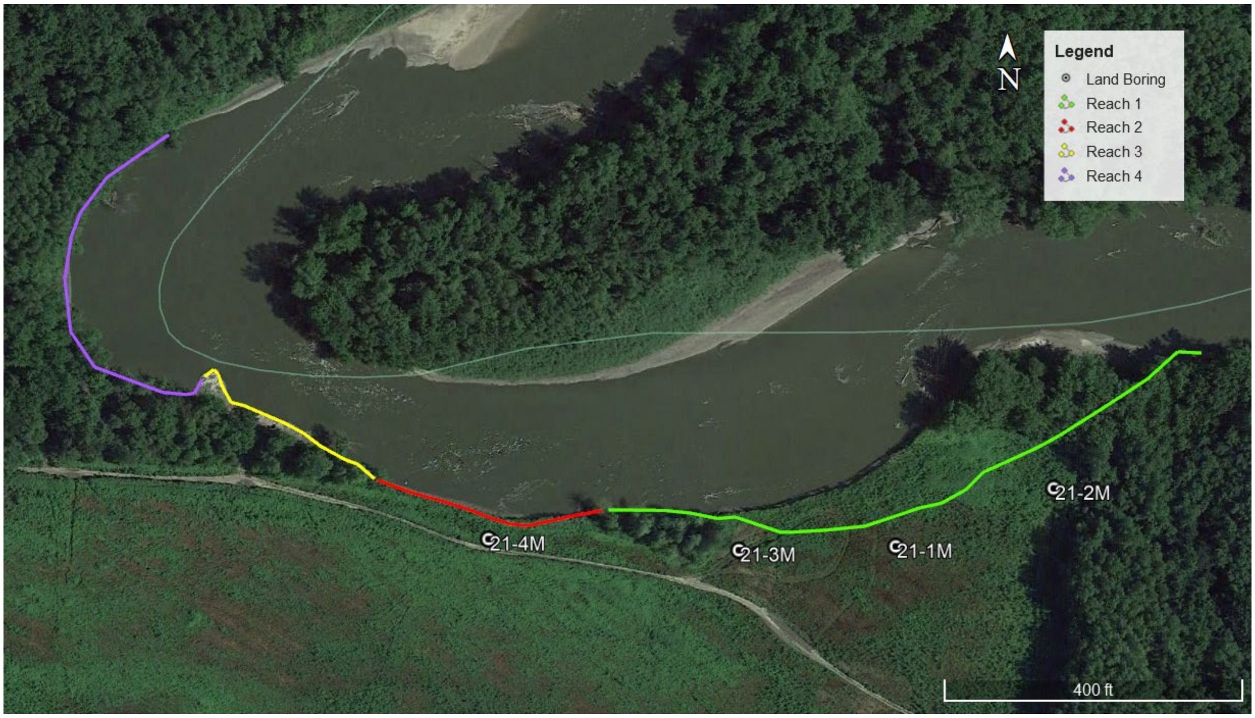


Figure 11 Obtained borings

SPT testing was performed using a 140-pound hammer with a 30-inch drop. An autohammer was used. The drillers ceased at depths when the weathered rock yielded high SPT values (e.g., near or above 50) or indicated refusal below the channel thalweg. The resulting USACE boring logs are available for review in this document under Attachments.

4.4 Site Stratigraphy

From the USACE boring logs and testing, the PDT developed a stratigraphy, which is shown in the following figure.

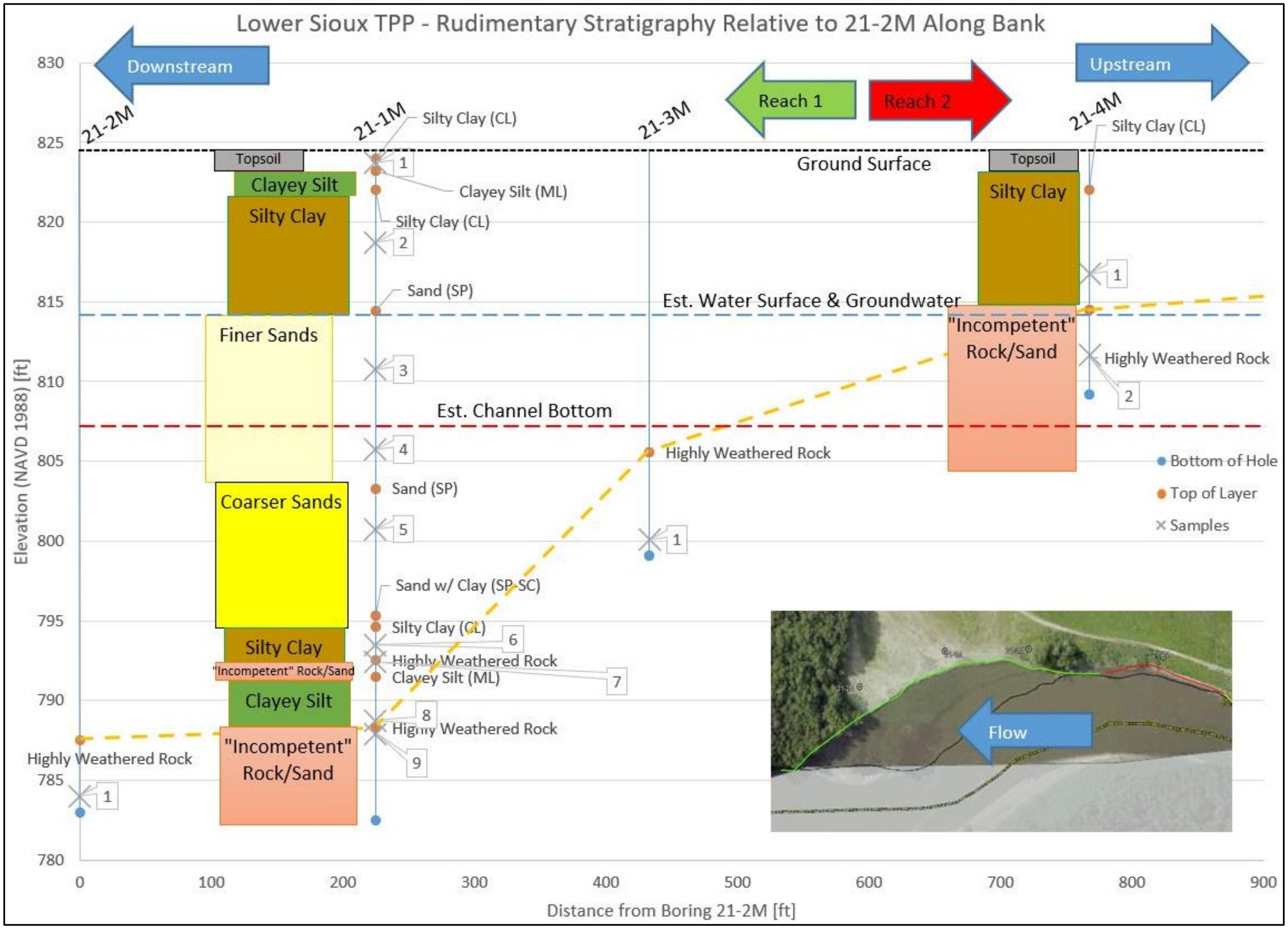


Figure 12 Rudimentary stratigraphy relative to 21-2M along the riverbank

Given the likely alluvial deposition of the units above the weathered bedrock, the cohesive units should be considered normally consolidated.

The weathered bedrock in this area matches the findings of the MNDOT borings, and its presence makes the bedrock outcrop visible in Reach 3 a clear anomaly that is not present in the eroding portions of the bank. This weathered rock is pictured in the sample jars in the figure below and illustrates a shift in color due to the presence of iron.

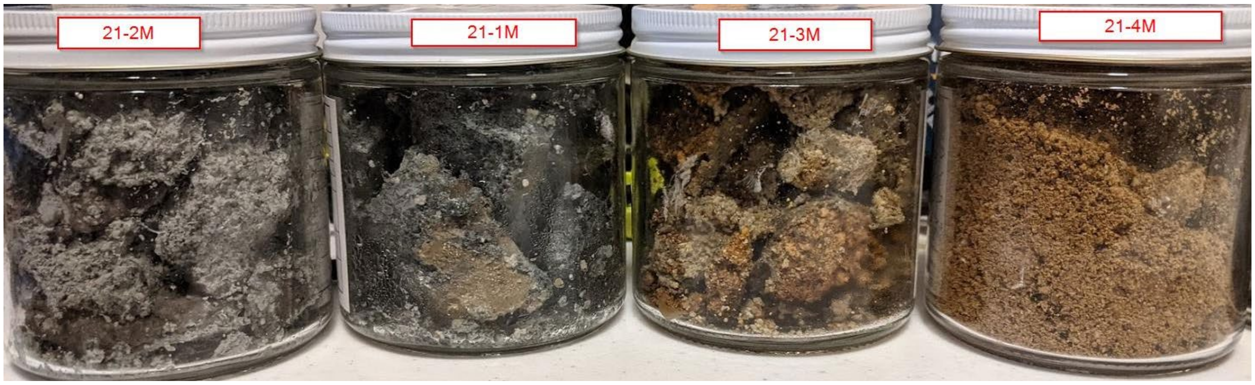


Figure 13 Weathered rock samples from the four borings

Generally, the sands and weathered bedrock will likely have a higher strength for vertical loading than the clays and silts, but these same sands and weathered bedrock provide low resistance to erosion, especially in the form of increased flows and debris impacts which are occurring at the site. These findings confirm why the meander has been slowed in Reaches 3 and 4 by the presence of a bedrock outcrop but continues relatively unabated in Reaches 1 and 2. Without directly applied channel armor over these erosion susceptible materials, the erosion will continue until the river redirects flows.

4.5 Water Levels

Water levels were tested in an offset hole to 21-1M and can be seen on the boring log (see Attachments). Water levels stabilized to an elevation within 45 minutes in the sand layer near the surface water elevation of the river, illustrating high connectivity between the sands and the river itself.

4.6 Sample Testing

Testing was limited due to funding. The testing request and results are available for review in this document under Attachments.

Of the 13 jar samples obtained, the PDT sent 11 jar samples to Braun Intertec for different testing to characterize and confirm the boring logs. Most jar samples (8 total) came from boring 21-1M due to this boring being the most detailed performed. The remaining jar samples came from the other three borings and provided measure of local variability from 21-1M. The testing also allowed development of the geologic conditions and design parameters for use in the GeoStudio stability analysis.

All samples were tested for moisture content. Moisture content tests were selected because they are a relatively inexpensive test that can be used to inform design parameters and the level of fines was unknown before testing. Cohesive units (clays and silts) were tested for liquid and plastic limits, specific gravity, and sieve analysis with hydrometers. Samples were selected based on elevation (i.e., upper and lower cohesive units). Non-cohesive units (sands) were tested with sieve analysis with #200 wash and specific gravity.

4.7 SPT Test Results

Sands were reported as very loose to medium dense. One foot of heave (slough) continued to occur in the sands as well as sand lock and bent shoes during SPT testing, which may have skewed the blow counts. See attached logs for more details.

4.8 Lab Test Results

Atterberg tests revealed the cohesive units were low plasticity silts and clays. Moisture contents revealed the lower unit existed mostly in a plastic state (liquidity indices ranged between 0.25 and 0.44) while the upper unit had liquidity indices of ranging from 0.45 to 0.86, approaching the liquid limit. This upper unit also had the presence of sand at slightly higher amounts than the lower unit.

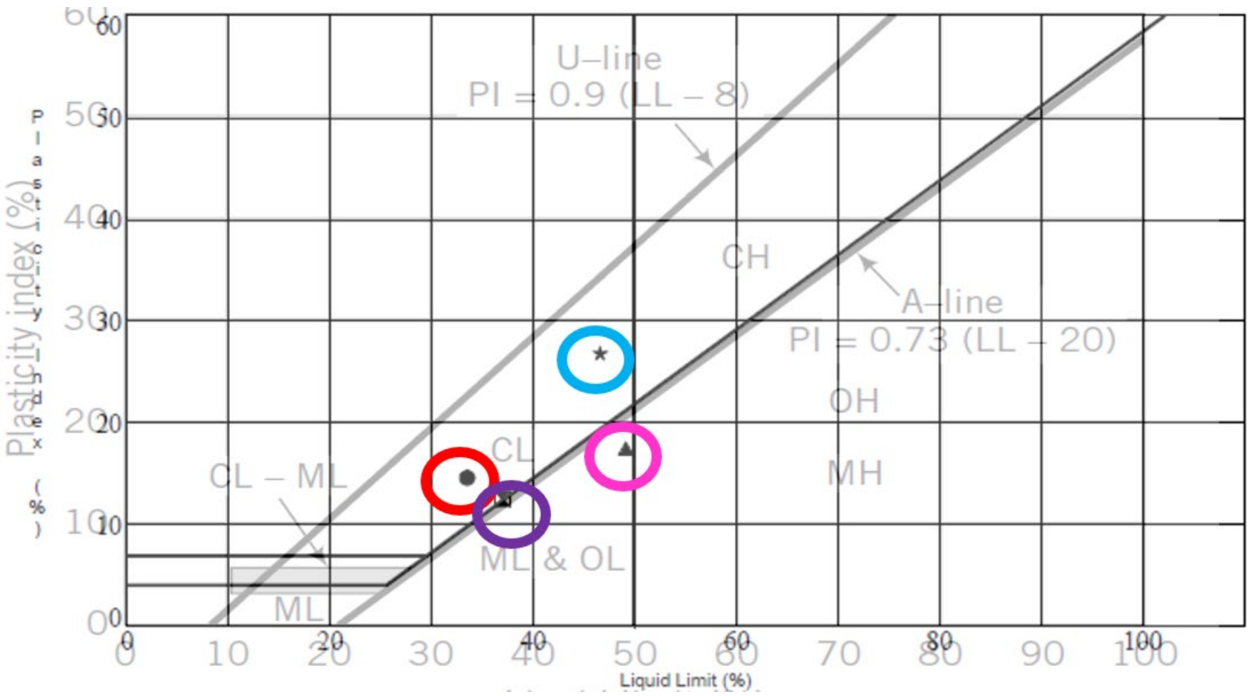
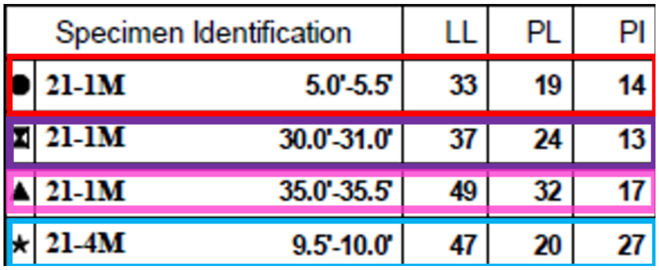


Figure 14 Samples of upper and lower clays plotted

The colors and symbols shown in Figure 14 reference the table below.

Table 1 Samples of upper and lower clays

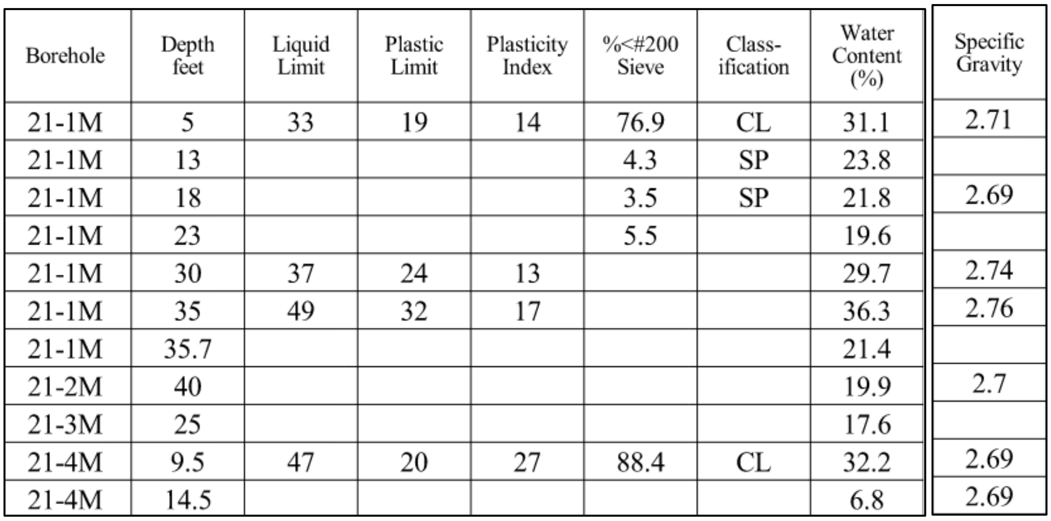


	Specimen Identification		LL	PL	PI
●	21-1M	5.0'-5.5'	33	19	14
⧗	21-1M	30.0'-31.0'	37	24	13
▲	21-1M	35.0'-35.5'	49	32	17
★	21-4M	9.5'-10.0'	47	20	27

Sieve testing of the sands illustrate a unit trending from finer sands to coarser sands as elevation decreased, again reflecting the alluvial deposition of the unit. Fines are not present in significant amounts, and moisture contents across these sand samples were in line with low presence of fines and high saturation. Both results indicate that high connectivity between the river and sands is more likely.

A summary of lab test results are shown in the table below.

Table 2 Lab Test Results Summary



Borehole	Depth feet	Liquid Limit	Plastic Limit	Plasticity Index	%<#200 Sieve	Class-ification	Water Content (%)	Specific Gravity
21-1M	5	33	19	14	76.9	CL	31.1	2.71
21-1M	13				4.3	SP	23.8	
21-1M	18				3.5	SP	21.8	2.69
21-1M	23				5.5		19.6	
21-1M	30	37	24	13			29.7	2.74
21-1M	35	49	32	17			36.3	2.76
21-1M	35.7						21.4	
21-2M	40						19.9	2.7
21-3M	25						17.6	
21-4M	9.5	47	20	27	88.4	CL	32.2	2.69
21-4M	14.5						6.8	2.69

5 Design Parameters

5.1 Unit Weights

The PDT estimated unit weights based on results from nearby MNDOT boring logs, which had testing data for similar geologic formations, and calculations based on Braun Intertec's testing data from USACE-obtained samples. Calculations can be found in Section 13 Attachments. Unit weights used in design are indicated in the table below.

Table 3 Unit weights

Material	Unit Weight (pcf)
Clay	115
Sand	125
Riprap	125
Topsoil	110
Weathered Rock	100

See 10.1.4 for more detail on riprap unit weight (bulk). Previous design iterations had shown 135 pcf (1.82 tons per cubic yard), but this value was modified to assume 125 pcf (1.69 tons per cubic yard), which should match more typical riprap values for the area.

5.2 Permeability Parameters

Machine borings indicated that the sands were hydraulically connected to the river, so the team created stability models based on three river levels provided by H&H (low, normal, and flood stages). Permeability testing was not performed, and permeability parameters were not developed.

5.3 Swell and Settlement Parameters

Because the team initially determined that large structures would not be placed in the river, the team did not obtain undisturbed samples for consolidation testing. The team did not develop consolidation parameters or perform consolidation testing or settlement analysis. The team briefly analyzed the activity of the clays and determined them to be inactive (activity less than 0.75), making swell an unlikely contributing factor to the erosion.

5.4 Shear Strength Parameters

Shear strength parameters for the clay formations is mainly based on index testing correlations from EM 1110-2-1913 supplemented with information from strength testing research on kaolin heavy clays that experience wet-dry cycles (Charkley, Zhang, & Mei, 2019). Values were checked against typical ranges of friction angles and empirical relationships (chiefly Mesri’s 1989 equation) (Budhu, 2011). Moisture content results illustrated the clay was at water contents close to the liquid limit and that collapse potential exists in the upper layers, indicating modeled strengths should be set low.

Shear strength parameters for sand and weathered rock are based on SPT blow counts and geologist classifications of the state of packing (e.g., “very loose”). Sand shear strength parameters were checked against typical ranges of friction angles, and a conservative estimate was selected given the possible skew in SPT blow counts (Budhu, 2011). Weathered rock was given high strength values due to consistently high blow counts and indications from EM 1110-1-2908 that “samples recovered [in weathered rock saprolites]… frequently end up as a disaggregated, crumbly material” that are not representative of the cohesion present in-situ (U.S. Army Corps of Engineers, 1994).

Riprap placement typically assumes that the riprap will be angular and placed in a manner to maximize interlock and minimize segregation. Riprap is typically modeled with an internal friction angle between 35° and 40° depending on the assumptions of how strong that interlock will be and how reduced the segregation is. Given the uncertainty at this stage in design (feasibility), the assumption of 35° as an internal friction angle for riprap is not overly conservative.

Table 4 Shear Strength Parameters

Formation	Long-Term (Drained) Effective Cohesion [psf]	Long-Term (Drained) Effective Friction Angle [°]	End-of-Construction (Undrained) Cohesion [psf]	End-of-Construction (Undrained) Friction Angle [°]
Clay	50	20	200	0
Sand	0	30	0	30
Topsoil	50	10	100	0
Weathered Rock	50	40	50	40
Riprap	0	35	0	35

5.5 Tension Cracks

Attempts at back-calculating strength parameters from tension cracks observed in the field proved difficult given the unknown depth of prairie plant roots present along the bank. Field observations yielded estimates of up to four feet along the unconfined edge of Reach 1, as shown in the figure below.

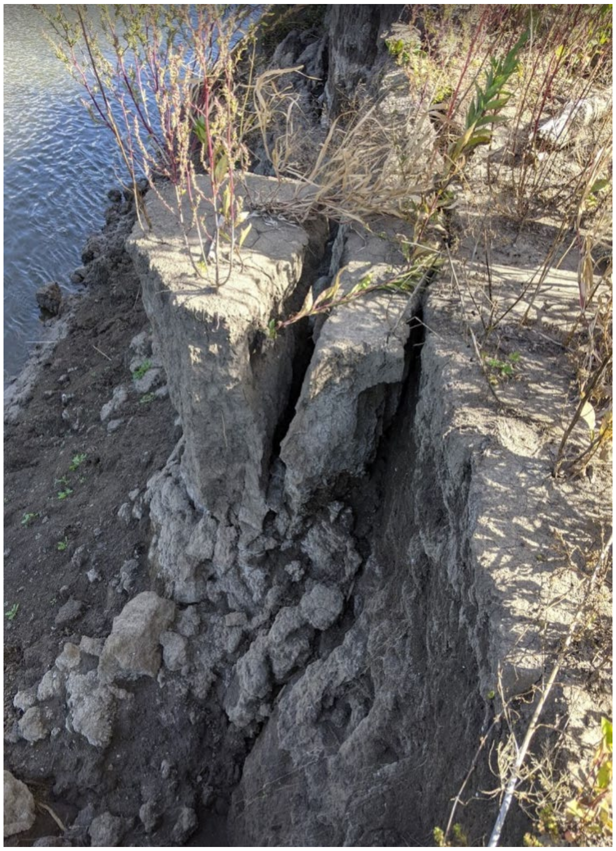


Figure 15 Tension cracks along unconfined bank

To model tension cracks in the computer-based models, the team used the method outlined in EM 1110-2-1902 in Appendix C (U.S. Army Corps of Engineers, 2003). See Section 6.5 of this report for more information.

6 Design and Analysis

Design and analysis during the feasibility stage consisted of selecting appropriate factors of safety for the project's slope stability and determining applicable design constraints from the literature. Riprap and bedding gradation and section sizing are covered in Section 10 of this report.

6.1 Constraints

The team considered the following design constraints related to geotechnical engineering.

6.1.1 Erosion resistance of exposed clays

Per EM 1110-2-2300, "performance of a clay is hard to predict, but… [c]lay material with a liquid limit above 40 percent and that plot above the "A" line would normally qualify as 'erosion resistant'" (U.S. Army Corps of Engineers, 2004, pp. C-5). A single sample tested in the upper clays in Reach 1 did meet these criteria; however, other samples tested did not. Exposed clays in the upper layers of the site also exhibit likelihood of erosion during flood events, as pictured below.

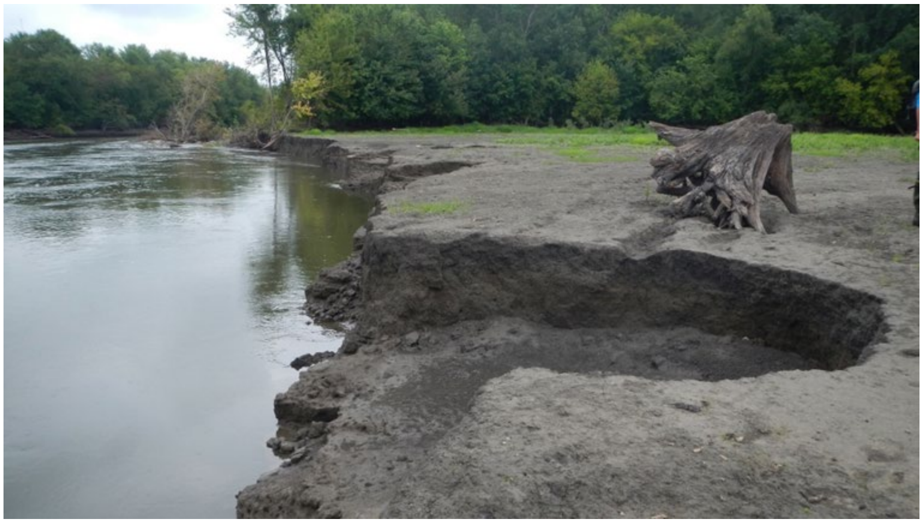


Figure 16 Significant Erosion on Reach 1 post-flood (estimated photo date is 2020)

Given this information, the history of debris impacts, the underlying sands, and the obvious continued erosion at the site, the team determined that the clays exposed at the site could not be relied upon to prevent erosion alone. The team deemed slope protection up the bank to be necessary to arrest the erosion during higher-than-normal stages.

6.1.2 Debris Impact

As detailed in Section 10.1, this site experiences heavy debris loads. Per EM 1110-2-1601, “riprapped slopes on streams with heavy debris loads should be no steeper than 1V on 2.5H” (U.S. Army Corps of Engineers, 1994, pp. 3-12). Alternative 3 calls for slopes at 1V:2H. Although seemingly contrary to this guidance from EM 1110-2-1601, H&H indicated that debris flows, although a concern, would be mitigated by the vanes.

Given the low consequences (no life-safety concerns) of the project, the PDT determined that these concerns were not a reason to extend the revetment out at a 1V:2.5H as recommended by EM 1110-2-1601. Extension of the revetment out at a steeper angle risked creating stage impacts and delaying the project given the limited funding (i.e., overflow outside the FEMA designated flood plain).

6.1.3 Operations and Maintenance (O&M)

Periodic additions of stone may be necessary. O&M should be further evaluated during the P&S stage.

6.2 Factor of Safety Requirements for Slope Stability

Per EM 1110-2-1902, the typical minimum acceptable values of factor of safety for a slope classified as “other” are about 1.3 for end of construction, 1.5 for normal long-term loading, and 1.1 to 1.3 for rapid drawdown (U.S. Army Corps of Engineers, 2003, pp. 3-4). Considering that this project has no consequences in terms of structures, utilities, or life-safety concerns, the team determined that the following factors of safety would be applicable to the slope stability analysis.

- 1.1 for End of Construction
- 1.2 for Long-Term Loading
- 1.1 for Rapid Drawdown

6.3 Infinite Slope Analysis

Infinite slope analysis assuming no seepage is a quick method for determining whether the riprap would remain stable given the selected parameters. Given a slope of 1V:2H (26.6°), the factor of safety would be 1.4 assuming the failure occurs through the riprap alone, meeting all required factors of safety. The following sections illustrate the use of GeoStudio to verify this simple calculation.

6.4 Overall Computer Modeling Methodology and Software Set Up

The team completed stability analyses following guidance outlined in EM 1110-2-1902 (U.S. Army Corps of Engineers, 2003). The team performed analyses on a critical section for the end-of-construction (undrained strengths), long-term (drained strengths), and rapid drawdown cases (a mixture of drained and undrained strengths). An additional case of loading by construction equipment during end-of-construction was also considered using a 250 pounds per linear foot surcharge.

For all models, given the low-permeability soils, the team performed the end-of-construction analysis using total stress conditions and long-term stability analyses using effective stress conditions with pore-water pressures at the steady-state condition. Given the hydrostatic conditions determined in the borings and the clear linkage to the river stage, the team modeled the groundwater as a horizontal piezometric line.

For the required limit equilibrium analysis, the team used the 2021 version of GeoStudio's Slope/W software for stability analyses (Geo-Slope International Ltd., 2020). The team set the analysis type to Spencer, used grid and radius slip surface delineations, set minimum slip surface depths to 2 feet, set the number of slices to 30, enabled optimization, and had the software perform 100 iterations.

6.5 Water Surface Elevations (Stages)

G&G modeled stages based on analysis provided by H&H. The three stages are flood stage (EL 825.6), normal (EL 820.6), and low (EL 813.0). For rapid drawdown analysis, the team analyzed drawdowns from flood stage to low stage.

6.6 Tension Cracks

EM 1110-2-1902 Slope Stability, Appendix C, covers tension crack depth requirements for modeling:

> "Because few soils have tensile strength that can be relied on for slope stability, tensile stresses should be eliminated before an analysis is considered acceptable. Tensile stresses can be eliminated from an analysis by introducing a vertical tension crack near the upper end of the slip surface... a range of crack depths can be assumed and the factor of safety calculated for each depth. The crack depth producing the minimum factor of

> safety is used for final analyses. The depth yielding the minimum factor of safety will correspond closely to the depth where tensile stresses are eliminated, but positive (driving) stresses are not." (U.S. Army Corps of Engineers, 2003).

The team considered the potential for the development of a tension crack for each analysis. The team ran the first analysis of a particular stability case and flood load without a tension crack. If the software returned a critical slip surface with tension forces, the team inserted a tension crack and varied the depths to return the shallowest tension crack depth that removed the tension forces. The team varied these depths by one-foot increments. After removing these tensile forces, the team filled the tension crack with water in the model to represent the critical state. This iterative method provided multiple critical failure surfaces with varied factors of safety; however, the results are similar and exceed the required factor of safety in each iteration. In other words, variation of the tension crack was not a controlling factor in any of the stability analyses.

For the existing slope in the end-of-construction case, the tension crack was generally 4 feet in depth for flood stage (EL 819.0), 9 feet in depth for low stage (EL 814.0), and 6 feet in depth for normal stage (EL 817.0). For the existing slope in the long-term case, the tension crack was generally 1 foot in depth for flood stage (EL 822.0), 9 feet in depth for low stage (EL 814.0), and 4 feet in depth for normal stage (EL 819.0). For the existing slope in the rapid drawdown from flood stage to low stage, the tension crack was generally 4 feet in depth (EL 819.0).

For models of the during- and post-construction slope, no tension cracks were necessary given that the critical slip surfaces were through the riprap (no cohesion).

7 Settlement and Seepage Results

Settlement and seepage analysis were not performed. Settlement of the slopes would increase the strength of the clays and make the slopes shallower, increasing the resulting factor of safety. As stated earlier, borings were limited but indicated the sands are hydraulically connected to river stages (see Section 4.3).

8 Stability Results and Analysis

Results of the GeoStudio model runs are indicated in the tables below.

The existing slope model indicates that failure is occurring due to loss of support from erosion of sands at the slope toe and block-topple of the clays above. Absent significant testing, the modeled parameters are conservative but not overly so. Considering the rapid erosion of this slope, multiple failure mechanisms may be occurring simultaneously (e.g., loss of support and slides). See Table 5 for results of the GeoStudio model of the existing slope.

The TSP model indicates all required factors of safety area passed. See Table 6.

During DQC review, a comment was brought forward that fill could be placed beneath the minimum required thickness of riprap as a cost savings measure. To determine if fill could be used from on-site materials, three separate GeoStudio models were run: fill as topsoil, clay, or sand. Only sand passed the required factors of safety and should be investigated further during P&S with additional cross sections. See Tables 7, 8, and 9.

Table 5 GeoStudio Results – Existing Slope

Stage	Case	Surcharge?	Calculated FS	Required FS	Failure?
Flood	End-of-Construction	No	0.62	N/A	N/A
	Long-Term	No	0.47	N/A	N/A
Normal	End-of-Construction	No	0.65	N/A	N/A
	End-of-Construction	Yes	0.69	N/A	N/A
	Long-Term	No	0.30	N/A	N/A
Low	End-of-Construction	No	0.12	N/A	N/A
	Long-Term	No	0.24	N/A	N/A
Flood-to-Low	Rapid Drawdown	No	0.35	N/A	N/A

Table 6 GeoStudio Results – During- and Post-Construction for Alternative 3 – 35° Internal Friction Angle for Riprap – Slope 1V:2H

Stage	Case	Surcharge?	Calculated FS	Required FS	Failure?
Flood	End-of-Construction	No	1.44	1.10	No
	Long-Term	No	1.43	1.20	No
Normal	End-of-Construction	No	1.33	1.10	No
	End-of-Construction	Yes	1.37	1.10	No
	Long-Term	No	1.32	1.20	No
Low	End-of-Construction	No	1.36	1.10	No
	Long-Term	No	1.38	1.20	No
Flood-to-Low	Rapid Drawdown	No	1.38	1.10	No

Table 7 GeoStudio Results – During- and Post-Construction for Alternative 3 – 35° Internal Friction Angle for Riprap – Slope 1V:2H – Random Fill as Topsoil Beneath 27” of Riprap

Stage	Case	Surcharge?	Calculated FS	Required FS	Failure?
Flood	End-of-Construction	No	1.13	1.10	No
	Long-Term	No	1.07	1.20	Yes
Normal	End-of-Construction	No	0.89	1.10	Yes
	End-of-Construction	Yes	0.87	1.10	Yes
	Long-Term	No	0.94	1.20	Yes
Low	End-of-Construction	No	0.56	1.10	Yes
	Long-Term	No	0.72	1.20	Yes
Flood-to-Low	Rapid Drawdown	No	0.55	1.10	Yes

Table 8 GeoStudio Results – During- and Post-Construction for Alternative 3 – 35° Internal Friction Angle for Riprap – Slope 1V:2H – Random Fill as Clay Beneath 27” of Riprap

Stage	Case	Surcharge?	Calculated FS	Required FS	Failure?
Flood	End-of-Construction	No	1.44	1.10	No
	Long-Term	No	1.43	1.20	No
Normal	End-of-Construction	No	1.33	1.10	No
	End-of-Construction	Yes	1.17	1.10	No
	Long-Term	No	1.26	1.20	No
Low	End-of-Construction	No	0.92	1.10	Yes
	Long-Term	No	1.08	1.20	Yes
Flood-to-Low	Rapid Drawdown	No	0.81	1.10	Yes

Table 9 GeoStudio Results – During- and Post-Construction for Alternative 3 – 35° Internal Friction Angle for Riprap – Slope 1V:2H – Random Fill as Sand Beneath 27” of Riprap

Stage	Case	Surcharge?	Calculated FS	Required FS	Failure?
Flood	End-of-Construction	No	1.36	1.10	No
	Long-Term	No	1.36	1.20	No
Normal	End-of-Construction	No	1.26	1.10	No
	End-of-Construction	Yes	1.24	1.10	No
	Long-Term	No	1.26	1.20	No
Low	End-of-Construction	No	1.23	1.10	No
	Long-Term	No	1.22	1.20	No
Flood-to-Low	Rapid Drawdown	No	1.21	1.10	No

Although only briefly covered in the tables above, surcharge of the existing bank by construction vehicles may induce instability. See Section 9.2 for more details.

Plates of the GeoStudio model definitions and results can be found in the attachments to this appendix.

9 Constructability

The following section covers constructability of the project.

9.1 Vegetation

During P&S, design should make every attempt to preserve existing vegetation and create additional habitat. Mitigation strategies through strategic planting and revegetation of the upper portions of the slopes, including willow poles, and riprap key-ins should be considered during P&S. The team discussed the potential for a contractor to construct an entrance point with a gradual lowering of the slope at the intersection of reaches 2 and 3 to allow placement of stone near the toe of reaches 1 and 2 and to preserve the existing vegetation along reach 3. This entrance point could later be used as a boat ramp or access. This discussion was not incorporated into plans generated during feasibility; however, it should be considered during P&S.

9.2 Construction Sequencing

Given the findings in Section 8, construction equipment and stockpiling should likely avoid using the tops of slopes. Access to the river and creation of a stable working platform is likely necessary. The outcropping could be used as a stable platform for construction of toe features initially. As rock is placed and stabilizes the bank toe, construction equipment can proceed to use the bank as a construction platform. These assumptions should be revisited during P&S.

9.3 Access Road

Construction at the site will require an access road consisting of a geotextile beneath an aggregate overlay. This access road will follow the existing dirt road. The team considered the following geotechnical factors affecting this access road:

(1) The overlying clays serving as the subbase of the access road would be weak (based on the obvious rutting from small truck traffic present at the site and the parameters determined in Section 5.4);
(2) A geotextile was considered necessary during Feasibility design to prevent pumping of the underlying soils into the aggregate and would help improve later access road removal efforts; and
(3) The aggregate sizing, geotextile parameter selection, and whether geogrid is advisable will be finalized during P&S.

The culvert and Texas crossing that currently exist along the access road alignment have not had a structural analysis, and their disrepair is concerning (see figures below). P&S should include structural analysis of these structures to determine if temporary reinforcement, buttressing, or repair is needed before passing heavy construction equipment over or around these structures.

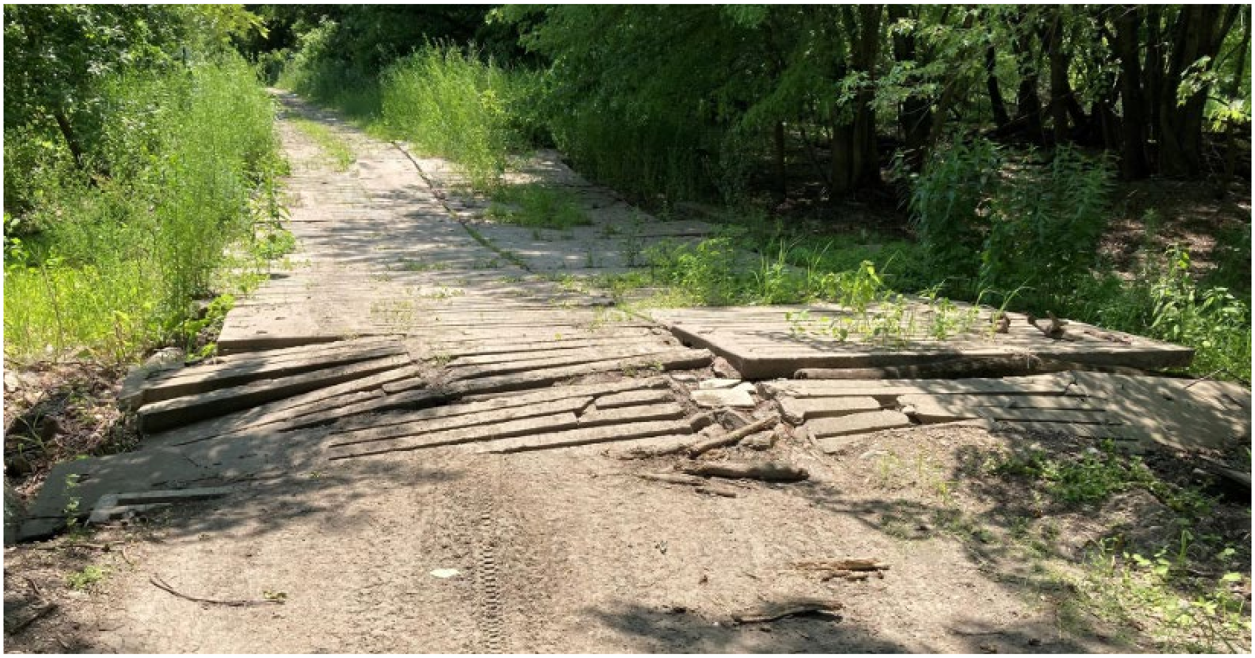


Figure 17 Texas crossing (damage, including erosion, concrete loss, debris impaction)

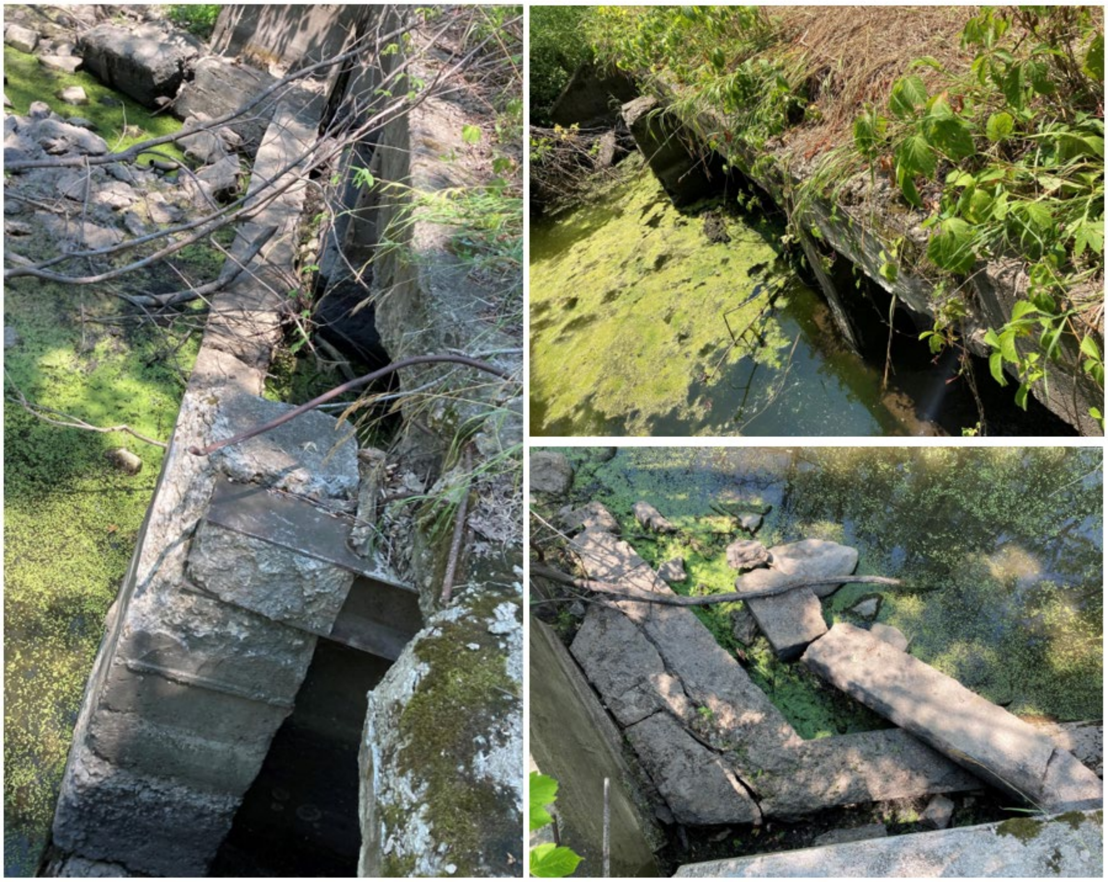


Figure 18 Culvert (damage, including exposed reinforcing steel and significant section loss)

10 Materials

10.1 Riprap

Riprap is required to prevent the slope from continued erosion. G&G assumed a specific gravity of 2.65 for the riprap, which is commonly assumed for CEMVP's AOR. The PDT eventually selected an R20 gradation for this stage in design.

The following sections cover analysis performed during feasibility stage related to riprap:

- H&H requirements provided to G&G (titled H&H Requirements);
- G&G selection of MVP's R20 gradation with comparison to USACE guidance and more recent BOR guidance (titled Gradation Development);
- G&G determination of the minimum section thickness given an R20 gradation (titled Section Thickness); and
- G&G determination of a bulk weight to volume conversion factor (titled Riprap Bulk Weight-to-Volume Conversion Factor).

10.1.1 H&H Requirements

H&H provided the following values for riprap:

Table 10 H&H-provided weights for riprap gradation design

Value	Weight [lbs]
W50 maximum	11
W50 minimum	7
W30 maximum	6

To assist the reader in envisioning the size of this riprap, conversions for diameter assuming 165 pounds per cubic foot are shown in the table below:

Table 11 H&H-provided weights converted to diameter of rock assuming 165 pcf

Weight [lbs]	Cube Size [inch]	Sphere Size [inch]	Average between Cube and Sphere Size [inch]
11	4.9	6.0	5.4
7	4.2	5.2	4.7
6	4.0	4.9	4.5

10.1.2 Gradation Development

EM 1110-2-1601 provides guidelines for “closed” and “open” gradations and indicates that “[s]tandardized gradations” that are “relatively narrow range in sizes” use a ratio of D_{85} to D_{15} of 1.4 to 2.2, but some applications allow for wider ranges as well (up to a ratio of 3) (U.S. Army Corps of Engineers, 1994, pp. 3-2).

Using H&H-provided values, the team followed the steps outlined in EM 1110-2-1601’s Appendix F for “closed” and “open” gradation bands (U.S. Army Corps of Engineers, 1994, pp. F-6). The results are shown in Figure 19. The team then created a gradation that followed the “open” gradation band and met H&H-proposed values, as shown Figure 20, and determined the ratio of D_{85} to D_{15} for this gradation met EM 1110-2-1601’s criteria.

Due to EM 1110-2-1601 being 27 years old, the team searched for newer guidance that incorporated advances in riprap research. BOR provides an updated method for sizing riprap in Design Standard Number 13, Chapter 7 (U.S. Department of the Interior, Bureau of Reclamation, 2014). Given the 20 years between publications, the team considered the use of BOR guidance appropriate.

BOR riprap sizing guidance requires 20% (tight) or 35% (wide) gradation bands “if the availability of properly sized material is a concern” (U.S. Department of the Interior, Bureau of Reclamation, 2014, pp. 7-20). Using H&H’s provided weights and BOR’s riprap sizing guidance for 20% (tight) and 35% (wide) gradation bands, the PDT determined the minimum gradations BOR would recommend, as shown in Figure 21 (U.S. Department of the Interior, Bureau of Reclamation, 2014, pp. 7-19).

As is typical of riprap design, available riprap gradations were limited. C&S provided information that riprap gradations available at nearby quarries were limited to standard gradations familiar to said quarries, namely MNDOT gradations and CEMVP's gradations established in the 1990s, so the use of non-standard gradations like the developed bands in Figure 20 and Figure 21 may prove difficult during P&S. Thus, the team compared MNDOT gradations and CEMVP's gradations established in the 1990s to H&H-provided values to determine which standard riprap gradation would be the most acceptable at this stage in design (see Figure 22).

Additionally, the team considered the following factors:

- Per EM 1110-2-1601, the W_{50} minimum should exceed 80 pounds to prevent theft and vandalism if it is a concern. R20's W50 minimum is 20 pounds and is therefore theoretically subject to vandalism.
- Debris loads, including ice jams and downed trees, are often present in the Minnesota River nearby the site (U.S. Army Corps of Engineers, CRREL, 2021). Larger gradations will have a higher likelihood of survival due to greater resistance to "impact and flow concentration effects" (U.S. Army Corps of Engineers, 1994, pp. 3-11). R20 is larger than the H&H-generated requirements for flow, but impact and flow concentration effects should be more closely examined during P&S to determine if larger gradations would be more applicable.
- Per C&S, slightly larger gradations were not expected to increase project costs significantly or require additional equipment that would not already be used to place the smaller standard gradations.
- Accidental dropping from excessive heights may cause additional breakage and segregation. Larger gradations may be reduced in size after construction and will be more likely than smaller gradations to meet H&H requirements after construction.
- Larger rock gradations create larger voids, which in turn produce "improved habitat for fish" (U.S. Army Corps of Engineers, 2012, pp. 4-28).
- "Placement of smaller stone in a fast moving current could cause a significant loss of stone," so larger gradations will be more likely to survive if the river stage is high during construction (U.S. Army Corps of Engineers, 2012, pp. 4-30).
- Ice plucking is less likely as stone size increases, and shallow slopes (1V:3H) can sustain little to no damage by ice shoving if the maximum riprap stone (D_{100}) is twice the ice thickness (Sodhi, Borland, & Stanley, 1996, p. 4 and 20). Unfortunately, no data was available for ice thickness on the Minnesota River at the project location.

Based on these considerations, the PDT selected CEMVP's R20 riprap gradation. Detailed explanation for this selection follows:

- Commonly used in CEMVP's AOR and developed in CEMVP, R20 is a gradation band that is available nearby the project site per C&S and has multi-decadal history of successful use in similar applications.
- R20 is larger than the gradation bands resulting from either USACE's or BOR's recommended gradation bands generated from H&H-provided values. The larger sizes

will alleviate concerns about breakage, underwater placement, high stage placement, and debris loading while creating more beneficial fish habitat.

- R20 generally meets EM 1110-2-1601's gradation bands when W50 minimum is set to 18 pounds, which is within the EM's requirement that the "upper limit of W50 stone should not exceed: five times the lower limit of W50 stone" set by H&H-provided requirements (U.S. Army Corps of Engineers, 1994, pp. F-6). See Figure 23.
- R20 does not match BOR recommendations precisely; however, a custom gradation that meets these recommendations is not an available option per C&S. See Figure 24.
- R20 does not meet vandalism prevention weight criteria (U.S. Army Corps of Engineers, 1994, pp. 3-6). The team determined that theft and vandalism would be a minor concern given how remote the location is and given that normal O&M may require periodic addition of stone (see Section 11.2).

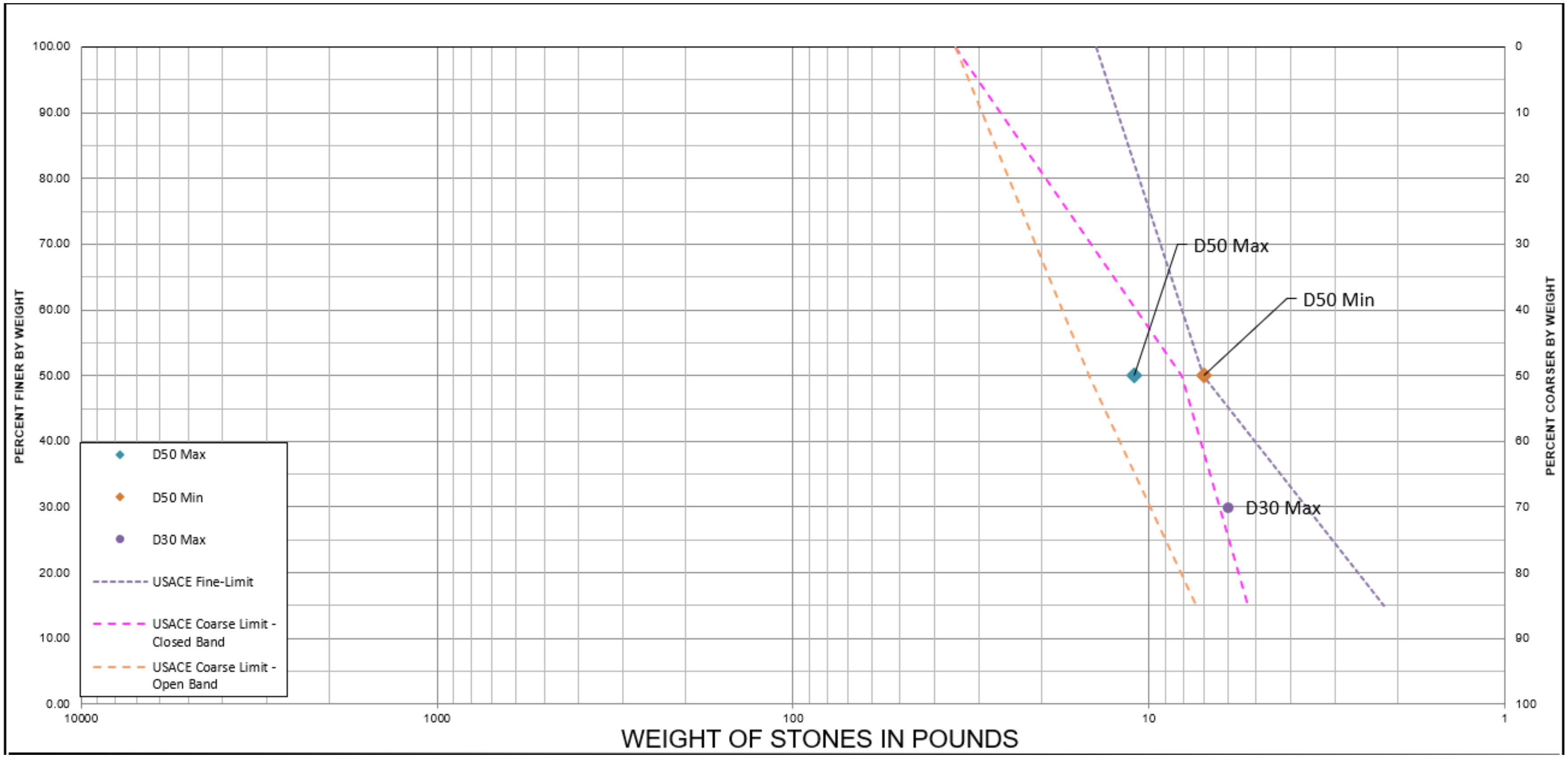


Figure 19 Estimated riprap gradation bands following guidance from EM 1110-2-1601. D50 max, D50 min, and D30 max are values determined by H&H.

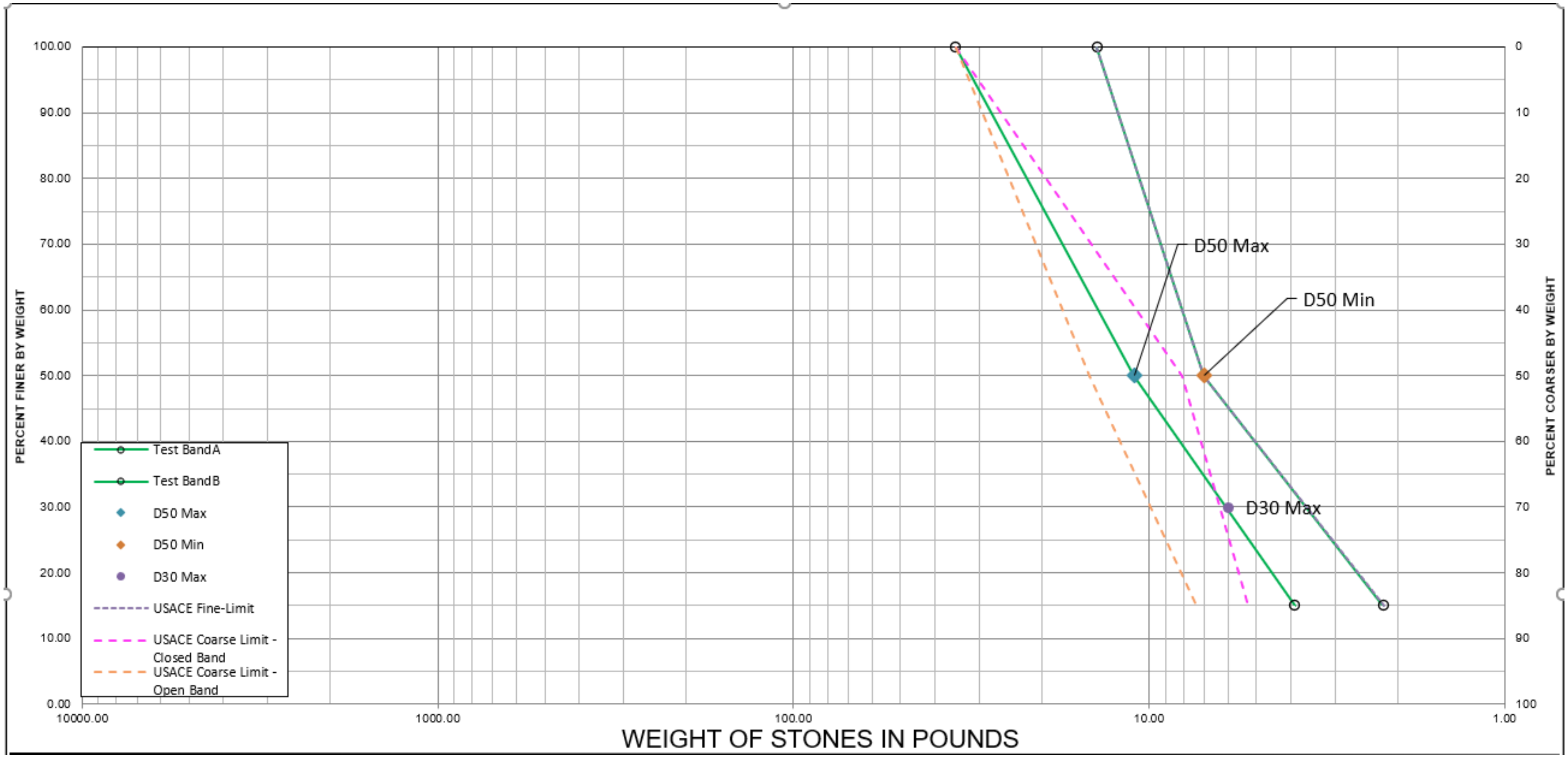


Figure 20 Test band shown meeting EM 1110-2-1601's design guidance—including a D85/D15 ratio of 1.4 to 1.5—and H&H required values.

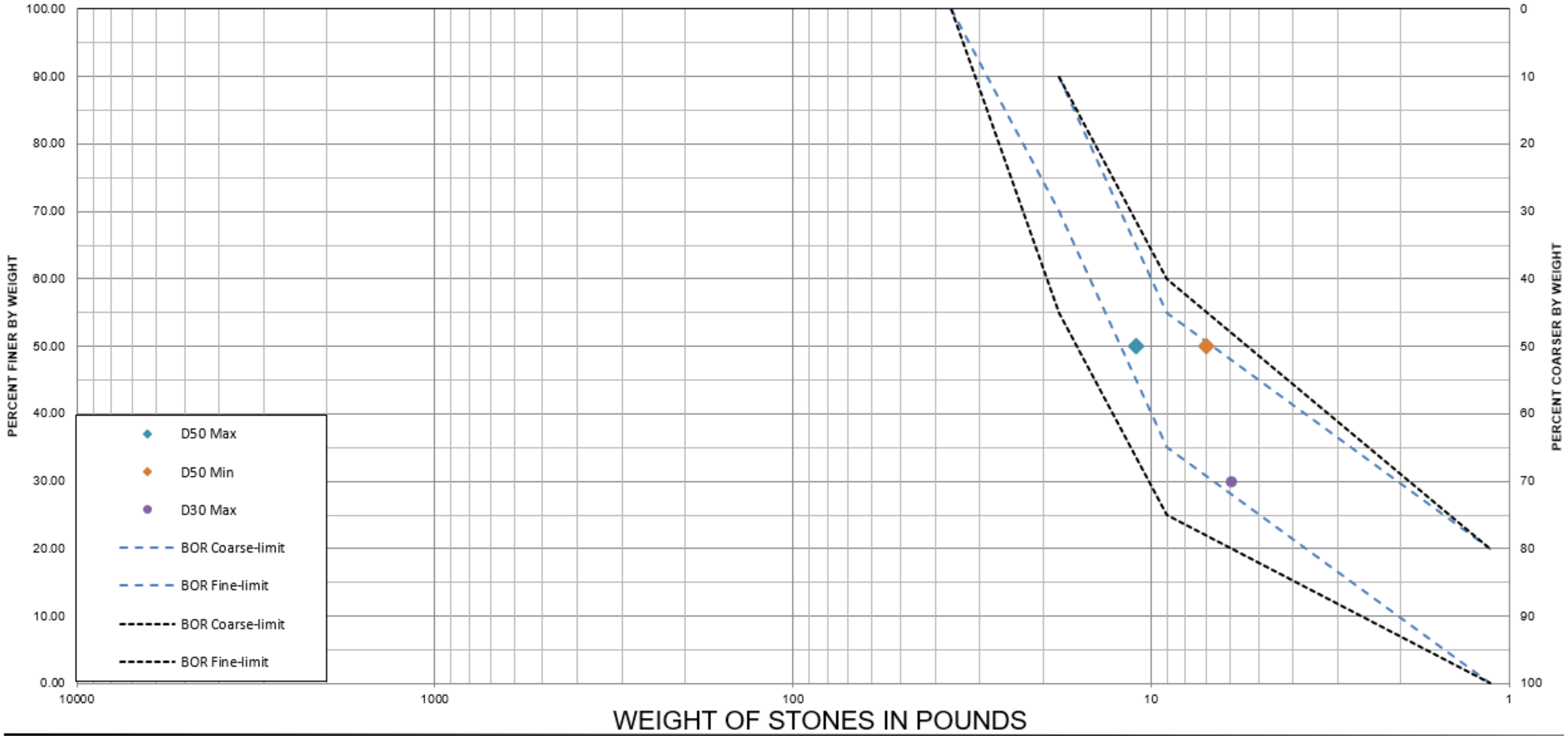


Figure 21 Non-USACE bands (20% and 35% bands created using BOR gradation guidance)

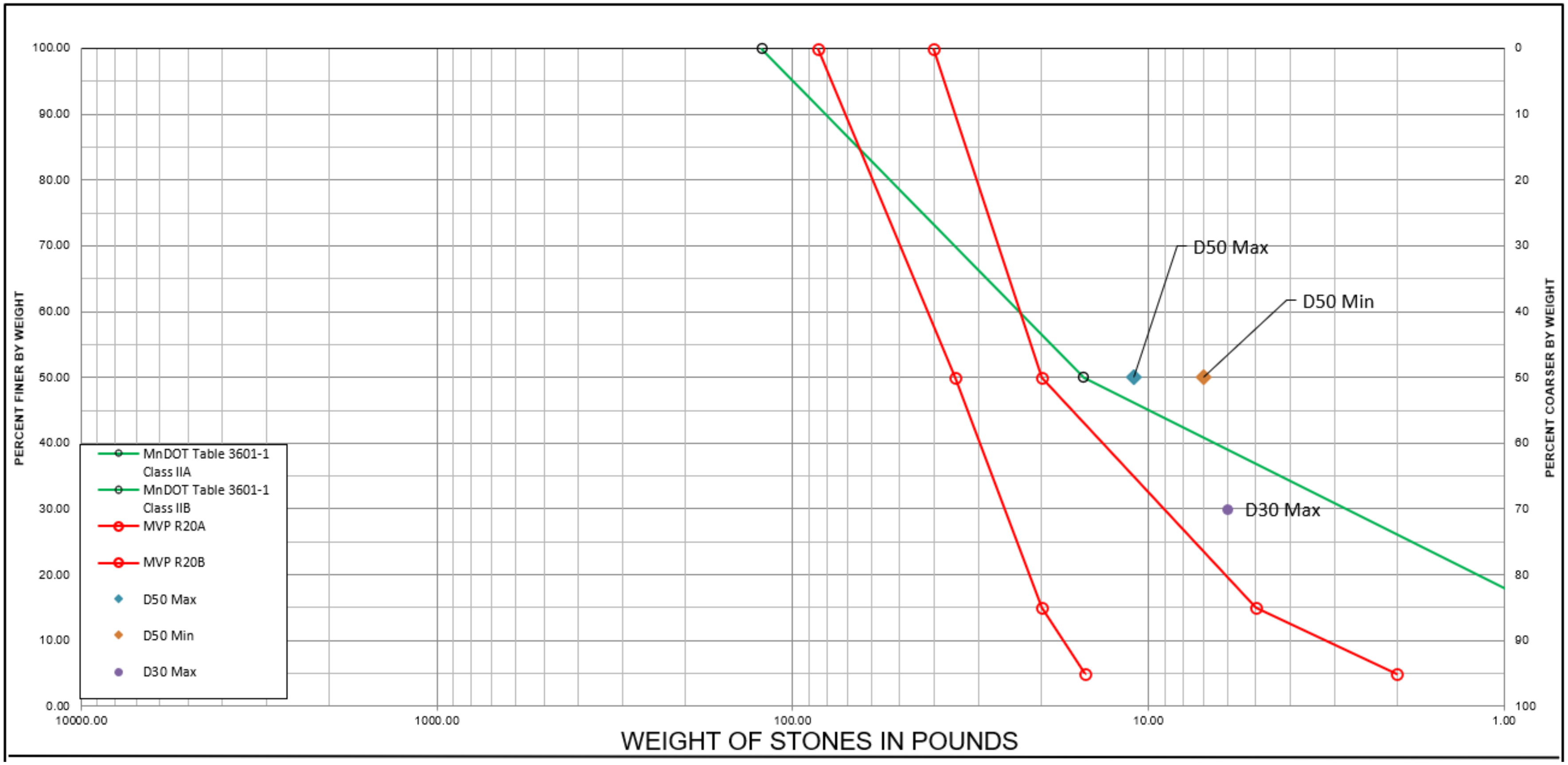


Figure 22 Comparison of standard riprap gradations (R20 in red; MNDOT Class 2 in green) available at nearby quarries closest to H&H requirements.

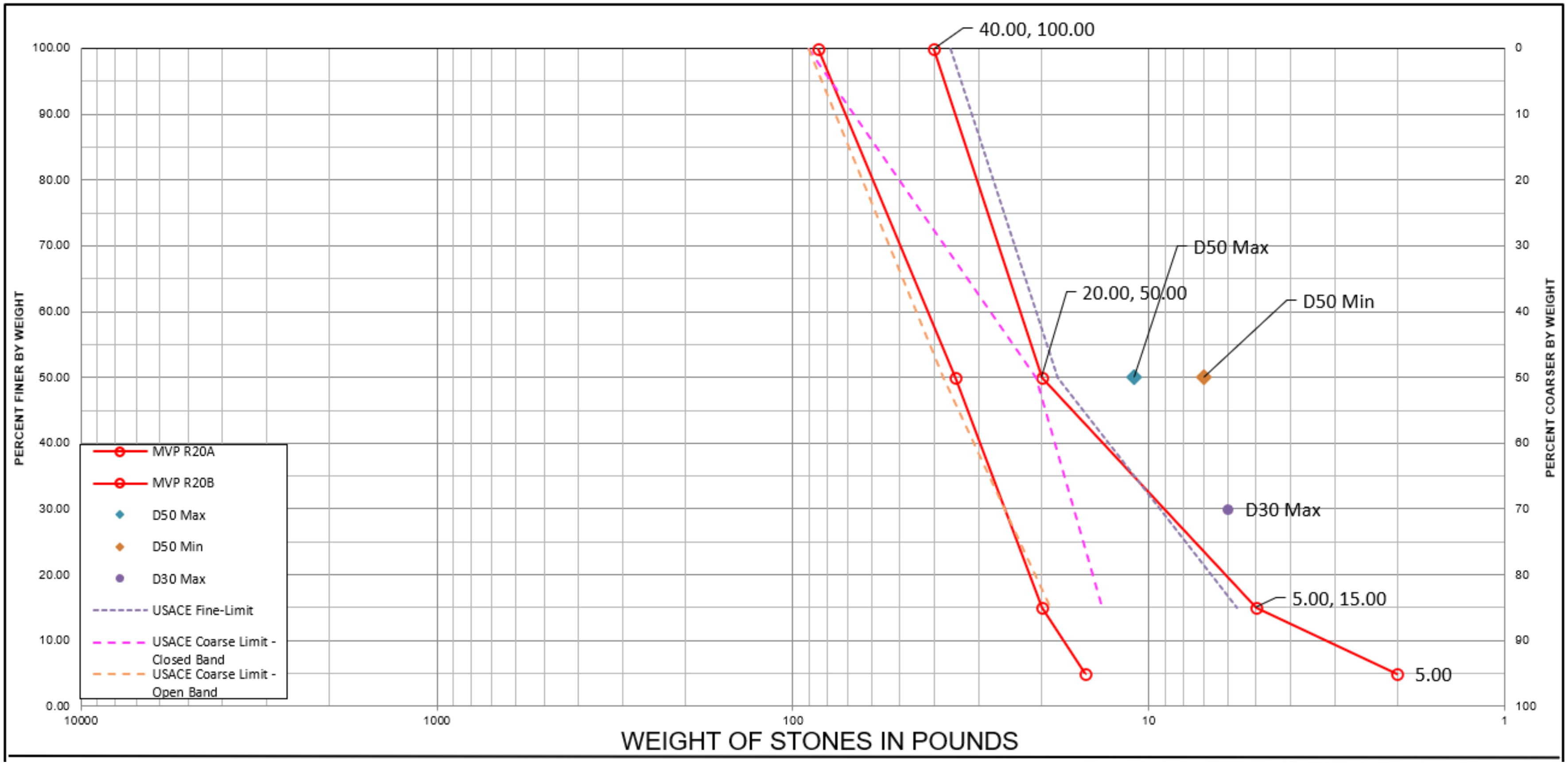


Figure 23 R20 gradation (red) compared to shifted EM 1110-2-1601 bands. R20 more closely matches the “open” gradation.

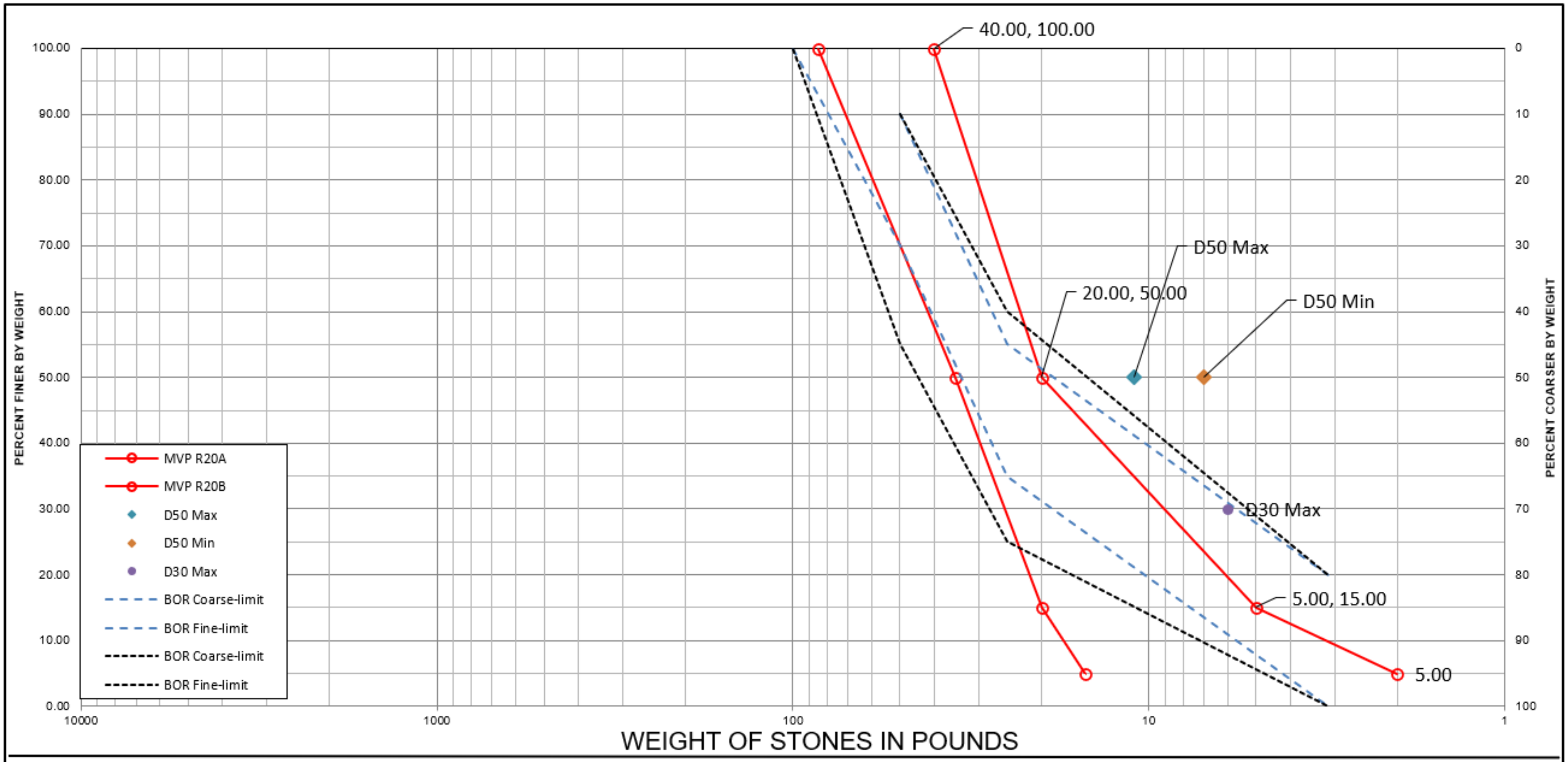


Figure 24 R20 gradation (red) compared to shifted BOR 20% and 35% bands

10.1.3 Section Thickness

For sizing of the R20 riprap section, the team considered EM 1110-2-1601 and CEMVP guidance (based on a paper by Neil Schwanz, former chief of G&G). Comparisons to BOR guidance are footnoted. The following figure elucidates the process followed.

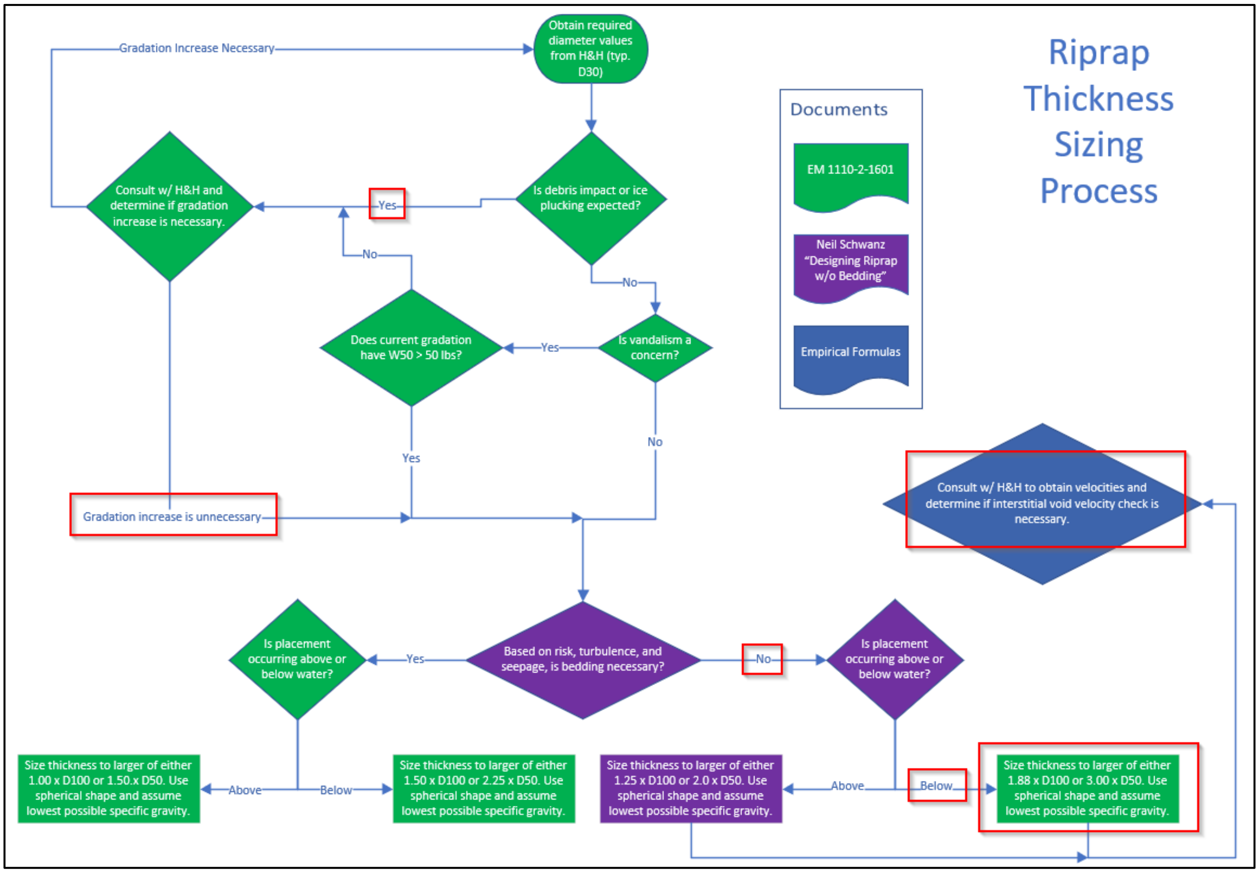

Riprap Thickness Sizing Process
Obtain required diameter values from H&H (typ. D30)
Gradation Increase Necessary
Consult w/ H&H and determine if gradation increase is necessary.
Is debris impact or ice plucking expected?
Yes
No
No
Does current gradation have W50 > 50 lbs?
Yes
Is vandalism a concern?
Yes
No
Gradation increase is unnecessary
Documents
EM 1110-2-1601
Neil Schwanz "Designing Riprap w/o Bedding"
Empirical Formulas
Consult w/ H&H to obtain velocities and determine if interstitial void velocity check is necessary.
Is placement occurring above or below water?
Yes
Based on risk, turbulence, and seepage, is bedding necessary?
No
Is placement occurring above or below water?
Size thickness to larger of either 1.00 x D100 or 1.50 x D50. Use spherical shape and assume lowest possible specific gravity.
Above
Below
Size thickness to larger of either 1.50 x D100 or 2.25 x D50. Use spherical shape and assume lowest possible specific gravity.
Size thickness to larger of either 1.25 x D100 or 2.0 x D50. Use spherical shape and assume lowest possible specific gravity.
Above
Below
Size thickness to larger of either 1.88 x D100 or 3.00 x D50. Use spherical shape and assume lowest possible specific gravity.

Figure 25 Flowchart and selections (in red boxes) for riprap thickness sizing

As previously stated, the project site is subjected to freezing conditions and debris flows. Per EM 1110-2-1601, "[i]ce attachment to… riprap also causes a decrease in stability" and "thickness should be increased by 6-12 in., accompanied by appropriate increase in stone size, for riprap subject to attack by large floating debris" (U.S. Army Corps of Engineers, 1994, pp. 3-11 to 3-12). H&H indicated that the "appropriate increase in stone size" is already accounted for by use of the R20 gradation, which is over and above the H&H-provided values. The application of a 6-to-12-inch increase in section thickness was not considered applicable by the PDT because R20 is so much larger than bands developed by EM 1110-2-1601's guidance.

Per EM 1110-2-1601, section size "should not be less than the spherical diameter of the upper limit W_{100} stone or less than 1.5 times the spherical diameter of the upper limit W_{50} stone, whichever results in the greater thickness" (U.S. Army Corps of Engineers, 1994, pp. 3-4). For

R20 at a specific gravity of 2.65, the D_{100} maximum spherical size is 12 inches, and 1.5 times the D_{50} maximum spherical size is 13 inches. Thus, the minimum section thickness if placed above water and with bedding is 13 inches for R20.[1]

It should be noted that this value (13 inches) contradicts the value in Figure 26 (12 inches), which has not been resolved at the time of this writing. Furthermore, according to Figure 26, CEMVP's standard section thickness for R20 riprap is typically 18 inches for turbulent flow conditions (CEMVP, 2014); however, that placement is assumed to be in the dry (Rydeen, 1992, p. 1). These values are provided for comparison with the following paragraphs.

Based on risk (low given only agricultural land is being protected without infrastructure), turbulence (which is expected to be low given vanes deflecting flow per H&H), and seepage (which is expected to be low given that the sands within the bank are hydraulically connected to the river and contain few fines and drawdown rapid enough to initiate and sustain internal erosion is unlikely), the PDT determined that bedding was unnecessary and followed CEMVP guidance to remove bedding. This guidance indicates that minimum thicknesses should be increased to 1.25 times the D100 size (15 inches for R20) or 2.0 times the D50 size (18 inches for R20), but the guidance does not state whether these values are applicable for below or above water placement. This guidance also does not state whether these values should be using a particular specific gravity or shape. Generally, within CEMVP, the guidance is understood to be a 25% increase in D100 sizing and a 50% increase in D50 sizing compared to EM 1110-2-1601's process, which is described in the previous paragraph.

Per EM 1110-2-1601, section size should be increased by 50 percent if riprap is placed underwater. Given maximum value from the previous paragraph (20 inches), the minimum section size increases to 27 inches for the portion of riprap placed underwater. The exact proportion will depend on river stage at the time of construction, and a range of acceptable water surface elevations for placement should be determined during the P&S stage and compared to section thicknesses provided in the plans.

EM 1110-2-1601 makes no assertion that rounding of the riprap section thickness is necessary, unlike BOR.[2] The P&S team may choose to round the section size; however, the PDT at this stage decided that 24 inches as a minimum section top width would be reasonable (likely above water placement) and made the assumption that section thickness beneath the top width would increase to at or above 27 inches. Key-ins may be deemed necessary by the PDT during P&S and should be explored.

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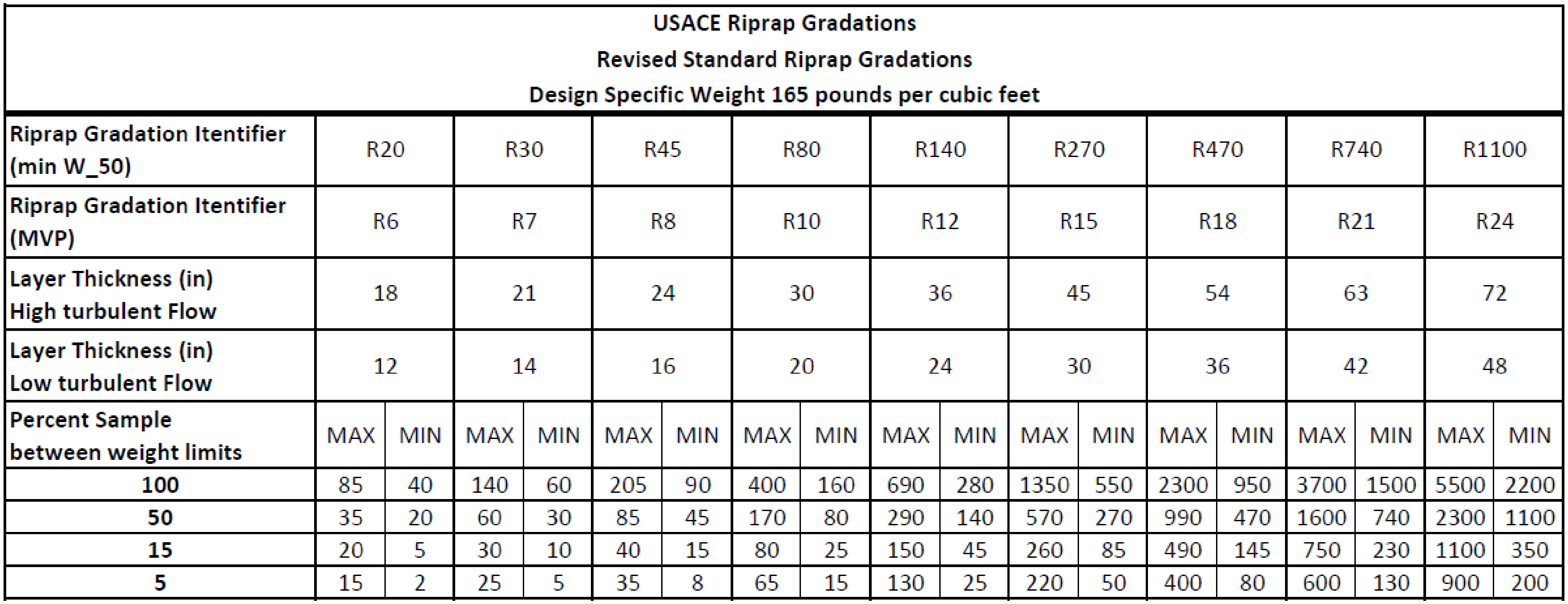
[1] This sizing is similar to BOR's recommended procedure. BOR recommends a minimum thickness for riprap of twice the size of the D50 stone when placed above water and with bedding (U.S. Department of the Interior, Bureau of Reclamation, 2014, pp. 7-19). It should be noted that BOR's sizing assumes the gradation bands put forth by the BOR, which make assumptions about the D100 and D50 ratio that are not applicable directly to CEMVP's R20. In the case of R20, twice the D50 maximum stone (spherical) is 18 inches.

[2] BOR indicates that "riprap thickness is typically specified in 12-inch increments for construction but can also be specified in 6-inch increments, if preferred" (U.S. Department of the Interior, Bureau of Reclamation, 2014, pp. 7-19).

During P&S, there may be opportunities to reduce this riprap section size. Water levels may be able to be reduced to a predictable band for construction during P&S by comparing the construction window with the expected flows.



USACE Riprap Gradations

Revised Standard Riprap Gradations

Design Specific Weight 165 pounds per cubic feet

Riprap Gradation Itentifier (min W_50)	R20		R30		R45		R80		R140		R270		R470		R740		R1100	
Riprap Gradation Itentifier (MVP)	R6		R7		R8		R10		R12		R15		R18		R21		R24	
Layer Thickness (in) High turbulent Flow	18		21		24		30		36		45		54		63		72	
Layer Thickness (in) Low turbulent Flow	12		14		16		20		24		30		36		42		48	
Percent Sample between weight limits	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN
100	85	40	140	60	205	90	400	160	690	280	1350	550	2300	950	3700	1500	5500	2200
50	35	20	60	30	85	45	170	80	290	140	570	270	990	470	1600	740	2300	1100
15	20	5	30	10	40	15	80	25	150	45	260	85	490	145	750	230	1100	350
5	15	2	25	5	35	8	65	15	130	25	220	50	400	80	600	130	900	200

Figure 26 CEMVP's standard riprap gradations at 165 pcf. Note some errors may exist in this table and that it should not be used as is for design. (CEMVP, 2014)

10.1.4 Riprap Bulk Weight-to-Volume Conversion Factor

If a specific gravity of 2.65 and a void ratio of between 30% and 70% is assumed, a conversion factor range of 1.3 to 1.7 tons per cubic yard (97.3 pcf and 127.2 pcf respectively) should be used during P&S stage to determine expected weight given volumetric quantities.

10.2 Bedding

Bedding does not appear necessary beneath the revetment given the low consequences of failure and thickness of the revetment section likely decreasing interstitial void velocities (Schwanz, N.D.). At the feasibility stage, the PDT assumed that seepage through the poorly graded sand layers is controlled by the river stage and should not drain so slowly that concentrated seepage and a loss of material results. This assumption should be checked at numerous cross-sections during the P&S design stage, especially if the section thickness or general design is altered. Interstitial void velocity checks by empirical formula may be necessary as well.

10.3 Incorporation of Nearby Boulders

Some boulders already exist at the site which could be incorporated into the ends of vanes or key-ins. These boulders should not be incorporated into the revetment slopes due to the potential for concentrated eddies forming and the plucking of smaller stones resulting.

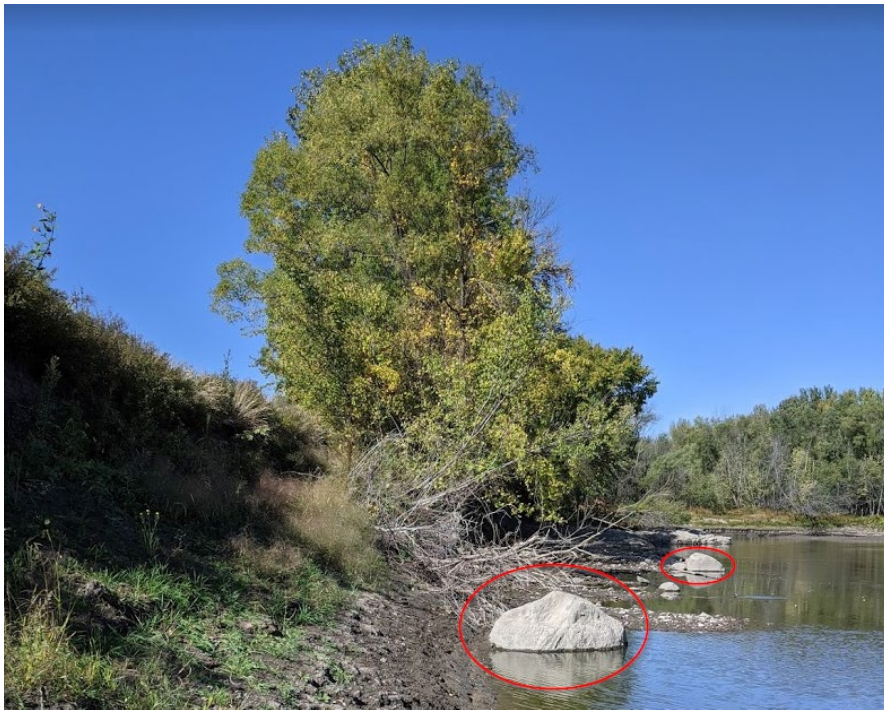


Figure 27 Existing boulders

11 Operations and Maintenance Considerations

11.1 Animal Burrows

The PDT located animal burrows sporadically along the riverbank, as illustrated in the figure below.

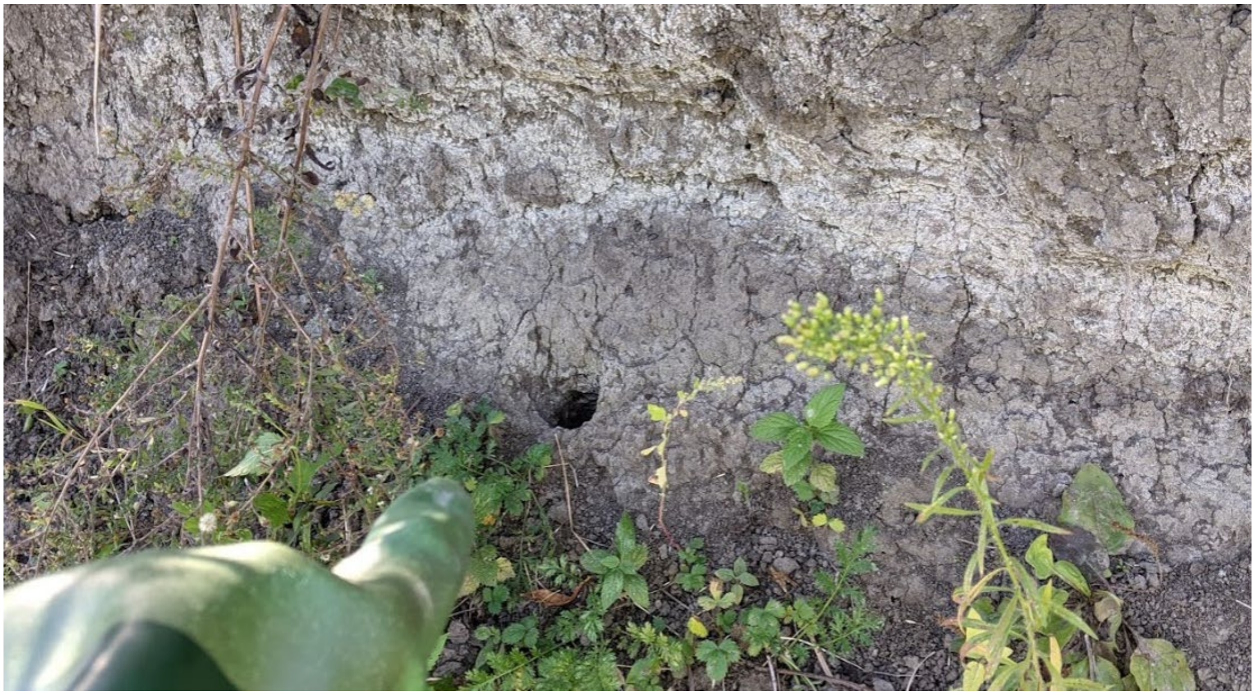


Figure 28 Animal burrows present in current slope along Reach 2

Although the riprap should reduce animal burrows into the slope, the owner should attempt to monitor any animal burrows or fill them if extensive activity occurs to discourage destabilization of the slope beneath the riprap. This concern should be addressed in any O&M documents developed during the P&S stage.

11.2 Seasonal and Post-Flood Checks

The owner should attempt to monitor any changes on the slopes, including seasonal (e.g., spring thaw) and post-flooding events. Spring brings ice-jams and other ice related issues, and floods bring increased flows and debris. The condition of the riprap should be monitored as minor failures can quickly increase to larger ones.

Monitoring methods that are easily employed are photographs. Surveys, aerial imagery, fly-over video via drones, LiDAR, and other checks may be employed.

11.3 Monitoring Methods

P&S should provide the tribe with alternatives for monitoring the riprap depth so that the tribe can simply monitor riprap for changes due to damage. A simple method would be installing fixed monitoring points at surveyed locations from which the tribe could photograph the slope over time (e.g., one point from above the slope, one point from upstream, one point from downstream). The tribe could compare photographs to attempt to detect changes in the slope as detailed in Section 11.2.

More complex methods could include an aerial LiDAR scan at the end of construction that may provide a baseline measure from which future maintenance activities can be determined. Regardless of the method, some form of quantifiable monitoring should be employed beyond mere human memory. Given that the contractor should obtain as-constructed topographic data after construction as a close-out submittal as is typical of QA/QC for most USACE projects, this baseline should not be hard to establish.

12 Future Work

During the plans and specifications stage, the following questions should be answered:

1. Free swell:
    a. Should assumptions described in 5.3 be verified with undisturbed testing?
2. Design:
    a. Is adding a key-in at the base of the revetment advantageous to increase stability?
    b. Should a key-in be added to prevent flanking at the intersection of reaches 3 and 4?
3. Analysis:
    a. During the P&S stage, the bulk density used for volumetric quantity conversion to weight should be checked against with assumed bulk densities used in the stability analysis. There is a conflict (albeit a conservative one) indicating that the bulk densities for conversion (max 127.2 pcf) are below the value used for stability analysis (135 pcf). During feasibility, G&G determined that this conflict was negligible given that variation in unit weights for modeling appeared to have a negligible effect on factors of safety. This sensitivity analysis was not fully examined and should be pursued during P&S, perhaps by modeling lower bulk density riprap sections.
    b. What assumptions should be made for working platforms? Should a cross-section with an assumed working platform atop the riprap section within the river be analyzed?
4. Specifications:
    a. Should the contractor's means and methods be limited for constructing the slope to prevent a slide from occurring due to surcharge?
    b. Should the contractor be held accountable for a slide if one were to occur? What would be the solution (e.g., rebuild the slope)?
5. Filter design:
    a. Does a need for bedding exist?
6. O&M:
    a. Does O&M lay out clear requirements for managing riprap, including maintenance steps to resolve animal burrows and encourage minimally rooted vegetation within the riprap?
    b. Does adding deep rooting vegetation in portions of the slope assist in
7. Riprap:
    a. Can section size be reduced?
    b. Is vandalism still not a concern?
    c. Are other gradations available?
    d. Is ice-thickness data for the site available that can be compared to selected gradation?
    e. Would selecting a different gradation to account for possible segregation during placement be advantageous?
8. Structural:
    a. Should the culvert and Texas crossing be analyzed for survivability during construction, i.e., will trucks loaded with rock damage these structures beyond repair?
    b. Should these structures be inspected, reinforced, buttressed, repaired, or replaced before use?

    c. Should specifications limit the weight of trucks passing over the structures or limit the number of cycles? Should structural checks be required?
    d. Could the foundations of the structures be at risk of failure given the loads and cycle of loading?
9. Parameters:
    a. Is additional boring/sampling/testing necessary for the gains in narrowing parameters? Or is sensitivity analysis a better, more cost-effective path during P&S?
    b. If additional boring/sampling/testing is necessary, can it be performed without damaging existing trees? Is it factored into the cost estimate created during P&S?
10. Critical cross section:
    a. Has the critical cross section moved due to erosion?
    b. Should additional cross sections be modeled?
    c. Should stockpiles and construction equipment loading be considered as well?
11. Secondary confirmation and peer review:
    a. As a secondary check to the computer modeling, the P&S team should recreate the computer models in a secondary software and obtain peer review of all models and this appendix.

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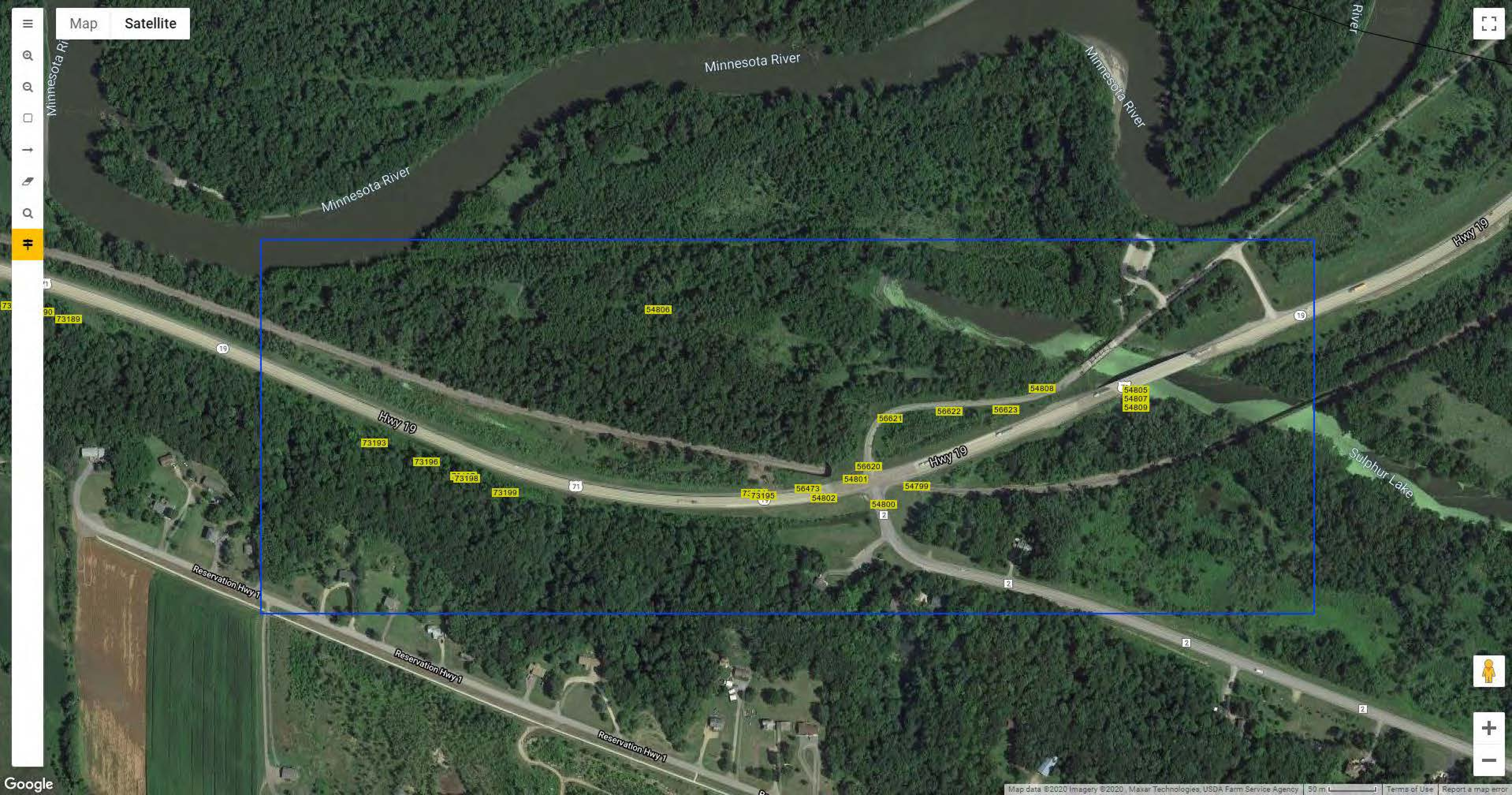
14 Attachments

Attachment 4 Subsurface Investigation


Map
Satellite
Minnesota River
Minnesota River
Minnesota River
Minnesota River
River
Hwy 19
Hwy 19
Hwy 19
Sulphur Lake
Reservation Hwy 1
Reservation Hwy 1
Reservation Hwy 1
19
19
71
71
2
2
2
2
73189
54806
54808
54805
54807
54809
56621
56622
56623
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73196
73198
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73195
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54801
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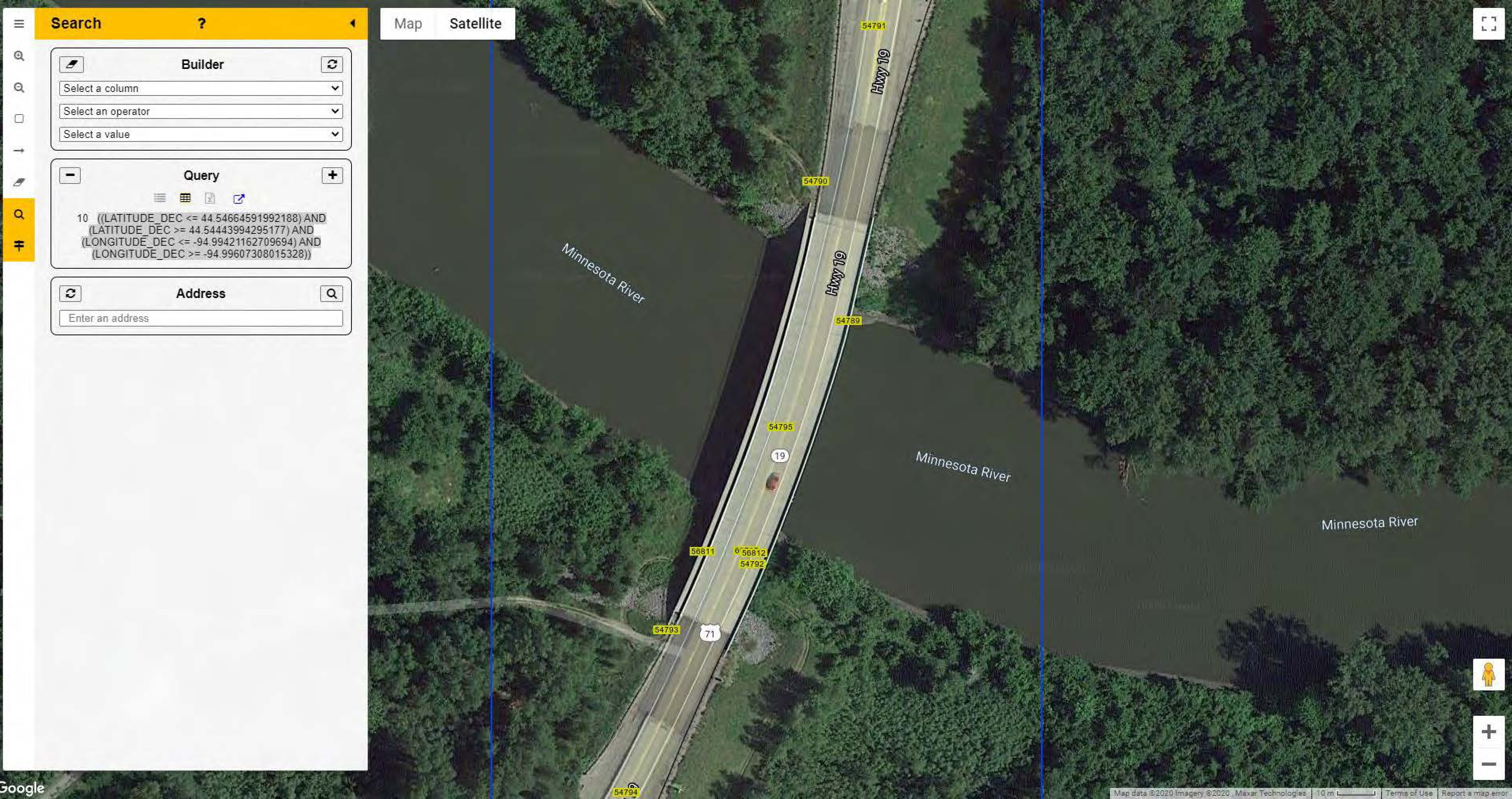
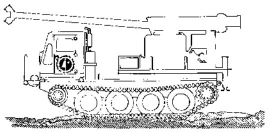
Google
Map data ©2020 Imagery ©2020 , Maxar Technologies, USDA Farm Service Agency
50 m
Terms of Use
Report a map error



10 ((LATITUDE_DEC <= 44.54664591992188) AND (LATITUDE_DEC >= 44.54443994295177) AND (LONGITUDE_DEC <= -94.99421162709694) AND (LONGITUDE_DEC >= -94.99607308015328))

Minnesota Department of Transportation
Geotechnical Section
Boring Log Descriptive Terminology (English Units)



USER NOTES, ABBREVIATIONS AND DEFINITIONS - Additional information available in Geotechnical Manual.

This boring was made by ordinary and conventional methods and with care deemed adequate for the Department's design purposes. Since this boring was not taken to gather information relating to the construction of the project, the data noted in the field and recorded may not necessarily be the same as that which a contractor would desire. While the Department believes that the information as to the conditions and materials reported is accurate, it does not warrant that the information is necessarily complete. This information has been edited or abridged and may not reveal all the information which might be useful or of interest to the contractor. Consequently, the Department will make available at its offices, the field logs relating to this boring.

Since subsurface conditions outside each borehole are unknown, and soil, rock and water conditions cannot be relied upon to be consistent or uniform, no warrant is made that conditions adjacent to this boring will necessarily be the same as or similar to those shown on this log. Furthermore, the Department will not be responsible for any interpretations, assumptions, projections or interpolations made by contractors, or other users of this log.

Water levels recorded on this log should be used with discretion since the use of drilling fluids in borings may seriously distort the true field conditions. Also, water levels in cohesive soils often take extended periods of time to reach equilibrium and thus reflect their true field level. Water levels can be expected to vary both seasonally and yearly. The absence of notations on this log regarding water does not necessarily mean that this boring was dry or that the contractor will not encounter subsurface water during the course of construction.

WR	Weight of Rod
Mud	Drilling Fluids in Sample
CS	Continuous Sample

SOIL/CORE TESTS

SPT N_{60}	ASTM D1586 Modified Blows per foot with 140 lb. hammer and a standard energy of 210 ft-lbs. This energy represents 60% of the potential energy of the system and is the average energy provided by a Rope & Cathead system.
MC	Moisture Content
COH	Cohesion
(	Sample Density
LL	Liquid Limit
PI	Plasticity Index
F	Phi Angle
REC	Percent Core Recovered
RQD	Rock Quality Description (Percent of total core interval consisting of unbroken pieces 4 inches or longer)
ACL	Average Core Length (Average length of core that is greater than 4 inches long)
Core Breaks	Number of natural core breaks per 2-foot interval.

DISCONTINUITY SPACING

Fractures	Distance	Bedding
Very Close	<2 inches	Very Thin
Close	2-12 inches	Thin
Mod. Close	12-36 inches	Medium
Wide	>36 inches	Thick

RELATIVE DENSITY

Compactness - Granular Soils	BPF
very loose	0-4
loose	5-10
medium dense	11-24
dense	25-50
very dense	>50

Consistency - Cohesive Soils	BPF
very soft	0-1
soft	2-4
firm	5-8
stiff	9-15
very stiff	16-30
hard	31-60
very hard	> 60

COLOR

blk	Black	**wht**	White
grn	Green	**brn**	Brown
orng	Orange	**yel**	Yellow
dk	Dark	**lt**	Light
IOS	Iron Oxide Stained		

GRAIN SIZE /PLASTICITY

VF	Very Fine	**pl**	Plastic
F	Fine	**slpl**	Slightly Plastic
Cr	Coarse		

SOIL/ROCK TERMS

C	Clay	**Lmst**	Limestone
L	Loam	**Sst**	Sandstone
S	Sand	**Dolo**	Dolostone
Si	Silt	**wx**	weathered
G	Gravel (No. 10 Sieve to 3 inches)		
Bldr	Boulder (over 3 inches)		
T	till (unsorted, nonstratified glacial deposits)		

WATER MEASUREMENT

AB	After Bailing
AC	After Completion
AF	After Flushing
w/C	with Casing
w/M	with Mud
WSD	While Sampling/Drilling
w/AUG	with Hollow Stem Auger

MISCELLANEOUS

NA	Not Applicable
w/	with
w/o	with out
sat	saturated

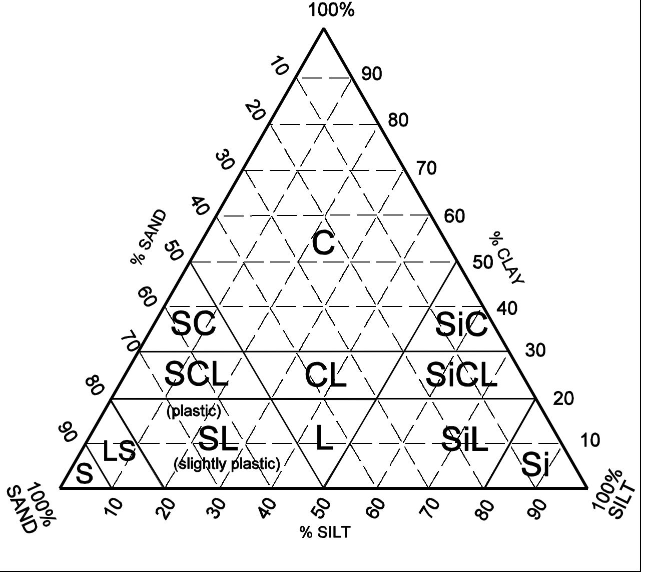
DRILLING OPERATIONS

AUG	Augered
CD	Core Drilled
DBD	Disturbed by Drilling
DBJ	Disturbed by Jetting
PD	Plug Drilled
ST	Split Tube (SPT test)
TW	Thinwall (Shelby Tube)
WS	Wash Sample
NSR	No Sample Retrieved
WH	Weight of Hammer

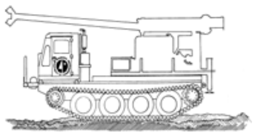
DRILLING SYMBOLS

▭	**Vane Shear Test**
WS	**Washed Sample** Collected during plug drilling
≀ ≀	**Augered**
PD	**Plug Drilled** (Rotary drilled with fluid)
☒	**Split Tube Sample** (SPT N_{60} with 2 in. split tube with liners)
▩	**Thin Wall Sample** (3 inch Thin Wall Tube)
▮ ▮	**Core Drilled** (NV Core Barrel, unless otherwise noted)
CS	**Continuous Soil Sample**
A/P	**Augered and Plug Drilled**
Jet	**Jetted**
A/J	**Augered and Jetted**

Mn/DOT TRIANGULAR TEXTURAL CLASSIFICATION SYSTEM



Minnesota Department of Transportation
Geotechnical Section
Cone Penetration Test Index Sheet 1.0 (CPT 1.0)



USER NOTES, ABBREVIATIONS AND DEFINITIONS

This Index sheet accompanies Cone Penetration Test Data. Please refer to the Boring Log Descriptive Terminology Sheet for information relevant to conventional boring logs.

This Cone Penetration Test (CPT) Sounding follows ASTM D 5778 and was made by ordinary and conventional methods and with care deemed adequate for the Department's design purposes. Since this sounding was not taken to gather information relating to the construction of the project, the data noted in the field and recorded may not necessarily be the same as that which a contractor would desire. While the Department believes that the information as to the conditions and materials reported is accurate, it does not warrant that the information is necessarily complete. This information has been edited or abridged and may not reveal all the information which might be useful or of interest to the contractor. Consequently, the Department will make available at its offices, the field logs relating to this sounding.

Since subsurface conditions outside each CPT Sounding are unknown, and soil, rock and water conditions cannot be relied upon to be consistent or uniform, no warrant is made that conditions adjacent to this sounding will necessarily be the same as or similar to those shown on this log. Furthermore, the Department will not be responsible for any interpretations, assumptions, projections or interpolations made by contractors, or other users of this log.

Water pressure measurements and subsequent interpreted water levels shown on this log should be used with discretion since they represent dynamic conditions. Dynamic Pore water pressure measurements may deviate substantially from hydrostatic conditions, especially in cohesive soils. In cohesive soils, water pressures often take extended periods of time to reach equilibrium and thus reflect their true field level. Water levels can be expected to vary both seasonally and yearly. The absence of notations on this log regarding water does not necessarily mean that this boring was dry or that the contractor will not encounter subsurface water during the course of construction.

CPT Terminology

CPT ....Cone Penetration Test
CPTU...........Cone Penetration Test with Pore Pressure measurements
SCPTU.........Cone Penetration Test with Pore Pressure and Seismic measurements
Piezocone...Common name for CPTU test

(Note: This test is not related to the Dynamic Cone Penetrometer DCP)

q_T TIP RESISTANCE

The resistance at the cone corrected for water pressure. Data is from cone with 60 degree apex angle and a 10 cm^2 end area.

f_s SLEEVE FRICTION RESISTANCE

The resistance along the sleeve of the penetrometer.

FR Friction Ratio

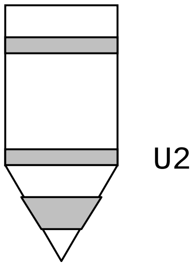
Ratio of sleeve friction over corrected tip resistance.
FR = fs/qt

V_s Shear Wave Velocity

A measure of the speed at which a siesmic wave travels through soil/rock.

PORE WATER MEASUREMENTS

Pore water measurements reported on CPT Log are representative of water pressures measured at the U2 location, just behind the cone tip, prior to the sleeve, as shown in the figure below. These measurements are considered to be dynamic water pressures due to the local disturbance caused by the cone tip. Dynamic water pressure decay and Static water pressure measurements are reported on a Pore Water Pressure Dissipation Graph.



SBT SOIL BEHAVIOR TYPE

Soil Classification methods for the Cone Penetration Test are based on correlation charts developed from observations of CPT data and conventional borings. Please note that these classification charts are meant to provide a guide to Soil Behavior Type and should not be used to infer a soil classification based on grain size distribution.

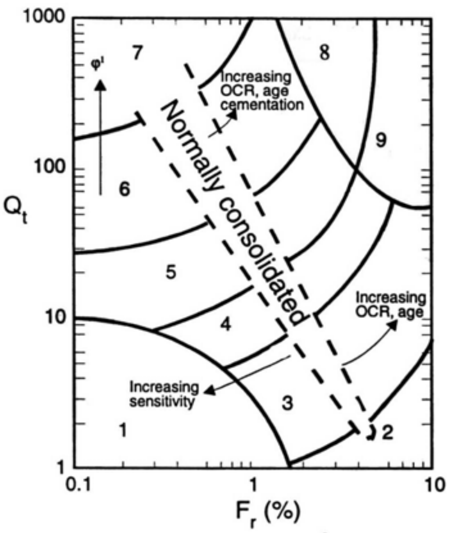
The numbers corresponding to different regions on the charts represent the following soil behavior types:

1. Sensitive, Fine Grained
2. Organic Soils - Peats
3. Clays - Clay to Silty Clay
4. Silt Mixtures - Clayey Silt to Silty Clay
5. Sand Mixtures - Silty Sand to Sandy Silt
6. Sands - Clean Sand to Silty Sand
7. Gravelly Sand to Sand
8. Very Stiff Sand to Clayey Sand
9. Very Stiff, Fine Grained

Note that engineering judgment, and comparison with conventional borings is especially important in the proper interpretation of CPT data in certain geo-materials.

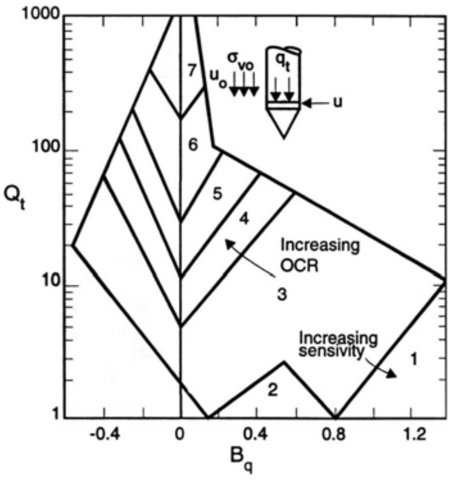
The following charts are used to provide a Soil Behavior Type for the CPT Data.

Robertson CPT 1990
Soil Behavior type based on friction ratio



$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \qquad F_r = \frac{f_s}{q_t - \sigma_{vo}} \times 100\%$$

Robertson CPTU 1990
Soil Behavior type based on pore pressure



$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \qquad B_q = \frac{u_2 - u_o}{q_t - \sigma_{vo}}$$

where ...

Q_T.......................... normalized cone resistance
B_q .... pore pressure ratio
F_r .... Normalized friction ratio
σ_{vo} .... overburden pressure
σ'_{vo} .... effective over burden pressure
u_2 .... measured pore pressure
u_0 .... equilibrium pore pressure

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54789

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **64010**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-1**	*Ground Elevation* **822.6** *(from Plan)*

Location **LOR4 TH 19, 331+56, 30' RT**

Redwood Co. Coordinate: X=560087 Y=227981 (ft.)

Latitude (North)=44°32'43.89" *Longitude (West)=95°00'10.36"*

Drill Machine **76504**

Hammer **Rope & Cathead**

SHEET 1 of 2

Drilling Completed **9/14/88**

Depth	Elev.	Classification
		slpl SiL, brn w/ dk brn; dry to 5', damp 5'-8.7'
8.7	813.9	SiCL w/ slpl SiL seams, gr w/ lt brn moist to 10', wet 10'-11.3'
11.3	811.3	Water measured @ 12.0' 9/13/88 WSD w/aug FS, brn; wet to 13', sat 13'-14.3'
14.3	808.3	S w/ some FG; LS seams at 19.3' & 26.5' gray-brn to 20', brn 20'-30'; sat
30.0	792.6	LVFS, grn-gray & wet
31.3	791.3	pl SiL, dk gray & wet
31.8	790.8	mixed VFS & slpl SiL, gray-brn & gray; wet
34.6	788.0	LS & FG w/ shells, dk gray-brn & wet
39.5	783.1	Driller's Note: WEATHERED "GRANITE" (no sample recovered until 50 ft)
50.0	772.6	VERY SEVERELY WEATHERED GRANITIC ROCK (Residual

SPT N60	MC (%)	COH (psf)	γ (pcf)	Other Tests Or Remarks
15	14			
10	10			
5	37			
13	20			
15	16			
6	13			
7	14			
9	13			
13	14			
47	13			Distorted blow count at 26', auger sanded in.
23	NSR			
5	36			
	39	350	112	
77	10			wx granite pieces at 36'.
75/.3	14			
75/.2	NSR			
				Residuum
75/.1	NSR			
				(smooth hard drilling - 43'-48')
75/.1	NSR			
75/.1	NSR			

Index Sheet Code 2 (Continued Next Page)

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54789

U.S. Customary Units

Mn/DOT GEOTECHNICAL SECTION - LOG & TEST RESULTS *SHEET 2 of 2*

State Project	*Bridge No. or Job Desc.*	*Trunk Highway/Location*	*Boring No.*	*Ground Elevation*
6404-04	**64010**	**MN Trunk Highway 19**	**T-1**	**822.6** *(from Plan)*

DEPTH	*Depth* / *Elev.*	*Lithology*	*Classification*	*Drilling Operation*	*SPT N60* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Soil* / *Rock*	*Other Tests Or Remarks* / *Formation or Member*
			Soil) Rock fabric discernible but mass effectively reduced to soil with only fragments of strong rock remaining, quartz with a few feldspars common, most of rock mass reduced to chlorite or similar clay mine	WS						
					75/.1	NSR				
60				WS						
					75/.4	18				
65				WS						
	69.1 753.5		Bottom of Hole - 69.1'		75/.1	NSR				

Soil Class:DB Rock Class: CRH Edit: JLD Date: 7/31/06
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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54790

U.S. Customary Units

State Project	*Bridge No. or Job Desc.*	*Trunk Highway/Location*	*Boring No.*	*Ground Elevation*
6404-04	**64010**	**MN Trunk Highway 19**	**T-2**	**822.0** *(from Plan)*

Location **LOR4 TH 19, 332+67, 27' LT**

Redwood Co. Coordinate: X=560084 Y=228309 (ft.)

Latitude (North)=44°32'47.13" *Longitude (West)=95°00'10.39"*

Drill Machine **76504**

Hammer **Rope & Cathead**

SHEET 1 of 1

Drilling Completed **9/20/88**

DEPTH	*Depth* / *Elev.*	*Classification*	*Formation or Member*
		slorg slpl SiL w/ seams of SiCL, some FS lt gray-brn w/ dk gray & brn; damp	
5	8.0 814.0	pl SiL, dk gray-brn & moist	
10	10.0 812.0	S & FG, brn & damp	
▼	11.5 810.5	Water measured @ 13.0' 9/14/88 WSD w/ aug S w/ some FG, bwn damp to 12.5', wet 12.5'-15', sat 15'-16.5'	
15	16.5 805.5	S, brn & sat	
20	20.5 801.5	FS w/ some shells, gray-brn & sat	
	24.0 798.0	S & G, gray-brn & sat	
25	29.0 793.0	S w/ some G, gray-brn & sat	
30	31.5 790.5	LFS & G w/ 2" org pl SiL seam at 32.5' dk gray-brn w/ blk to 34', gray-brn 34'-36.5', sat	
35	36.5 785.5	FS & FG, gray-brn & sat	
	38.0 784.0	SEVERELY WEATHERED GRANITIC ROCK (Residual Soil), rock fabric clear and evident, but reduced in strength to a strong soil (mostly sand sized material), red & brn	Residuum
40 45	49.8 772.2	Bottom of Hole - 49.8'	

Drilling Operation	*SPT N60* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Soil* / *Rock*	*Other Tests Or Remarks*
	5	28				
	4	32				
		4				
	10	8				
	6	16				
	9	16				
A/P						
	11	17				
PD						
	7	21				
A/P						
	21	12				
PD						
	16	16				
A/P						
	14	16				
PD						
	28	13				
A/P						
	27	15				
PD						
	9/.5 75/.9	12				
A/P						
	75/.2	18				
WS						
	75/.1	NSR				
WS						
	75/.3	NSR				

Index Sheet Code 2

Soil Class:DB Rock Class: CRH Edit: JLD Date: 7/31/06

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54791

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **64010**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-3**	*Ground Elevation* **824.0** *(from Plan)*

Location **LOR4 TH 19, 334+12, C/L**

Redwood Co. Coordinate: X=560084 Y=228309 (ft.)

Latitude (North)=44°32'47.13" *Longitude (West)=95°00'10.39"*

Drill Machine **76504**

Hammer **Rope & Cathead**

SHEET 1 of 1

Drilling Completed **9/21/88**

DEPTH	Depth / Elev.	Classification	Formation or Member
0–4.5	4.5 / 819.5	slorg slpl SiL w/ some roots, dk brn & damp	
4.5–9.0	9.0 / 815.0	S w/ some FG, brn & damp	
9.0–16.5	16.5 / 807.5	FS, brn; damp to 11.5', moist 11.5'-14', sat 14'-16.5' Water measured @ 15.5' 9/21/88 WSD w/ aug	
16.5–18.3	18.3 / 805.7	LS & FG, gray & sat	
18.3–21.5	21.5 / 802.5	FS w/ some G at 21' gray-brn to 20.5', gray 20.5'-21.5'; sat	
21.5–24.0	24.0 / 800.0	Cr S, gray & sat	
24.0–31.5	31.5 / 792.5	FS w/ some FG at 30', LS seam at 30.5'; gray-brn & sat	
31.5–39.0	39.0 / 785.0	S, brn & sat	
39.0–40.2	40.2 / 783.8	LFS w/ some shells, gray & sat	
40.2–44.7	44.7 / 779.3	VERY SEVERELY WEATHERED GRANITIC ROCK (Residual Soil), some rock fabric is discernible but mass is effectively reduced to soil, green, wht & pink	Residuum
		Bottom of Hole - 44.7'	

Depth scale: 5, 10, ▼15, 20, 25, 30, 35, 40

Drilling Operation	SPT N60	MC (%)	COH (psf)	γ (pcf)	Other Tests Or Remarks
		12			
	9	4			
	7	4			
	10	3			
	9	6			
	9	21			
	19	18			
	8	12			
	10	14			
	11	15			
	4	17			
	10	21			
A/P	24	17			
A/P	10	20			
A/P	41	11			
A/P	36/.5 75/.7	11			
WS	75/.2	23			

REC (%) / RQD (%) / ACL (ft) / Core Breaks: no entries

Index Sheet Code 2

Soil Class:DB Rock Class: CRH JLD Edit: Date: 7/31/06

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54792

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **64010**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-4**	*Ground Elevation* **832.0** *(from Plan)*

Location **LOR4 TH 19, 329+28, 18' RT**
Redwood Co. Coordinate: X=560087 Y=227981 (ft.)
Latitude (North)=44°32'43.89" *Longitude (West)=95°00'10.36"*

Drill Machine **76504**
Hammer **Rope & Cathead**
SHEET 1 of 1
Drilling Completed **10/4/88**

DEPTH	*Depth* *Elev.*	*Classification*	*Drilling Operation*	*SPT N60* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Soil* / *Rock*	*Other Tests Or Remarks* / *Formation or Member*
	4.0 828.0	Driller's Notes: SiL (fill); gray & damp							
5	6.0 826.0	LFS w/ some slpl SiL seams; brn w/ gray-brn; damp		11	5				
10	11.0 821.0	seams of LFS & pl SiL; brn & gray-brn; damp		9 11	9 11				
	13.5 818.5	pl SiL w/ seams of SiCL & LFS gray-brn w/ gray & brn; damp		11	20				
15	16.0 816.0	seams of FS & slpl SiL; brn w/ gray-brn; damp		10	13				
	18.5 813.5	LFS w/ some slpl SiL seams, brn & moist		6	12				
▼ 20	23.5 808.5	Water measured @ 19.5' 9/27/88 WSD w/aug S w/ .5" SiCL seams at 20' & 22'; LS w/ some shells at 22.5'; brn w/ dk gray & gray-brn wet to 19.5', sat 19.5'-23.5'	A/P	8 3	16 22				
25	26.0 806.0	FS, lt brn & sat	PD	11	20				
	29.7 802.3	S & G w/ stone chips, brn & sat	PD	36	11				
30 35 40 45	49.1 782.9	RESIDUAL SOIL, parent rock is granitic, mass effectively reduced to a strong soil with only small rock fragments remaining, kaolinite and chlorite predominate, yel-brn & wht to 46', dk grn from 46'-49.1'.	PD PD PD PD PD	31 35/.5 75/.5 45/.5 75/.3 75/.3 75/.3 75/.1	16 16 16 NA 16 NSR				Residuum (smooth hard drilling - 30.5'-44')
		Bottom of Hole - 49.1'							

Index Sheet Code 2

Soil Class:DB Rock Class: CRH Edit: JLD Date: 7/31/06
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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54793

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
6404-04	**64010**	**MN Trunk Highway 19**	**T-5**	**828.0** (from Plan)

Location **LOR4 TH 19, 328+45, 30' LT**

Redwood Co. Coordinate: X=560086 Y=227649 (ft.)

Latitude (North)=44°32'40.61" Longitude (West)=95°00'10.39"

Drill Machine **76504**

Hammer **Rope & Cathead**

SHEET 1 of 1

Drilling Completed **9/27/88**

Depth / Elev.	Classification	Formation or Member
14.0 / 814.0	slpl SiL w/ 3" SiCL layer at 12.5'; brn w/ dk brn moist to 4.5', damp 4.5'-11.5', moist 11.5'-14'	
19.0 / 809.0	FS w/ some shells at 18', brn moist to 16.5', sat 16.5'-19'	
26.5 / 801.5	S w/ some shells; Driller's Notes G layer at 26' brn to 24', gray 24'-26.5'; sat Water measured @ 19.7' 9/26/88 WSD w/ aug	
29.5 / 798.5	LS & G; dk brn to 27.7', brn, 27.7'-29.5'; wet	
35.0 / 793.0	RESIDUAL SOIL, parent rock is likely granitic, rock is reduced to soil, yel-brn & wht	Residuum
44.7 / 783.3	VERY SEVERELY WEATHERED GRANITIC ROCK (Residual Soil), some rock fabric evident but mass is effectively reduced to a strong soil w/some rock fragments remaining.	

Bottom of Hole - 44.7'

Drilling Operation	SPT N60	MC (%)	COH (psf)	γ (pcf)	Other Tests Or Remarks
		15			
	5	12			
	5	12			
	4	14			
	7	21			
	8	7			
	8	22			
	9	18			
A/P	13	17			
PD	6	21			
A/P	40	12			
WS	25/.5 75/.5	12			
WS	75/.3	15			
WS	75/.2	NSR			
	75/.2	NSR			

REC (%)	RQD (%)	ACL (ft)	Core Breaks	Formation or Member

Index Sheet Code 2

Soil Class:DB Rock Class: CRH Edit: JLD Date: 1/2/08

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54794

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **64010**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-6**	*Ground Elevation* **825.3** *(from Plan)*

Location **LOR4 TH 19, 327+00, C/L**

Redwood Co. Coordinate: X=560086 Y=227649 (ft.)

Latitude (North)=44°32'40.61" Longitude (West)=95°00'10.39"

Drill Machine **76504**

Hammer **Rope & Cathead**

SHEET 1 of 1

Drilling Completed **10/5/88**

Depth *Elev.*	*Classification*	*Drilling Operation*	*SPT N60* *REC (%)*	*MC (%)* *RQD (%)*	*COH (psf)* *ACL (ft)*	*γ (pcf)* *Core Breaks*	*Other Tests Or Remarks* *Formation or Member*
4.0 821.3	Driller's Notes: LFS, brn & damp						
6.0 819.3	marly slpl SiL, brn & damp		11	20			
11.0 814.3	SiCL w/ FS seams at 10' & 10.4'; brn w/ lt brn; moist		7	27			
			6	22			
15.3 810.0	Water measured @ 13.0' 10/5/88 WSD w/aug SiC, dk brn & moist		5	30			
			5	36			
16.0 809.3	marly SiC, brn & moist						
18.2 807.1	marly slpl SiL w/ pl SiL seams; lt brn w/ brn; moist			30		118	
19.7 805.6	SiCL, brn & moist						
22.3 803.0	pl SiL w/ some marl, gray & moist		4	35			
24.2 801.1	SiCL, gray & moist		7	28			
25.6 799.7	Crumbly pl SiL w/ some marl, gray & moist			35	520	116	
32.5 792.8	CL w/ shells from 30'-31', gray & moist		8	33			
				41	460	103	LL-59; PI-31 %Si-43; %C-29
			10	43			
34.0 791.3	Driller's Notes: LS & G, wet		75/.0	NSR			
49.2 776.1	VERY SEVERELY WEATHERED GRANITIC ROCK (Residual Soil), mass is effectively reduced to a strong soil w/ feldspathic rock fragments remaining, green, white & pink.	WS	75/.2	NSR			Residuum
		PD	75/.1	NSR			(hard rough drilling - 34'-40')
		PD	75/.2	NA			(hard drilling - 40'-49.2')
	Bottom of Hole - 49.2'	PD	75/.2	NA			

Index Sheet Code 2

Soil Class:DB Rock Class: CRH Edit: JLD Date: 1/2/08

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54795

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **64010**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-7**	*Ground Elevation* **809.8** *(from Plan)*

Location **LOR4 TH 19, 330+50, C/L**
Redwood Co. Coordinate: X=560087 Y=227981 (ft.)
Latitude (North)=44°32'43.89" *Longitude (West)=95°00'10.36"*

Drill Machine **84486 Mobile Track**
Hammer **Rope & Cathead**
SHEET 1 of 1
Drilling Completed **1/24/89**

DEPTH	*Depth / Elev.*	*Classification*	*SPT N_{60}* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Other Tests Or Remarks* / *Formation or Member*
	1.4 808.4	Driller's Notes: ice from 0-1.2', water, 1.2'-1.4'					
		FS; brn to 2.8', gray, 2.8'-12'; sat	3	25			
5			2	NSR			
			2	19			
10			15	18			
	12.0 797.8	S & G & wx granite; gray-brn w/ brn; wet	20/.5 75/.8	9			
15			16/.5 75/.8	12			
	15.0 794.8	VERY SEVERELY WEATHERED GRANITIC ROCK (Residual Soil), some rock fabric is present but mass has been effectively reduced to strong soil, yel-brn w/ some iron oxide staining.	42/.5 75/.1	20			Residuum
20			75/.4	24			(changed to hard drilling at 20')
			75/.1	NSR			
25		(as above)	75/.1	NSR			
	27.0 782.8	RESIDUAL SOIL, parent rock is likely granitic, very little rock fabric is discernible, mass is reduced to soil, chlorite & kaolinite clay minerals predominate, dk green-gray & wht, w/ some pink	75/.4	19			
30			75/.2	22			
	30.7 779.1	Bottom of Hole - 30.7'					

Index Sheet Code 2

Soil Class:DB Rock Class: CRH Edit: JLD Date: 1/2/08
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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54799

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
6404-04	**64008**	**TH 19**	**T-1**	**845.0** (HL)

Location **Line M.V.R.R., 4913+80, 35' RT**

Redwood Co. Coordinate: X=559464 Y=226145 (ft.)

Latitude (North)=44°32'25.78" Longitude (West)=95°00'19.03"

Drill Machine **76504**

Hammer **Rope & Cathead**

SHEET 1 of 2

Drilling Completed **10/20/88**

DEPTH	Depth / Elev.	Classification	BPF / REC (%)	MC (%) / RQD (%)	COH (psf) / ACL (ft)	γ (pcf) / Core Breaks	Other Tests Or Remarks / Formation or Member
		slpl SiL, gray-brn & damp		12			
5	5.0 840.0	org slpl SiL w/ shells, dk gray-brn & damp					
	6.0 839.0	marly slpl SiL, brn & damp		24			
	7.0 838.0	pl SiL w/ some shells & pebbles, brn & moist	8	20			
10 ▼	8.5 836.5	slpl FSL w/ some FS, lt brn & moist Water meaasured @ 10.5' 10/20/88 WSD w/aug	6	14			
15	12.0 833.0	LS w/ some G, lOS brn; moist to 13.8', wet, 13.8'-17'	8 12	14 17			
	17.0 828.0	pl FSL w/ pebbles, brn & wet	2	36			
	18.7 826.3	SiCL w/ some marl; brn w/ gray; wet					
20	19.5 825.5	pl SiL w/ wx shale; gray w/ grn; wet					
	21.0 824.0	mixed marly slpl FSL & LS; lOS brn w/ gray; wet		31			
	22.0 823.0	seams of SiCL, pl SiL, LFS & FS, w/ some peat seams; gray-brn, gray & dk brn; wet	6	121			
25	25.0						

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54799

U.S. Customary Units

Mn/DOT GEOTECHNICAL SECTION - LOG & TEST RESULTS *SHEET 2 of 2*

State Project	*Bridge No. or Job Desc.*	*Trunk Highway/Location*	*Boring No.*	*Ground Elevation*
6404-04	**64008**	**TH 19**	**T-1**	**845.0** *(HL)*

DEPTH	*Depth* / *Elev.*	*Classification*	*Drilling Operation*	*BPF* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Other Tests Or Remarks* / *Formation or Member*
	820.0	VERY SEVERELY WEATHERED GRANITIC ROCK (Residual Soil), rock fabric is discernible but strength is greatly reduced (sample easily crumbles), resulting soil is similar to a coarse sand w/ some finer material (silt-sized) red, white, pink and green.			15			Residuum
				69	11			
30				75/.4	14			
			PD					
35				75/.1	NSR			
	38.0 807.0	VERY SEVERELY WEATHERED SCHISTOSE ROCK OR POSSIBLE COMPLETELY WEATHERED GRANITIC ROCK (Residual Soil), very little rock fabric discernible, but some is more cohesive and stronger than above, green and white, with some black.	PD					
40								
	41.0 804.0			80/.5	14			
		Bottom of Hole - 41.0'						

Soil Class:DB Rock Class: CRH Edit: JLD Date: 1/10/05
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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54800

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **64008**	*Trunk Highway/Location* **TH 19**	*Boring No.* **T-2**	*Ground Elevation* **849.5** *(Plan)*

Location **Line M.V.R.R., 4914+92, 44' LT**

Redwood Co. Coordinate: X=559139 Y=226149 (ft.)

Latitude (North)=44°32'25.83" *Longitude (West)=95°00'23.52"*

Drill Machine **80755**

Hammer **Rope & Cathead**

SHEET 1 of 2

Drilling Completed **10/26/88**

DEPTH	*Depth / Elev.*	*Classification*	*BPF* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Other Tests Or Remarks* / *Formation or Member*
		slpl SiL, brn & damp					
	1.0 848.5	LS, brn & damp		15			
	2.0 847.5	slorg slpl SiL, dk brn & damp					
5	3.0 846.5	varved marly pl SiL & marly slpl SiL w/ some org pl SiL; IOS brn to 3.7', lt gray & wht, 3.7'-5.6'; damp to 3.7', dry, 3.7'-5', damp, 5'-5.6'		25			
	5.6 843.9	LS w/ some pebbles, gray-brn & damp	18	10			
	7.3 842.2	peaty slpl SiL, blk & damp	14	34			
10	10.0 839.5	pl FSL w/ some pebbles, brn & damp	6	19			
	12.5 837.0	slpl FSL w/ some pebbles, brn; damp to 13', wet 13'-13.6'					
	13.5 836.0	LS w/ some pebbles, brn & wet		22	150	128	
▼ 15	14.4 835.1	Water measured @ 14.5' 10/26/88 WSD w/aug S w/ some pebbles, brn & sat	2	NSR			
	17.3 832.2	SiCL, lt brn w/ IOS, wet	3	35			
20	20.0 829.5	marly pl SiL w/ S seams; lt gray w/ gray-brn; wet	2	34			
	22.5 827.0	FS w/ some seams of SiC; gray-brn w/ gray; sat		29			
25							

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54800

U.S. Customary Units

Mn/DOT GEOTECHNICAL SECTION - LOG & TEST RESULTS *SHEET 2 of 2*

State Project	*Bridge No. or Job Desc.*	*Trunk Highway/Location*	*Boring No.*	*Ground Elevation*
6404-04	**64008**	**TH 19**	**T-2**	**849.5** *(Plan)*

DEPTH	Depth / Elev.	Classification	Drilling Operation	BPF / REC (%)	MC (%) / RQD (%)	COH (psf) / ACL (ft)	γ (pcf) / Core Breaks	Other Tests Or Remarks / Formation or Member
	25.7 823.8	SiC, gray-brn & wet		13	48			
	27.3 822.2	FS, gray-brn & wet						
	28.0 821.5	S, gray-brn & wet			20			(TW refusal at 29.0')
30	29.0 820.5	RESIDUAL SOIL, parent rock is likely granitic, rock fabric not discernible, mass effectively reduced to strong soil, predominantly kaolinite and chlorite clay minerals, coarse sand size pieces of rock common, dk gray-green w/ white.		42	16			
				75/.5	16			Residuum
35			PD					
				75/.2	20			
40			WS					(rougher & harder drilling at 41')
	43.1 806.4	Bottom of Hole - 43.1'		75/.1	NSR			

Soil Class:DB Rock Class: CRH Edit: JLD Date: 1/10/05

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54801

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **64008**	*Trunk Highway/Location* **TH 19**	*Boring No.* **T-3**	*Ground Elevation* **841.3** *(Plan)*

Location **Line M.V.R.R., 4915+95, 31' RT**

Redwood Co. Coordinate: X=559139 Y=226149 (ft.)

Latitude (North)=44°32'25.83" *Longitude (West)=95°00'23.52"*

Drill Machine **76504**

Hammer **Rope & Cathead**

SHEET 1 of 2

Drilling Completed **10/25/88**

DEPTH	Depth / Elev.	Classification	Drilling Operation	BPF / REC (%)	MC (%) / RQD (%)	COH (psf) / ACL (ft)	γ (pcf) / Core Breaks	Other Tests Or Remarks / Formation or Member
		slpl SiL, brn; dry to 1', damp 1'-4.5'			15			
5	4.5 836.8	marly well-decomposed peat w/ peaty marl seam at 6' brn w/ lt brn; damp			64	560	77	
	6.5 834.8	peaty pl SiL w/some marl brn; damp to 7.5', moist 7.5'-9'		3	50			
▼10	9.0 832.3	slpl SiL, dk brn & wet Water measured @ 10' 10/25/88 WSD w/aug						NSR w/ TW, two attempts. Pushed ST for sample.
	10.5 830.8	FS w/ some pebbles, lt brn & sat			18			
	11.5 829.8	S w/ some G, IOS brn & sat		2	49			
	14.0 827.3	SiC, w/ some marl, grn-gray & moist		2	33			
15	15.5 825.8	FS w/ pl SiL seam at 17.6' brn to 16.5', IOS brn 16.5'-18'; sat		8	23			
20	18.0 823.3	LFS w/ SiCL seam at 20' lt brn to 19', dk gray-brn 19'-21.5'; sat		2	19			
	21.5 819.8	FS, gray-brn & sat		37/.5 75/.6	6			
25	23.0 818.3	VERY SEVERELY WEATHERED GRANITE (Residual Soil), rock reduced to soil, except near 23' where a quartz dike or stringer was encountered, brown, pink and white	A/P					

Index Sheet Code 2.0

(Continued Next Page)

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 54801

U.S. Customary Units

Mn/DOT GEOTECHNICAL SECTION - LOG & TEST RESULTS *SHEET 2 of 2*

State Project	*Bridge No. or Job Desc.*	*Trunk Highway/Location*	*Boring No.*	*Ground Elevation*
6404-04	**64008**	**TH 19**	**T-3**	**841.3** *(Plan)*

DEPTH	Depth / Elev.	Lithology	Classification	Drilling Operation	BPF / REC (%)	MC (%) / RQD (%)	COH (psf) / ACL (ft)	γ (pcf) / Core Breaks	Soil: Other Tests Or Remarks / Rock: Formation or Member
			(as above)		75/.3	11			
	26.0 815.3		RESIDUAL SOIL, parent rock is likely granitic, rock reduced to predominantly chlorite and kaolinite clay minerals w/ some small amount of rock fragments, soil strength is weak (easily crumbles), gray and white	PD					Residuum
					75/.3	NSR			
									(very hard layer, 28.5'-29.1')
				WS					
30									
					75/.3	NSR			
				WS					
35									
	37.3 804.0		Bottom of Hole - 37.3'		75/.3				

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 56473

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
6404-04	**Retaining Wall**	**TH 19**	**T-5**	**846.1** (S)

Location **Prop TH 19 LOR4, 291+14, 54' LT**
Redwood Co. Coordinate: X=559039 Y=226149 (ft.)
Latitude (North)=44°32'25.83" *Longitude (West)=95°00'24.90"*

Drill Machine **84486 Mobile Track**
Hammer **Rope & Cathead**
SHEET 1 of 2
Drilling Completed **12/21/94**

Depth	Elev.	Classification	BPF	MC (%)	COH (psf)	γ (pcf)	Other Tests Or Remarks
		org pl L w/ some pebbles; some S, some sawdust; brick pieces at 6.5'; calcareous pl SiL seam at 6.7'; dk brn, brn & gray-brn; Vmoist		58			1927 coordinate X=937658 Y=36172
				71			
			12	67			
8.0	838.1	marl w/ SiCL mixed in, gray-brn & Vwet					
9.0	837.1	mixed marly S & FG, & S; gray-brn & brn; wet Water measured 12/28/94 WSD w/Aug		52			%CaCO3 -51
10.5	835.6	S, brn & sat	5	32			
14.3	831.8	SiCL w/ some clayey shale; gray & gray-grn; moist	4	33			
15.5	830.6	mixed S, org pl SiL & marly pl SiL; brn, blk & gray-brn; Vmoist	8	27			
18.5	827.6	VERY SEVERELY WEATHERED GRANITE (Residual Soil), some rock fabric is discernible but mass is effectively reduced to a strong soil, many very small fragments of quartz, dk grn gry	26	16			(smooth hard drilling at 18.5') RESIDUUM
21.0	825.1	SEVERELY WEATHERED GRANITE (Residual Soil), rock fabric evident but mass effectively reduced to a strong soil, predominantly chlorite and similar clay minerals w/ fragments of quartz and feldspar rich rock, grn gry w/pink	50/.5	14			(smooth very hard drilling at 21')
			50/.3	13			(semi-rough hard drilling at 23.5')

Index Sheet Code 2.0 (Continued Next Page) *Soil Class:DB Rock Class: NMW Edit: JLD Date: 1/10/05*
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UNIQUE NUMBER 56473

U.S. Customary Units

Mn/DOT GEOTECHNICAL SECTION - LOG & TEST RESULTS *SHEET 2 of 2*

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
6404-04	**Retaining Wall**	**TH 19**	**T-5**	**846.1** (S)

DEPTH	Depth / Elev.	Lithology	Classification	Drilling Operation	BPF / REC (%)	MC (%) / RQD (%)	COH (psf) / ACL (ft)	γ (pcf) / Core Breaks	Soil / Rock	Other Tests Or Remarks / Formation or Member
			(as above)							(semi-rough extremely hard drilling, 26'-28.5')
	28.5 817.6		Bottom of Hole - 28.5'		50/.0	NSR				(no penetration w/ ST, 50 blows)

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 56620

U.S. Customary Units

State Project **6404**	*Bridge No. or Job Desc.* **CSAH 2 Emb**	*Trunk Highway/Location* **US Highway 71**	*Boring No.* **T-20**	*Ground Elevation* **831.7** *(S)*

Location **TH 19 & 71 LOR 4, 299+26, 120' Lt**

Redwood Co. Coordinate: X= Y= (ft.)

Latitude (North)= *Longitude (West)=*

Drill Machine

Hammer

SHEET 1 of 1

Drilling Completed **10/11/95**

DEPTH	*Depth* *Elev.*	*Classification*	*Drilling Operation*	*SPT N60* *REC (%)*	*MC (%)* *RQD (%)*	*COH (psf)* *ACL (ft)*	*γ (pcf)* *Core Breaks*	*Soil* *Rock*	*Other Tests Or Remarks* *Formation or Member*
	1.0 830.7	peaty L, dk brn & moist			76	419	94		Project Coordinate X=938398 Y=36457
	2.0 829.7	pl SiL w/ some marl; brn & gray; moist		WH	152				
5		seams & layers of peaty marl, partially decomposed peat, org pl L & marly peat, w/ shells; brn & gray moist to 4.5', Vmoist 4.5'-8.7'			NSR				
				WH	49				
	8.7 823.0								
10		C, gray & wet			32	80	121		
	10.5 821.2	marly mixed S & CL, gray-brn & Vmoist		2	24				
	12.5 819.2								
15		S & G, brn & sat		2	12				
				2	17				
	18.0 813.7								
20				5	31				
		layers of LFS, FS, well decomposed peat & marly pl L brn, gray-brn & gray; wet	A/P						
25				1	70				
	26.0 805.7	mixed slpl L & shells, dk gray & wet							
	27.3 804.4	LS & G, dk gray-brn & Vmoist		32	9				
	28.0 803.7		PD						
30				76	17				
		VERY SEVERELY WEATHERED GNEISS (Residual Soil), rock fabric is discernible but mass is effectively reduced to strong soil, predominantly kaolinite and chlorite, some IOS, grn, damp.	PD	50/.3	18				
			PD	50/.3	20				
35		Top of Bedrock	PD						
	36.5 795.2			50/.2	NSR				
		GNEISS, fresh, quartz and feldspars abundant, some amphiboles, pink and dk gry	WS						Precambrian Granitic Gneiss
40									
	41.6 790.1	Bottom of Hole - 12.7 m No water measurement taken		50/.1	NSR				

Index Sheet Code 2

Soil Class:DB Rock Class: NMW Edit: JLD Date: 4/1/08

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 56621

U.S. Customary Units

State Project **6404**	*Bridge No. or Job Desc.* **CSAH #2 Emb**	*Trunk Highway/Location* **US Highway 71**	*Boring No.* **T-21**	*Ground Elevation* **831.4** *(S)*

Location **TH 19& 71 LOR 4, 297+39, 185' Lt**

Redwood Co. Coordinate: X= Y= (ft.)

Latitude (North)= *Longitude (West)=*

Drill Machine

Hammer

SHEET 1 of 1

Drilling Completed **10/12/95**

DEPTH	*Depth* *Elev.*	*Lithology*	*Classification*	*Drilling Operation*	*SPT N60* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Soil* / *Rock*	*Other Tests Or Remarks* / *Formation or Member*
	1.0 830.4		org pl L w/ a few shells, dk brn & moist			61		91		
▼ 5	5.5 825.9		seams & layers of slorg pl SiL, org pl L, marly pl SiL & partially decomposed peat w/ some shells; gray-brn, dk brn, lt gray-brn & blk; damp to 2', moist, 2'-5.5'		WH	123 87	200	88		Project Coordinate X=938200 Y=36450
	7.5 823.9		pl L w/ some marl, some fibers; dk gray-brn & Vmoist		WH	54				
10	10.5 820.9		marly CL w/ 2" S layer at 9.5', gray & wet		7	27				
15	19.0 812.4		S & G w/ C seams at 14.5' & 16' brn to 13', gray-brn w/gray 13'-17', brn 17'-19'; sat Top of Bedrock	PD PD PD PD	3 2 17 50/.5	15 28 14 NA				very hard rock 19'-21' (per driller)
20 25 30	31.0 800.4		GNEISS, fresh, quartz and feldspars common, amphiboles occasional to common, pink and dk gry	WS WS WS WS	40/.0	NSR				Precambrian Granitic Gneiss

Bottom of Hole - 31.0'

Index Sheet Code 2

Soil Class:DB Rock Class: NMW Edit: JLD Date: 4/1/08

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 56622

U.S. Customary Units

State Project	Bridge No. or Job Desc.	Trunk Highway/Location	Boring No.	Ground Elevation
6404	**CSAH #2 Emb**	**US Highway 71**	**T-22**	**831.7** (S)

Location **TH 19 & 71, 295+26, 239' Lt**	Drill Machine	SHEET 1 of 1
Redwood Co. Coordinate: X= Y= (ft.)	Hammer	Drilling Completed **10/17/95**
Latitude (North)= Longitude (West)=		

DEPTH	Depth Elev.	Lithology	Classification	Drilling Operation	SPT N60 REC (%)	MC (%) RQD (%)	COH (psf) ACL (ft)	γ (pcf) Core Breaks	Soil / Rock	Other Tests Or Remarks Formation or Member
	1.0		well decomposed peat, dk brn & damp			82	130	81		
	830.7		well decomposed peat w/ shells, S seam at 1' dk brn & damp							Project Coordinate X=937996 Y=36434
	2.0		org L, dk brn & damp		2	51				
▼	829.7									
5	3.5		org pl SiL w/ some pebbles, dk brn & wet			38	200	112		
	828.2									
					wh	43				
	5.5									
	826.2		CL w/ some pebbles, dk gray-brn & Vwet							
10	10.0					NSR				
	821.7			PD						
			S & G, brn & sat		5	11				
	13.0									
	818.7			PD						
					wh	51				
15			seams & layers of CL, FS, marly pl SiL & org CL dk gray-brn, brn, gray-brn & blk; wet	PD						
						36				
	18.0									
	813.7		mixed C, G & fine stone chips; dk gray-brn & Vmoist		15	20				
20	20.0			PD						
	811.7		SEVERELY WEATHERED GNEISS (Residual Soil), rock fabric discernible but mass effectively reduced to strong soil w/ fragments of rock, kaolinite and chlorite minerals common, some IOS, grn, moist. Top of Bedrock		50/.4	11				
				PD						
					50/.3	15				
25	25.6			PD						Hard drilling - 25.6'-26'
	806.1				20/.0					
				WS						Precambrian Granitic Gneiss
30			GNEISS, fresh, quartz and feldspars abundant, amphiboles common, pink and black							
				WS						
35	36.0									
	795.7		Bottom of Hole - 36.0'							

Index Sheet Code 2

Soil Class:DB Rock Class: NMW Edit: JLD Date: 4/1/08

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 56623

U.S. Customary Units

State Project **6404**	*Bridge No. or Job Desc.* **CSAH 2 Emb**	*Trunk Highway/Location* **US Highway 71**	*Boring No.* **T-23**	*Ground Elevation* **842.4** *(S)*
Location **TH 19 & 71, 293+73, 103' Lt**		*Drill Machine*		SHEET 1 of 1
Redwood Co. Coordinate: X= Y= (ft.)		*Hammer*		*Drilling Completed* **10/24/95**
Latitude (North)= *Longitude (West)=*				

DEPTH	*Depth* *Elev.*	*Classification*	*Drilling Operation*	*SPT N60* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Other Tests Or Remarks* / *Formation or Member*
	2.8 839.6	org slpl SL w/ some marly pl SL layers, some shells dk brn; dry to damp		 3	31 59			Project Coordinate X=937896 Y=36265
	3.3 839.1	peaty pl L, blk & damp						
5	5.5 836.9	mixed S, slpl SiL & sawdust; brn & damp			57	270	77	
▼ 10	10.5 831.9	seams & layers of partially decomposed peat w/ shells, marly peat & org pl SiL; dk brn, brn & blk; moist		4	73 93	 700	 89	
	12.0 830.4	CL w/ some pebbles, gray-brn & wet		8	NSR 17			
15	15.5 826.9	FS, brn & sat		17	NSR			
	19.5 822.9	seams of C, org SiCL & FS; dk gray-brn, blk & brn; wet	PD PD	2 WH	21 55			
20	20.5 821.9	marly pl SiL, lt brn & wet	PD					
	23.0 819.4	SiCL w/ S seam at 22'; dk gray w/ brn; Vwet	PD	2	43			
25	28.0 814.4	VERY SEVERELY WEATHERED GNEISS (Residual Soil), rock fabric discernible but mass effectively reduced to strong soil w/ some rock fragments, kaolinite and chlorite common, grn, moist. approximate Top of Bedrock	PD PD	84/.8 50/.4	15 15			
30 35	36.0 806.4	GNEISS, fresh, fine to coarse grained, quartz and feldspars abundant, some biotite, pink.	WS WS	50/.1 50/.1	NSR NSR			Precambrian Granitic Gneiss
		Bottom of Hole - 36.0'						

Index Sheet Code 2

Soil Class:DB Rock Class: NMW Edit: JLD Date: 4/1/08

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 56811

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **64010**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-400**	*Ground Elevation* **825.8** *(Surveyed)*

Location **TH 71, 329+22, 27' Lt working line**

Redwood Co. Coordinate: X=561976 Y=228073 (ft.)

Latitude (North)=44°32'44.75" *Longitude (West)=94°59'44.28"*

Drill Machine **93165 GEFCO F6 6x6**

Hammer

SHEET 1 of 1

Drilling Completed **8/20/96**

Depth / Elev.	Classification	SPT N60	Other Tests Or Remarks

			Project Coordinate
			X=940813
			Y=37979
			No moisture samples taken.

21.0 804.8	Severely weathered granitic rock, not in place.	60	
22.0 803.8	Driller's Notes: S & G	40/.5	
24.0 801.8	Driller's Notes: LS w/G		
26.0 799.8	Driller's Notes: LS Top of Residuum	65/.5	
29.0 796.8	VERY SEVERELY WEATHERED GNEISS (Residual Soil), rock fabric somewhat discernible but mass effectively reduced to strong soil w/ a few rock fragments; IOS, kaolinite and chlorite common, olive grn w/ orange & white.	50/.3	Smooth drilling - 28.5'-32.5'
32.5 793.3	Bottom of Hole - 32.5' No water measurement taken	50/.2	

Index Sheet Code 2

Soil Class: Rock Class: NMW Edit: JLD Date: 7/31/06

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 56812

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **64010**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-401**	*Ground Elevation* **820.4** *(Surveyed)*

Location **TH 71, 329+38, 8' Rt working line**

Redwood Co. Coordinate: X=561976 Y=228073 (ft.)

Latitude (North)=44°32'44.75" *Longitude (West)=94°59'44.28"*

Drill Machine **93165 GEFCO F6 6x6**

Hammer

SHEET 1 of 1

Drilling Completed **8/20/96**

DEPTH	*Depth / Elev.*	*Lithology*	*Classification*	*Drilling Operation*	*SPT N60* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Soil* / *Rock*	*Other Tests Or Remarks* / *Formation or Member*
0–15										Project Coordinate X=940851 Y=37981 No moisture samples taken.
15	15.3 805.1		Cr G, S & boulders Top of Residuum							Rough drilling - 15.3'-18.8'
20	18.8 801.6		VERY SEVERELY WEATHERED GNEISS (Residual Soil), rock fabric somewhat discernible but mass effectively reduced to strong soil w/ a few small rock fragments, kaolinite and chlorite common, olive grn & white.		67/1.0					Smoother drilling at 18.8'
	20.3 800.1		Bottom of Hole - 20.3' Crooked augers at 20.3', rig moved 5' No water measurement taken							

Index Sheet Code 2

Soil Class: Rock Class: NMW Edit: JLD Date: 7/31/06

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 69737

U.S. Customary Units

State Project	*Bridge No. or Job Desc.*	*Trunk Highway/Location*	*Boring No.*	*Ground Elevation*
6404-04	**64010**	**MN Trunk Highway 19**	**T-401**	**820.4** *(Surveyed)*

Location Redwood Co. Coordinate: X=562088 Y=227906 (ft.)

Latitude (North)=44°32'43.09" Longitude (West)=94°59'42.74"

TH 71, 329+38, 8' Rt working line

Drill Machine **93165 GEFCO F6 6x6**

Hammer

SHEET 1 of 1

Drilling Completed **8/20/96**

DEPTH	*Depth* / *Elev.*	*Classification*	*SPT N60*	*MC (%)*	*COH (psf)*	*γ (pcf)*	*Other Tests Or Remarks*
							Project Coordinate X=940851 Y=37981
5							No moisture samples taken.
10							
15	15.3 805.1	Cr G, S & boulders Top of Residuum					Rough drilling - 15.3'-18.8'
	18.8 801.6	VERY SEVERELY WEATHERED GNEISS (Residual Soil), rock fabric somewhat discernible but mass effectively reduced to strong soil w/ a few small rock fragments, kaolinite and chlorite common, olive grn & white.	67/1.0				Smoother drilling at 18.8'
20	20.3 800.1	Bottom of Hole - 20.3' Crooked augers at 20.3', rig moved 5' No water measurement taken					

Index Sheet Code 2

Soil Class: Rock Class: NMW Edit: JLD Date: 3/1/11

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 73193

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **Retaining Wall**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-17**	*Ground Elevation* **878.0** *(Hand Leveled)*

Location Redwood Co. Coordinate: X=557425 Y=226214 (ft.)

Latitude (North)=44°32'26.52" Longitude (West)=95°00'47.19"

LOR4 TH 19, 276+88, 60' RT

Drill Machine **76504 CME**

Hammer **140#, 30" drop**

SHEET 1 of 1

Drilling Completed **11/29/88**

Depth / Elev.	Classification	SPT N60 / REC (%)	MC (%) / RQD (%)	COH (psf) / ACL (ft)	γ (pcf) / Core Breaks	Other Tests Or Remarks / Formation or Member
	slightly plastic Silt Loam, gray and damp					
2.0 876.0	slightly plastic Fine Sandy Loam, brown and damp		12			
3.0 875.0	Loamy Sand with some Gravel, dark brown and moist					
5.0 873.0	Fine Sand with some Gravel and stone chips, light brown and moist	16	14			
9.0 869.0	RESIDUAL SOIL; Granitic parent rock. Tan w/ some IOS, some green stains.	76	11			
12.0 866.0	RESIDUAL SOIL; Parent rock granitic. Kaolinite-feldspar layer over gray biotite-rich layer; white and gray.	82	13			
14.5 863.5	RESIDUAL SOIL; Parent rock granitic; Abundant kaolinite; gray.	8 75/.9 18 75/.8	15 16			
21.3 856.7	Bottom of Hole - 21.3' No water encountered or measured during drilling					

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION
LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 73194

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **Retaining Wall**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-5**	*Ground Elevation* **853.0** *(from Plan)*

Location Redwood Co. Coordinate: X=558773 Y=226037 (ft.)
Latitude (North)=44°32'24.74" Longitude (West)=95°00'28.57"
LOR4 TH 19, 289+25, 60' LT

Drill Machine **76504 CME**
Hammer **140#, 30" drop**
SHEET 1 of 1
Drilling Completed **11/2/88**

DEPTH	Depth / Elev.	Classification	SPT N60	MC (%)	COH (psf)	γ (pcf)	Other Tests Or Remarks
		slightly organic plastic Silt Loam, dark brown and damp		20			
5	4.0 / 849.0	Sand and Gravel with some seams of Clay Loam, brown with gray, moist		9			
▼	6.0 / 847.0	Loamy Sand and Gravel with some slightly plastic Fine Sandy Loam at 10.0'; brown; wet to 7.5', moist	3 2	17 20			
10	11.0 / 842.0	organic Clay Loam with shells, dark brown and wet	2	48			
	13.5 / 839.5	calcareous slightly plastic Silt Loam with some Coarse Sand, IOS brown and very wet		62			
15	16.0 / 837.0	slightly plastic Silt Loam, IOS brown and very wet	2	48			
	17.5 / 835.5	seams of Fine Sand, marly Peat and organic plastic Silt Loam with wood at 20.3'; gray-brown and dark brown; wet	2	155			
20	21.0 / 832.0	seams of Sand and Silty Clay, brown and gray-brown, wet	3 3	47 49			
25	26.0 / 827.0	Sand with seams of plastic Silt Loam, brown with gray, saturated	10	30			
30	28.5 / 824.5	RESIDUAL SOIL; Parent rock is likely granitic. Rock mass has been reduced to soil composed primarily of clay weathering minerals such as kaolinite and chlorite, with little or no rock structure remaining.	53 75/.2	18 NSR			
	34.2 / 818.8	Bottom of Hole - 34.2' Water measured at 7.8' while sampling and/or drilling with augers					

Index Sheet Code 3.0

Soil Class:DEB Rock Class: Edit: JLD Date: 3/9/11
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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 73195

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **Retaining Wall**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-6**	*Ground Elevation* **854.5** *(from Plan)*

Location Redwood Co. Coordinate: X=558806 Y=226030 (ft.)

Latitude (North)=44°32'24.67" Longitude (West)=95°00'28.13"

LOR4 TH 19, 290+75, 50' LT

Drill Machine **76504 CME**

Hammer **140#, 30" drop**

SHEET 1 of 1

Drilling Completed **11/1/88**

DEPTH	*Depth* / *Elev.*	*Classification*	*SPT N60* / *REC (%)*	*MC (%)* / *RQD (%)*	*COH (psf)* / *ACL (ft)*	*γ (pcf)* / *Core Breaks*	*Other Tests Or Remarks* / *Formation or Member*
5	5.5 849.0	slightly organic slightly plastic Silt Loam with roots and a 1" Peat seam at 4.8', brown with dark brown, damp		27 56			
	6.0 848.5	slightly plastic Fine Sandy Loam with some organic matter, brown with IOS, damp					
10	10.0 844.5	partially decomposed Peat with some shells; black to 8.0', dark brown; damp to 8.0', moist	5	173 151			
▼	11.0 843.5	mixed Loamy Fine Sand and Fine Sand with a seam of Silty Clay Loam, gray-brown and wet					
	13.3 841.2	organic Silty Clay Loam with shells and seams of Fine Sand, dark gray-brown and wet	1	51			
15	15.3 839.2	marly Silty Clay Loam, gray-brown and wet	3	67			
	16.0 838.5	plastic Sandy Loam, bowrn and wet					
	19.3 835.2	Silty Clay Loam with a seam of Marl at 17.5'; gray to 17.3', brown 17.3'-17.8', gray-brown; wet	1	29			
20	22.3 832.2	Sand with seams of Silty Clay Loam and partially decomposed wood at 21.0'; brown with gray, dark brown; sat	45	71 16			
25	25.0 829.5	Loamy Sand and Gravel with a seam of peaty plastic Silt Loam at 24.5', brown and saturated	20	18			
	29.3 825.2	RESIDUAL SOIL; Parent rock is likely granitic. Rock mass has been reduced to soil, with little or no rock structure remaining. Kaolinite and chlorite clay minerals appear to be major constituents. Greenish-gray and white.	34 75/.3 75/.3	13 NSR			NSR at 29.3'

Bottom of Hole - 29.3'

Water measured at 11.7' while sampling and/or drilling with augers

Index Sheet Code 3.0

Soil Class:DEB Rock Class: CRH Edit: JLD Date: 3/9/11

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 73196

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **Retaining Wall**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-7**	*Ground Elevation* **877.0** *(from Plan)*

Location Redwood Co. Coordinate: X=557609 Y=226148 (ft.)

Latitude (North)=44°32'25.86" Longitude (West)=95°00'44.65"

LOR4 TH 19, 278+60, 60' RT

Drill Machine **76504 CME**

Hammer **140#, 30" drop**

SHEET 1 of 1

Drilling Completed **11/21/88**

Depth / Elev.	*Classification*	*SPT N60*	*MC (%)*	*COH (psf)*	*γ (pcf)*	*Other Tests Or Remarks*
	organic Clay Loam, black and damp					
2.0 875.0	Clay Loam, brown and damp		19			
5.0 872.0	calcareous slightly plastic Silt Loam with some Fine Sand, light brown and damp	27	11			
7.0 870.0	Sand and Fine Gravel, light brown and damp	29	4			
9.5 867.5	slightly plastic Sandy Loam with pebbles and Silty Clay Loam seams, brown asnd moist	8	8			
12.0 865.0	Clay Loam with some Sand and pebbles, brown and moist	30 8	13 12			
17.0 860.0	seams of Clay Loam with pebbles, Sand and Silty Clay Loam; brown, gray and gray-brown; wet	5 6 40	19 13 14			Driller's Notes: hit water while sampling 17.5'-19.0'
23.3 853.7	VERY SEVERELY WEATHERED GRANITE; Rock fabric evident in places. Abundant kaolinite. Gray & white to 25.0', gray 25.0'-28.0'.	40 80/.5	14			
28.0 849.0	SEVERELY WEATHERED GRANITE; Alternation of lighter and darker minerals in some places suggests color banding. Gray with white and tan.	34 75/.4	14			
30.9 846.1	Bottom of Hole - 30.9' No water encountered or measured during drilling					

Index Sheet Code 3.0

Soil Class:DEB Rock Class: CLB Edit: JLD Date: 3/9/11

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 73197

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **Retaining wall**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-8**	*Ground Elevation* **889.0** *(from Plan)*

Location Redwood Co. Coordinate: X=557742 Y=226096 (ft.)

Latitude (North)=44°32'25.35" Longitude (West)=95°00'42.81"

LOR4 TH 19, 280+00, 60' RT

Drill Machine **76504 CME**

Hammer **140#, 30" drop**

SHEET 1 of 1

Drilling Completed **11/17/88**

Depth	*Elev.*	*Classification*	*SPT N60*	*MC (%)*	*COH (psf)*	*γ (pcf)*	*Other Tests Or Remarks*
1.0	888.0	Driller's Notes: Silt Loam, black and moist					
2.0	887.0	Driller's Notes: Loamy Fine Sand, dark brown and moist					
2.6	886.4	slightly plastic Fine Sandy Loam, dark brown and moist	11	16			
3.2	885.8	Silty Clay Loam, brown and moist					
4.0	885.0	plastic Silt Loam with Sand, brown and red-brown, moist					
5.5	883.5	Sand and fine stone pieces, light gray-brown and damp	44	13			
15.1	873.9	RESIDUAL SOIL; Parent rock is likely granitic. Reduced in strength to soil, consisting primarily of kaolinite and chlorite. Green and white.	82 15 75/.7 75/.6	15 13 13			

Bottom of Hole - 15.1'

No water encountered or measured during drilling

Index Sheet Code 3.0

Soil Class:DEB Rock Class: CRH Edit: JLD Date: 3/9/11

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MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 73198

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **Retaining Wall**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-8A**	*Ground Elevation* **888.0** *(from Plan)*

Location Redwood Co. Coordinate: X=557751 Y=226090 (ft.)

Latitude (North)=44°32'25.29" Longitude (West)=95°00'42.68"

LOR4 TH 19, 280+04, 57' RT

Drill Machine **76504 CME**

Hammer **140#, 30" drop**

SHEET 1 of 1

Drilling Completed **11/28/88**

DEPTH	*Depth / Elev.*	*Classification*	*SPT N60*	*MC (%)*	*COH (psf)*	*γ (pcf)*	*Other Tests Or Remarks*
0–15		See nearby boring labeled T-8 for soil description 0'-15'.					
15	15.0 873.0	RESIDUAL SOIL; Parent rock is granitic. Rock fabric is not discernible; rock mass reduced to soil, predominantly clay minerals - chlorite and kaolinite. Green and white.	71	18			
			43	28			
			73	11			
25	25.5 862.5	VERY SEVERELY WEATHERED GRANITIC ROCK; Some rock fabric discernible, but mass effectively reduced to soil. Soil portion predominantly clay minerals - chlorite and kaolinite. Green and white, with pink	22 78/.5	12			
			19 75/.8	13			
	31.3 856.7	Bottom of Hole - 31.3' No water encountered or measured during drilling					

MINNESOTA DEPARTMENT OF TRANSPORTATION - GEOTECHNICAL SECTION

LABORATORY LOG & TEST RESULTS - SUBSURFACE EXPLORATION

UNIQUE NUMBER 73199

U.S. Customary Units

State Project **6404-04**	*Bridge No. or Job Desc.* **Retaining Wall**	*Trunk Highway/Location* **MN Trunk Highway 19**	*Boring No.* **T-9**	*Ground Elevation* **892.0** *(from Plan)*

Location Redwood Co. Coordinate: X=557890 Y=226039 (ft.)

Latitude (North)=44°32'24.78" Longitude (West)=95°00'40.76"

LOR4 TH 19, 281+30, 60' RT

Drill Machine **76504 CME**

Hammer **140#, 30" drop**

SHEET 1 of 1

Drilling Completed **11/22/88**

Depth *Elev.*	*Classification*	*SPT N60*	*MC (%)*	*COH (psf)*	*γ (pcf)*	*Other Tests Or Remarks*
	organic slightly plastic Sandy Loam to slightly organic slightly plastic Sandy Loam, black to brown, dry		14			
5.0 887.0	slightly organic slightly plastic Silt Loam with pebbles, brown and dry	28	19			
7.2 884.8	calcareous slightly plastic Silt Loam, tan and dry	26	5			
9.5 882.5	Sand and Fine Gravel, tan and dry	25	2			
13.2 878.8	SEVERELY WEATHERED GRANITE; Rock fabric visible. Some IOS, also some dark brown stains. Staining was more prevelent from 18'-21.5' Possibly remnant mineral banding. Gray to 18.0', tan	14	20			
		20 75/.5	17			
21.5 870.5	SEVERELY WEATHERED GRANITE; Rock fabric visible. Kaolinite abundant. Gray and white.	21 75/.9	17			
25.0 867.0	SEVERELY WEATHERED GRANITE; Rock fabric visible. Kaolinite abundant. Alternation of gray and white in some areas suggests mineral banding 25.0'-28.0' and readily apparent below 30.8' with kaolinite-rich bands alternating with biotite-rich bands	21 75/.6	14			
		24 75/.5	16			
31.0 861.0	Bottom of Hole - 31.0 Water measurement taken is not conclusive.					

Index Sheet Code 3.0

Soil Class:NM Rock Class: CLB Edit: JLD Date: 3/9/11

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Hole No. 21-1M

DRILLING LOG	DIVISION mVD	INSTALLATION St. Paul Dist	SHEET 1 OF 6 SHEETS

1. PROJECT Lower Sioux
2. LOCATION (Coordinates or Station) See Pg. 6
3. DRILLING AGENCY Interstate Drilling Services
4. HOLE NO. (As shown on drawing title and file number) #1
5. NAME OF DRILLER Jared Zak
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN —
8. DEPTH DRILLED INTO ROCK —
9. TOTAL DEPTH OF HOLE 41.5
10. SIZE AND TYPE OF BIT 3¼" HSA / 2 15/16" RB
11. DATUM FOR ELEVATION SHOWN (TBM or MSL) NAVD88
12. MANUFACTURER'S DESIGNATION OF DRILL Diedrich D-50
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED 9 Jars — UNDISTURBED —
14. TOTAL NUMBER CORE BOXES —
15. ELEVATION GROUND WATER 814.4
16. DATE HOLE — STARTED 1-20-2021 — COMPLETED 1-20-2021
17. ELEVATION TOP OF HOLE 824.0
18. TOTAL CORE RECOVERY FOR BORING — %
19. SIGNATURE OF INSPECTOR Colin Roldich

ELEVATION 824.0 a	DEPTH 0.0 b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
		CL	Silty Clay (CL) (TOPSOIL) Soft Dry Med. Plast. Black 80% Clay 20% silt	2+2½ P O U	SN1 0.0 0.5	• SPT = 140 lbs @ 30" drop, Autohammer used
823.2	0.8 1.0	ML	Clayey Silt (ML) Soft Dry Low-No Plast. Brown Laminated 100% fines Trace f Sand	N D R 2.5 T 3.0		LOCATION N E NAD83-UTM15
822.0	2.0 3.0 4.0	CL	Silty Clay (CL) Soft Dry-Wet Med. Plast. Dark Brown Occ. Jumbled texture 100% fines Trace f. Sand	SPT 1 1 1 1 R 0.2 T 5.0		• Set HSA to 5.0
	5.0 6.0 7.0	CL CL		2+2½ P O U N D R 2.8 T 8.0	SN 2 5.0 5.5	WATER LEVEL Set HSA to 31.0 Sampled to 32.0 TIME W.L. BOH 1021 13.2 31.0 1049 10.9 30.9 1101 10.2 30.9 1116 9.8 30.8 1130 9.7 30.8 1135 9.6 30.8 1145 9.6 30.8
	8.0			SPT 1		
815.2	8.8 9.0		Wet	1 1		• Set HSA to 10.0
814.4	9.6	▽ SP	(See Next Page)	1 R 1.6 T 10.0		
814.0	10.0					

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PROJECT Lower Sioux — HOLE NO. 21-1M

Hole No. 21-1M

DRILLING LOG

DIVISION: MVD

INSTALLATION: St Paul Dist.

SHEET 2 OF 6 SHEETS

1. PROJECT: Lower Sioux
2. LOCATION (Coordinates or Station)
3. DRILLING AGENCY
4. HOLE NO. (As shown on drawing title and file number)
5. NAME OF DRILLER
6. DIRECTION OF HOLE ☐ VERTICAL ☐ INCLINED ____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK
9. TOTAL DEPTH OF HOLE
10. SIZE AND TYPE OF BIT
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN | DISTURBED | UNDISTURBED
14. TOTAL NUMBER CORE BOXES
15. ELEVATION GROUND WATER
16. DATE HOLE | STARTED | COMPLETED
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING %
19. SIGNATURE OF INSPECTOR: Colin Reddick

ELEVATION 814.0 a	DEPTH 10.0 b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) (Cont'd...) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
		SP	Poorly Sorted Sand (SP) Loose Wet Tan 95% f-m Sand 5% C Sand Trace Silt	2x2½ P O U N D		
	11.0					
	12.0					· Set HSA to 12.0
	13.0	SP		R2.2 T13.0		
				SPT 2	Sn 3 13.0 13.5	
				3		
	14.0			4		· Set HSA to 15.0
809.3	14.7		Occ. Fe Staining	6 R1.9 T15.0		
	15.0			2x2½		~1.0 of heave @ 15.0
808.4	15.6		Occ. C. Sand Seams	P O		
	16.0	SP		U		
	17.0			N D		· Set HSA to 18.0
				R2.8 T18.0		
	18.0			SPT 5		~1.0 of heave prior to SPT, blows may be erroneous
				4	Sn 4 18.0 18.5	
	19.0	SP		3		
				2 R1.7 T20.0		· Set HSA to 20.0
804.0	20.0					

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PROJECT: Lower Sioux

HOLE NO. 21-1M

Hole No. 21-1M

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist	SHEET 3 OF 6 SHEETS

1. PROJECT Lower Sioux
2. LOCATION (Coordinates or Station)
3. DRILLING AGENCY
4. HOLE NO. (As shown on drawing title and file number)
5. NAME OF DRILLER
6. DIRECTION OF HOLE ☐ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK
9. TOTAL DEPTH OF HOLE
10. SIZE AND TYPE OF BIT
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN | DISTURBED | UNDISTURBED —
14. TOTAL NUMBER CORE BOXES —
15. ELEVATION GROUND WATER
16. DATE HOLE | STARTED | COMPLETED
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING — %
19. SIGNATURE OF INSPECTOR Colin Kiddick

ELEVATION 804.0 a	DEPTH 20.0 b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) (Cont'd...) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
		SP	Poorly Graded Sand (SP) Loose-M. Dense Wet Reddish Tan 85% F-M Sand 15% C Sand Trace Silt (Occ. F. gravel @ 21.0 + below)	2x2½ P O U N D		
803.3	20.7		Coarse Sand Content inc. ~15%			
	21.0					• Set HSA to 23.0
	22.0			R2.4 T23.0		1.0' of heave prior to SPT, reset casing, 0.5' of heave, blows may be erroneous. Continual difficulty w/removing tooling due to sand lock
	23.0	SP		SPT 11 12 13 6	SNS 23.0 23.5	
	24.0			R2.0 T25.0		• Set HSA to 25.0
	25.0	SP		2x2½ P O U N D		Unable to advance 2x2½ beyond 25.9; shoe bent
	26.0			SPT 4 7		
	27.0			7 8 R2.0 T28.0		• Set HSA to 28.0
796.4	27.6		C. Gravel			
	28.0			SPT 5		1.0' of heave prior to SPT
795.3	28.7	SP-SC	(Sharp) Sand w/Clay (SP-SC) M. Dense Wet Gray 90% F-C sand 10% fines	7		
	29.0			8		• Set HSA to 30.0, rough drill action
794.6	29.4	CL		8		
794.0	30.0		(See Next Page)	R1.7 T30.0		

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PROJECT Lower Sioux | HOLE NO. 21-1M

Hole No. 21-1M

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist.
		SHEET 4 OF 6 SHEETS

1. PROJECT Lower Sioux
2. LOCATION (Coordinates or Station)
3. DRILLING AGENCY
4. HOLE NO. (As shown on drawing title and file number)
5. NAME OF DRILLER
6. DIRECTION OF HOLE ☐ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK
9. TOTAL DEPTH OF HOLE
10. SIZE AND TYPE OF BIT
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN | DISTURBED | UNDISTURBED
14. TOTAL NUMBER CORE BOXES
15. ELEVATION GROUND WATER
16. DATE HOLE | STARTED | COMPLETED
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING %
19. SIGNATURE OF INSPECTOR Colin

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
794.0	30.0	CL	Silty Clay (CL) Stiff Wet-Moist Bluish-Gray, turning gray mottled w/ tan @ 30.6 100% fines Occ. Med. Sand	SPT 3	SN6 30.0 31.0	
793.4	30.6			5		
	31.0			6		Unable to advance HSA beyond 31.0
792.5	31.5	SP-SC		10 R 1.7 T 32.0	SN 7 31.5 31.7	
792.0	32.0		(FLOAT) Highly Wx Rock (SP-SC) M. Dense-V. Dense Moist Gray-White, Some Fe Staining Blocky texture w/ obscured laminations 90% Wx Rock 10% Fines			Mixed 80 gal H_2O w/25 lbs bentonite, Drilled out + Cleaned hole to 35.0, easy drilling @ 32.5, inferred Silt/Wx float contact
791.5	32.5					
	33.0					
	34.0					
789.0	35.0	ML	Clayey Silt (ML) Hard Sl. Moist Laminated Greenish-Tan 100% fines Occ. Wood	SPT 10	SN 8 35.0 35.5	
788.3	35.7		Highly Wx Rock V. Weak Dry Clayey in part Blocky texture Gray w/ black specks	12	SN 9 35.7 36.5	
788.0	36.0	Feldspar Seam		28		
				55 R 1.6 T 37.0		
787.0	37.0					Cleaned + drilled out hole to 38.0 w/RB
786.0	38.0			SPT 50	R 0.2	Refusal @ 38.2
	39.0					Cleaned + drilled out hole to 40.0 w/RB
784.0	40.0					

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PROJECT Lower Sioux

HOLE NO. 21-1M

Hole No. 21-1M

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist
SHEET 5 OF 6 SHEETS		

1. PROJECT Lower Sioux
2. LOCATION (Coordinates or Station)
3. DRILLING AGENCY
4. HOLE NO. (As shown on drawing title and file number)
5. NAME OF DRILLER
6. DIRECTION OF HOLE ☐ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK
9. TOTAL DEPTH OF HOLE
10. SIZE AND TYPE OF BIT
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN | DISTURBED | UNDISTURBED
14. TOTAL NUMBER CORE BOXES
15. ELEVATION GROUND WATER
16. DATE HOLE | STARTED | COMPLETED
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING %
19. SIGNATURE OF INSPECTOR Colin

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
784.0	40.0		(Cont'd.)			
			Highly Wx Rock (See previous description)	SPT 15		
783.2	40.8		Feldspar seam @40.8	28		•Backfilled hole w/ tremied bentonite-cement grout
	41.0			55 R1.5 T41.5		
782.5	41.5		(Bottom of Hole)			

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PROJECT Lower Sioux

HOLE NO. 21-1M

Hole No. 21-1M

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist	SHEET 6 OF 6 SHEETS

1. PROJECT Lower Sioux	10. SIZE AND TYPE OF BIT
2. LOCATION (*Coordinates or Station*)	11. DATUM FOR ELEVATION SHOWN (*TBM or MSL*)
3. DRILLING AGENCY	12. MANUFACTURER'S DESIGNATION OF DRILL
4. HOLE NO. (*As shown on drawing title and file number*)	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED — UNDISTURBED
5. NAME OF DRILLER	14. TOTAL NUMBER CORE BOXES
	15. ELEVATION GROUND WATER
6. DIRECTION OF HOLE ☐ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.	16. DATE HOLE — STARTED — COMPLETED
7. THICKNESS OF OVERBURDEN	17. ELEVATION TOP OF HOLE
8. DEPTH DRILLED INTO ROCK	18. TOTAL CORE RECOVERY FOR BORING %
9. TOTAL DEPTH OF HOLE	19. SIGNATURE OF INSPECTOR Colin [illegible]

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (*Description*) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (*Drilling time, water loss, depth of weathering, etc., if significant*) g
			LOCATION MAP			•Not drawn ~~to~~ scale

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PROJECT Lower Sioux	HOLE NO. 21-1M

Hole No. 21-2M

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist	SHEET 1 OF 2 SHEETS

1. PROJECT Lower Sioux
2. LOCATION (Coordinates or Station) See drawing pg. 2
3. DRILLING AGENCY Interstate Drilling Services
4. HOLE NO. (As shown on drawing title and file number) #3
5. NAME OF DRILLER Jared Zak
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN —
8. DEPTH DRILLED INTO ROCK —
9. TOTAL DEPTH OF HOLE 41.5
10. SIZE AND TYPE OF BIT 3 1/4" HSA / 2 15/16" RB
11. DATUM FOR ELEVATION SHOWN (TBM or MSL) NAVD 88
12. MANUFACTURER'S DESIGNATION OF DRILL Diedrich D-50
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN DISTURBED 1 Jar UNDISTURBED —
14. TOTAL NUMBER CORE BOXES —
15. ELEVATION GROUND WATER Not Determined
16. DATE HOLE STARTED 1-20-2021 COMPLETED 1-20-2021
17. ELEVATION TOP OF HOLE 824.5
18. TOTAL CORE RECOVERY FOR BORING — %
19. SIGNATURE OF INSPECTOR Colin

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
824.5	0.0					• SPT = 140 lbs @ 30" drop, Autohammer used LOCATION N E NAD83-UTM15 • Set HSA to 9.5, mixed 80 gal H_2O w/20 lbs bentonite • Sl. rough drill action @13.0, possible gravels • Firm drilling @ 37.0, wood in cuttings, increase in downpressure below 37.0
787.5	37.0		(Approx. Contact) Highly Wx Rock V. Weak Dry - Sl. Moist Clayey Blocky Texture Green - Gray			
784.5	40.0			SPT 24 25 55 R 1.5 T 41.5	SN 1 40.0 41.0	• Backfilled hole w/tremied bentonite-cement grout
783.0	41.5		(Bottom of Hole)			

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PROJECT Lower Sioux

HOLE NO. 21-2M

Hole No. 21-2M

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist	SHEET 2 OF 2 SHEETS

1. PROJECT Lower Sioux
2. LOCATION (Coordinates or Station)
3. DRILLING AGENCY
4. HOLE NO. (As shown on drawing title and file number)
5. NAME OF DRILLER
6. DIRECTION OF HOLE
☐ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK
9. TOTAL DEPTH OF HOLE
10. SIZE AND TYPE OF BIT
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN | DISTURBED | UNDISTURBED
14. TOTAL NUMBER CORE BOXES
15. ELEVATION GROUND WATER
16. DATE HOLE | STARTED | COMPLETED
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING %
19. SIGNATURE OF INSPECTOR Colin Riddick

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
			LOCATION MAP			
						·Not drawn to scale

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PROJECT Lower Sioux

HOLE NO. 21-2M

(TRANSLUCENT)

Hole No. 21-3M

DRILLING LOG	DIVISION mvD	INSTALLATION St Paul Dist	SHEET 1 OF 2 SHEETS

1. PROJECT Lower Sioux
2. LOCATION (Coordinates or Station) See drawing pg. 2
3. DRILLING AGENCY Interstate Drilling Services
4. HOLE NO. (As shown on drawing title and file number) #4
5. NAME OF DRILLER Jared Zak
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN —
8. DEPTH DRILLED INTO ROCK —
9. TOTAL DEPTH OF HOLE 26.5
10. SIZE AND TYPE OF BIT 3 1/4" HSA / 2 15/16" RB
11. DATUM FOR ELEVATION SHOWN (TBM or MSL) NAVD 88
12. MANUFACTURER'S DESIGNATION OF DRILL Diedrich D-50
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED 1 Jar — UNDISTURBED —
14. TOTAL NUMBER CORE BOXES —
15. ELEVATION GROUND WATER Not Determined
16. DATE HOLE — STARTED 1-20-2021 — COMPLETED 1-2[illegible]-2021
17. ELEVATION TOP OF HOLE 825.6
18. TOTAL CORE RECOVERY FOR BORING — %
19. SIGNATURE OF INSPECTOR Cole Ridder

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
825.6	0.0					• SPT = 140 lbs @ 30" drop, Autohammer used Location N E NAD83-UTM15 • Set HSA to 9.5, mixed 80 gal H_2O w/20 lbs bentonite • Sl. rough drill action @ 17.0, c. sand + gravel in cuttings • Inc. in down pressure @ 20.0
805.6	20.0		(Approx. Contact)			
	21.0					
	22.0					• Chattery drill action @ 22.0
803.1	22.5			SPT 50	@ 0.2 T22.7	
	23.0		Highly Wx Rock V. Weak - Weak Dry - Sl. Moist Clayey in part Blocky texture FE Staining in Zones Tan			• Backfilled hole w/tremied bentonite-cement grout, chipped upper 5.0'
	24.0					
	25.0			SPT 26	SN1 25.0 / 26.0	
				73		
	26.0			54		
799.1	26.5		(Bottom of Hole)	R1.5 T26.5		

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PROJECT Lower Sioux

HOLE NO. 21-3M

Hole No. 21-3m

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist	SHEET 2 OF 2 SHEETS

1. PROJECT
Lower Sioux
2. LOCATION (*Coordinates or Station*)
3. DRILLING AGENCY
4. HOLE NO. (*As shown on drawing title and file number*)
5. NAME OF DRILLER
6. DIRECTION OF HOLE
☐ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK
9. TOTAL DEPTH OF HOLE
10. SIZE AND TYPE OF BIT
11. DATUM FOR ELEVATION SHOWN (*TBM or MSL*)
12. MANUFACTURER'S DESIGNATION OF DRILL
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN | DISTURBED | UNDISTURBED
14. TOTAL NUMBER CORE BOXES
15. ELEVATION GROUND WATER
16. DATE HOLE | STARTED | COMPLETED
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING %
19. SIGNATURE OF INSPECTOR
Colin [illegible]

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (*Description*) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (*Drilling time, water loss, depth of weathering, etc., if significant*) g
			LOCATION MAP			
						•Not drawn to Scale

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MAR 71 (TRANSLUCENT)

PROJECT
Lower Sioux

HOLE NO.
21-3m

Hole No. 21-4M

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist	SHEET 1 OF 3 SHEETS

1. PROJECT Lower Sioux
2. LOCATION (Coordinates or Station) See drawing pg. 3
3. DRILLING AGENCY Interstate Drilling
4. HOLE NO. (As shown on drawing title and file number) #2
5. NAME OF DRILLER Jared Zak
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN —
8. DEPTH DRILLED INTO ROCK —
9. TOTAL DEPTH OF HOLE 17.3
10. SIZE AND TYPE OF BIT 3 1/4" HSA
11. DATUM FOR ELEVATION SHOWN (TBM or MSL) NAVD 88
12. MANUFACTURER'S DESIGNATION OF DRILL Diedrich D-50
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED 2 Jars — UNDISTURBED —
14. TOTAL NUMBER CORE BOXES —
15. ELEVATION GROUND WATER Not Determined
16. DATE HOLE — STARTED 1-20-2021 — COMPLETED 1-20-2021
17. ELEVATION TOP OF HOLE 826.5
18. TOTAL CORE RECOVERY FOR BORING — %
19. SIGNATURE OF INSPECTOR Colin Kiddish

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
826.5	0.0					• SPT = 140 lbs @ 30" drop, Auto hammer used
	1.0					LOCATION N E NAD83-UTM15
	2.0					
	3.0					• Drilled out to 4.5 w/HSA
	4.0					
822.0	4.5		Silty Clay (CL) Soft Sl. Moist Med. Plast. Gray-Black 100% fines Trace F. sand Occ. organics	SPT 2		
	5.0	CL		2		
				2		
	6.0			4 R9.2 6.5		
820.0	6.5					
	7.0					
	8.0					• Drilled out to 9.5 w/HSA
	9.0					
817.0	9.5			SPT	SN1 9.5 10.0	
816.5	10.0	CL		2		

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PROJECT Lower Sioux

HOLE NO. 21-4M

Hole No. 21-4M

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist	SHEET 2 OF 3 SHEETS

1. PROJECT Lower Sioux	10. SIZE AND TYPE OF BIT
2. LOCATION (Coordinates or Station)	11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
3. DRILLING AGENCY	12. MANUFACTURER'S DESIGNATION OF DRILL
4. HOLE NO. (As shown on drawing title and file number)	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN · DISTURBED · UNDISTURBED
5. NAME OF DRILLER	14. TOTAL NUMBER CORE BOXES
6. DIRECTION OF HOLE ☐ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.	15. ELEVATION GROUND WATER
	16. DATE HOLE · STARTED · COMPLETED
7. THICKNESS OF OVERBURDEN	17. ELEVATION TOP OF HOLE
8. DEPTH DRILLED INTO ROCK	18. TOTAL CORE RECOVERY FOR BORING %
9. TOTAL DEPTH OF HOLE	19. SIGNATURE OF INSPECTOR Colin Kobler

ELEVATION 816.5 a	DEPTH 10.0 b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) (Cont'd...) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
816.3	10.2	CL	~~Silty Clay (CL)~~ ~~Soft~~ ~~Sl. Moist~~ ~~Med. Plast.~~ ~~Gray-Black~~ ~~100% Fines~~ ~~Trace F. sand~~ ~~Occ. organics~~ Color change Dk. Gray →	2 2 2 R 1.2 T 11.5		
	11.0					
815.0	11.5					
814.5	12.0					·Rough drill action @ 12.0, set HSA to 14.5
	13.0					
	14.0		~~Highly Wx Rock (SP-SC)~~			
812.0	14.5	SP-SC	~~V. Dense~~ ~~Dry - Sl. Moist~~ ~~Heavy Fe Staining~~ ~~90% F-C Sand~~ ~~10% fines~~ ~~(Rock)~~	SPT 61	SW 2 14.5 15.2	
	15.0			50	R 0.7 T 15.2	
811.3	15.2					·Very slow advancement of HSA, set HSA to 17.0
	16.0					
809.5	17.0	SP-SC		SPT 100	R 0.3 T 17.3	
809.2	17.3		(Bottom of Hole)			·Backfilled hole w/ bentonite chips

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PROJECT Lower Sioux

HOLE NO. 21-4M

Hole No. 21-4M

DRILLING LOG	DIVISION MVD	INSTALLATION St Paul Dist	SHEET 3 OF 3 SHEETS

1. PROJECT Lower Sioux
2. LOCATION (Coordinates or Station)
3. DRILLING AGENCY
4. HOLE NO. (As shown on drawing title and file number)
5. NAME OF DRILLER
6. DIRECTION OF HOLE ☐ VERTICAL ☐ INCLINED ____________ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN
8. DEPTH DRILLED INTO ROCK
9. TOTAL DEPTH OF HOLE
10. SIZE AND TYPE OF BIT
11. DATUM FOR ELEVATION SHOWN (TBM or MSL)
12. MANUFACTURER'S DESIGNATION OF DRILL
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN | DISTURBED | UNDISTURBED
14. TOTAL NUMBER CORE BOXES
15. ELEVATION GROUND WATER
16. DATE HOLE | STARTED | COMPLETED
17. ELEVATION TOP OF HOLE
18. TOTAL CORE RECOVERY FOR BORING %
19. SIGNATURE OF INSPECTOR Colin Riddick

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
			LOCATION MAP			-Not drawn to scale

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE. | PROJECT Lower Sioux | HOLE NO. 21-4M

Project: Lower Sioux TPP Feasibility Study
Subject: Disturbed Testing - Phase 1
Author: Anthony Levine
Date: 2/9/2021

Test Request: **1**
Laboratory: Braun Intertec
Contract Number: Credit Card

St. Paul District
GEOLOGY
GEOTECHNICAL
US Army Corps of Engineers

Est. Delivery: 2/12/2021
Delivery By: Anthony Levine

TEST ASTM	**D4318**	**D2216**	**D854**	**D6913**	**D422 & D7928**
Tests in Request #1	**4**	**11**	**7**	**1**	**4**
Unit Price	*$ 90.00*	*$ 15.00*	*$ 100.00*	*$ 110.00*	*$ 140.00*
Test Request #1 Subtotal	$ 360.00	$ 165.00	$ 700.00	$ 110.00	$ 560.00

SAMPLES MUST BE RETAINED BY LAB OR RETURNED TO USACE.

Test Request #1 Total $ 1,895.00

FINAL AMOUNT TO BE PAID VIA GOV VISA

Disturbed Testing - Phase 1: Test Request: 1

						Atterberg Limits (Liquid Limit and Plastic Limit)	Moisture Content	Specific Gravity	Sieve Analysis with #200 Wash	Hydrometer with sieve analysis
Boring	Material	Sample	Sample Type	Sample Depth Start	Sample Depth End	D4318	D2216	D854	D6913	D422 & D7928
21-1M	Topsoil	1	Jar	0.0	0.5					
21-1M	Silty Clay (CL)	2	Jar	5.0	5.5	x	x	x		See Note
21-1M	Poorly Sorted Sand (SP)	3	Jar	13.0	13.5		x			See Note
21-1M	Poorly Sorted Sand (SP)	4	Jar	18.0	18.5		x	x		See Note
21-1M	Poorly Sorted Sand (SP)	5	Jar	23.0	23.5		x		x	
21-1M	Silty Clay (CL)	6	Jar	30.0	31.0	x	x	x		
21-1M	Highly Weathered Rock (SP-SC) - Sample Not Sent to Lab	7	Jar	31.5	31.7					
21-1M	Clayey Silt (ML)	8	Jar	35.0	35.5	x	x	x		
21-1M	Highly Weathered Rock (SP-SC)	9	Jar	35.7	36.5		x			
21-2M	Highly Weathered Rock (SP-SC)	1	Jar	40.0	41.0		x	x		
21-3M	Highly Weathered Rock (SP-SC)	1	Jar	25.0	26.0		x			
21-4M	Silty Clay (CL)	1	Jar	9.5	10.0	x	x	x		See Note
21-4M	Highly Weathered Rock (SP-SC)	2	Jar	14.5	15.2		x	x		

Note: Sieve/Hydrometers should only be performed if enough sample material is available to meet the ASTM requirements.

Borehole	Depth feet	Liquid Limit	Plastic Limit	Plasticity Index	%<#200 Sieve	Class-ification	Water Content (%)	Dry Density (pcf)	Organic Content (%)	Specific Gravity	Electrical Resistivity (ohm-cm)
21-1M	5	33	19	14	76.9	CL	31.1			2.71	
21-1M	13				4.3	SP	23.8				
21-1M	18				3.5	SP	21.8			2.69	
21-1M	23				5.5		19.6				
21-1M	30	37	24	13			29.7			2.74	
21-1M	35	49	32	17			36.3			2.76	
21-1M	35.7						21.4				
21-2M	40						19.9			2.7	
21-3M	25						17.6				
21-4M	9.5	47	20	27	88.4	CL	32.2			2.69	
21-4M	14.5						6.8			2.69	

Braun Project B2101436
Lower Sioux TPP Feasibility Study
Disturbed Testing - Phase 1

LABORATORY RESULTS SUMMARY

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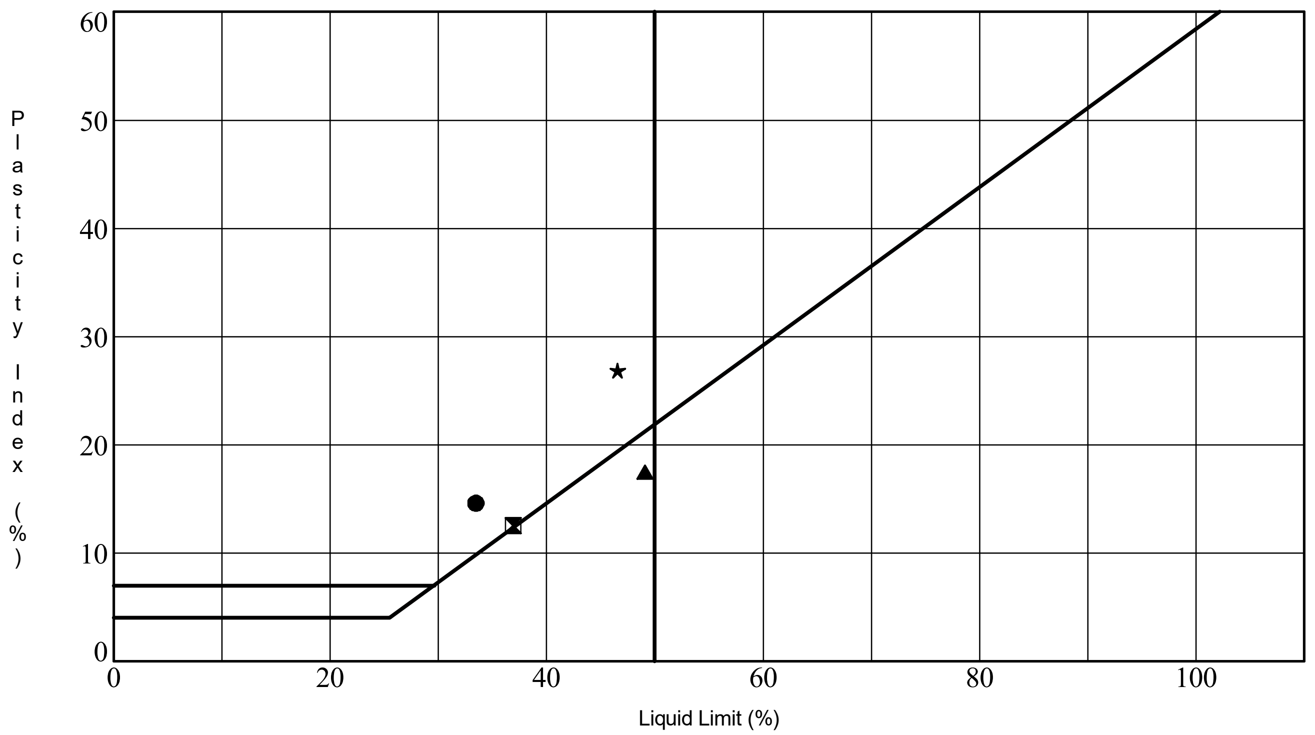
INTERTEC



	Specimen Identification		LL	PL	PI	Fines	Classification
●	21-1M	5.0'-5.5'	33	19	14	77	LEAN CLAY with SAND(CL)
⧗	21-1M	30.0'-31.0'	37	24	13		
▲	21-1M	35.0'-35.5'	49	32	17		
★	21-4M	9.5'-10.0'	47	20	27	88	LEAN CLAY(CL)

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Lower Sioux TPP Feasibility Study
Disturbed Testing - Phase 1

ATTERBERG LIMITS RESULTS

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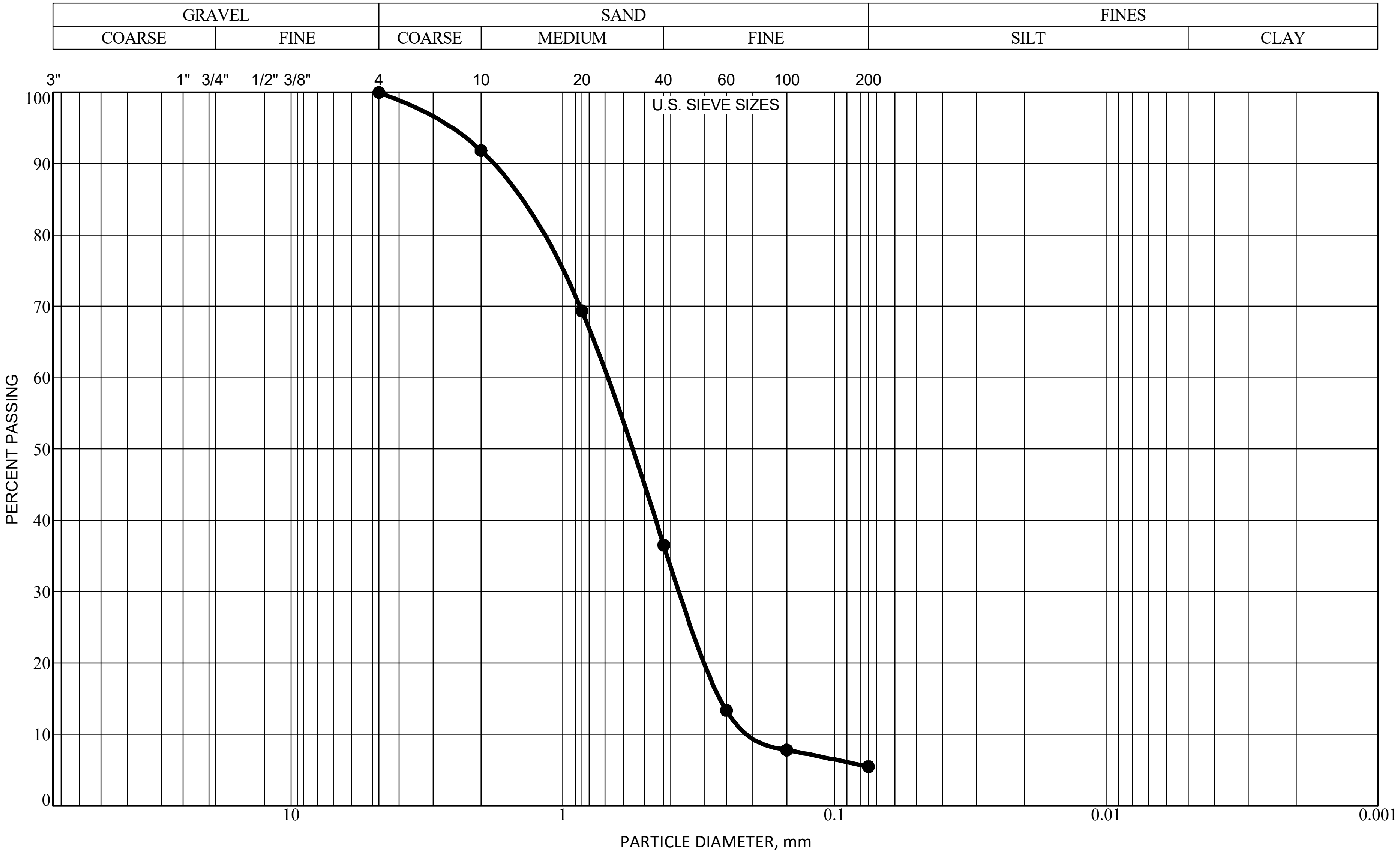
GRAIN SIZE ACCUMULATION CURVE (ASTM)



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Lower Sioux TPP Feasibility Study
Disturbed Testing - Phase 1

BORING: 21-1M SAMPLE: 5 DEPTH: 23.0'-23.5'

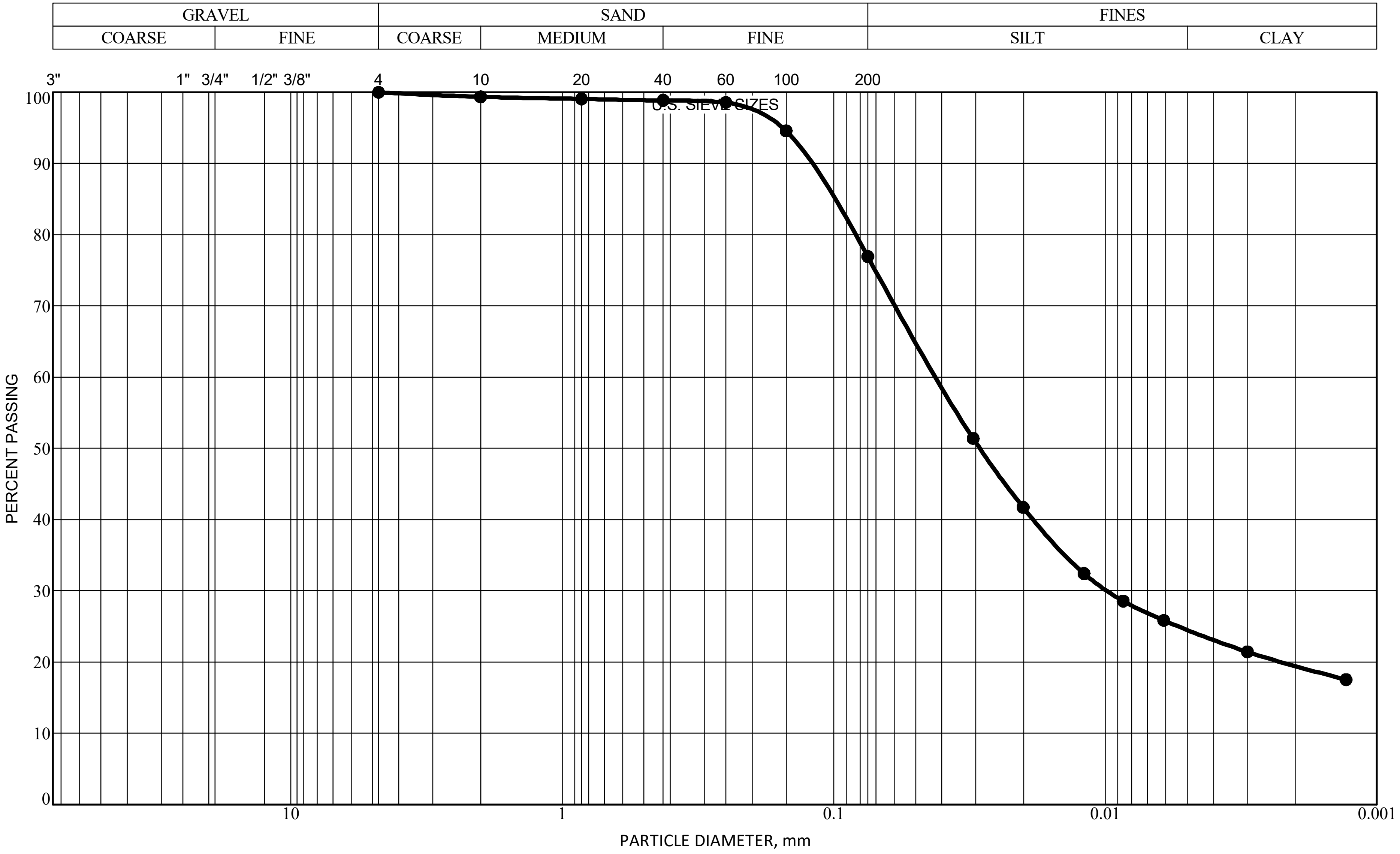
GRAVEL	0.0%
SAND	94.5%
FINES	5.5%

D60=0.698
D30=0.366
D10=0.183

Cu=3.8
Cc=1.0

CLASSIFICATION:
POORLY GRADED SAND with SILT(SP-SM)

GRAIN SIZE ACCUMULATION CURVE (ASTM)



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Lower Sioux TPP Feasibility Study
Disturbed Testing - Phase 1

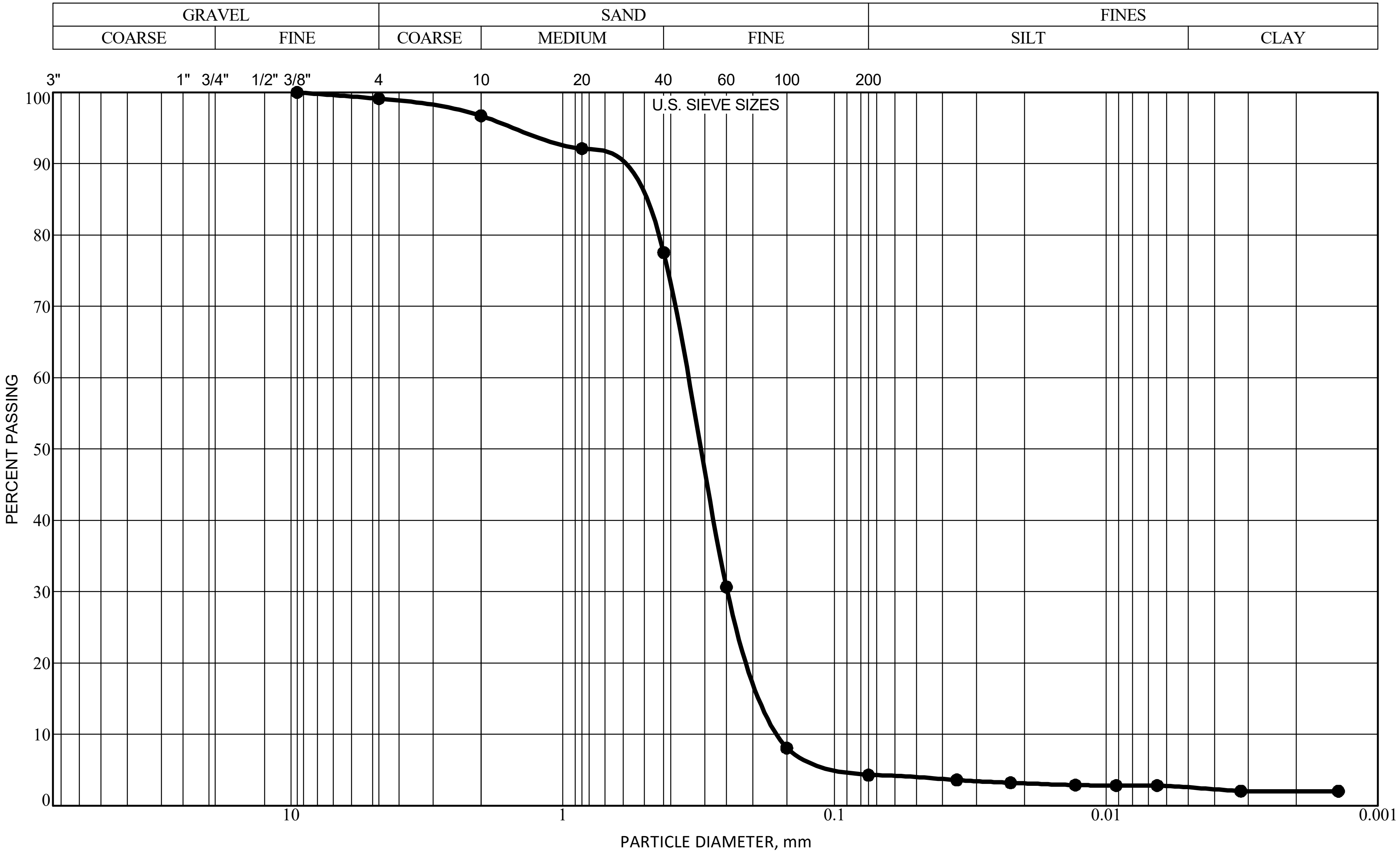
BORING: 21-1M SAMPLE: 2 DEPTH: 5.0'-5.5'

GRAVEL	0.0%
SAND	23.1%
SILT	52.3%
CLAY	24.6%
D60=0.041	
D30=0.010	Cu=
D10=	Cc=

CLASSIFICATION:
LEAN CLAY with SAND(CL)

GS ASTM N:\GINT\PROJECTS\X-GEOLAB\1-GINT FILES\AX PROJECTS GEO LAB\2021\B2101436-NEW.GPJ BRAUN_V8_CURRENT.GDT 3/1/21 14:57

GRAIN SIZE ACCUMULATION CURVE (ASTM)



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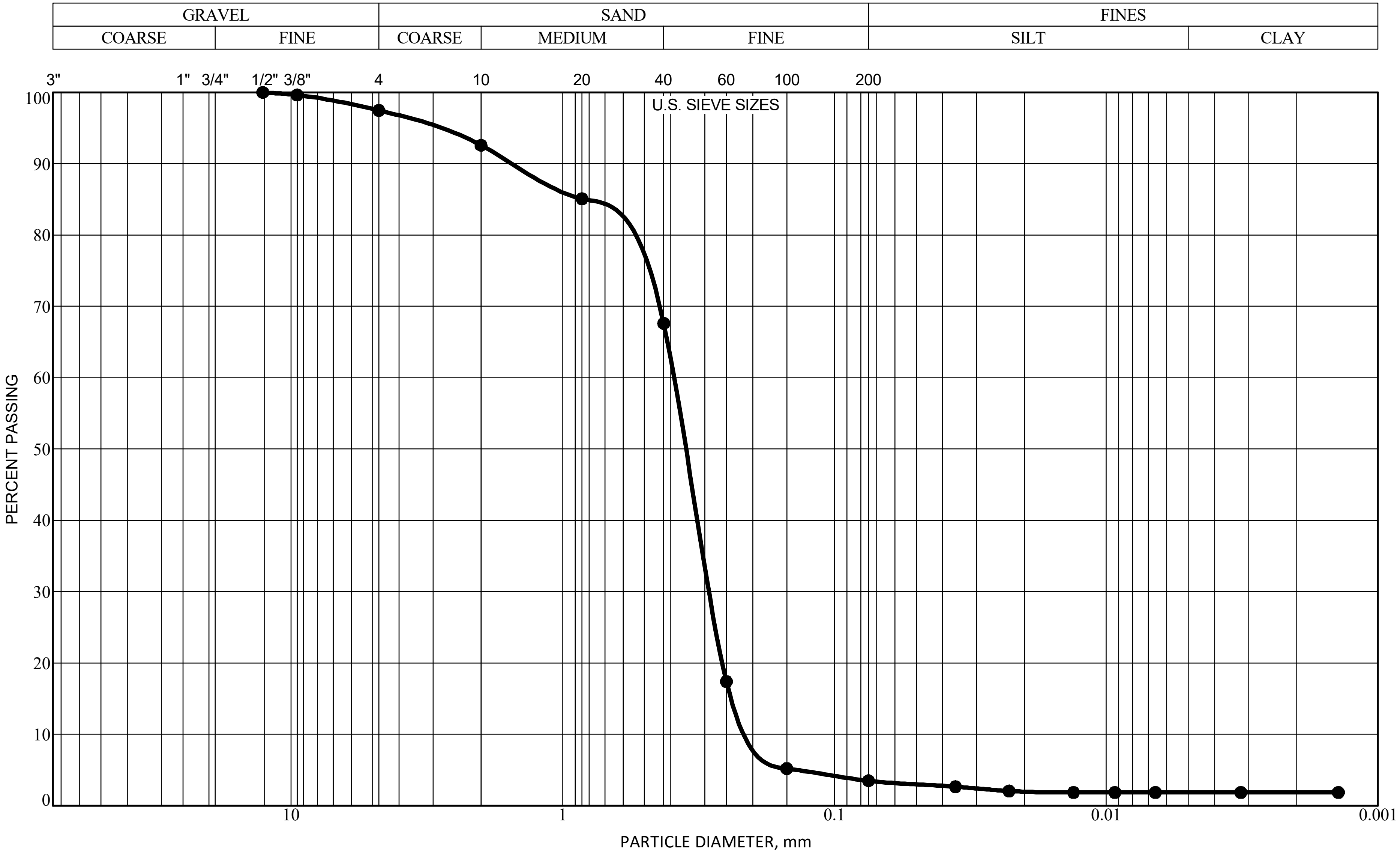
Lower Sioux TPP Feasibility Study
Disturbed Testing - Phase 1

BORING: 21-1M SAMPLE: 3 DEPTH: 13.0'-13.5'

GRAVEL	0.9%
SAND	94.8%
SILT	1.7%
CLAY	2.5%
D60=0.348	
D30=0.246	Cu=2.2
D10=0.157	Cc=1.1

CLASSIFICATION:
POORLY GRADED SAND(SP)

GRAIN SIZE ACCUMULATION CURVE (ASTM)



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Braun Project B2101436

Lower Sioux TPP Feasibility Study

Disturbed Testing - Phase 1

BORING: 21-1M SAMPLE: 4 DEPTH: 18.0'-18.5'

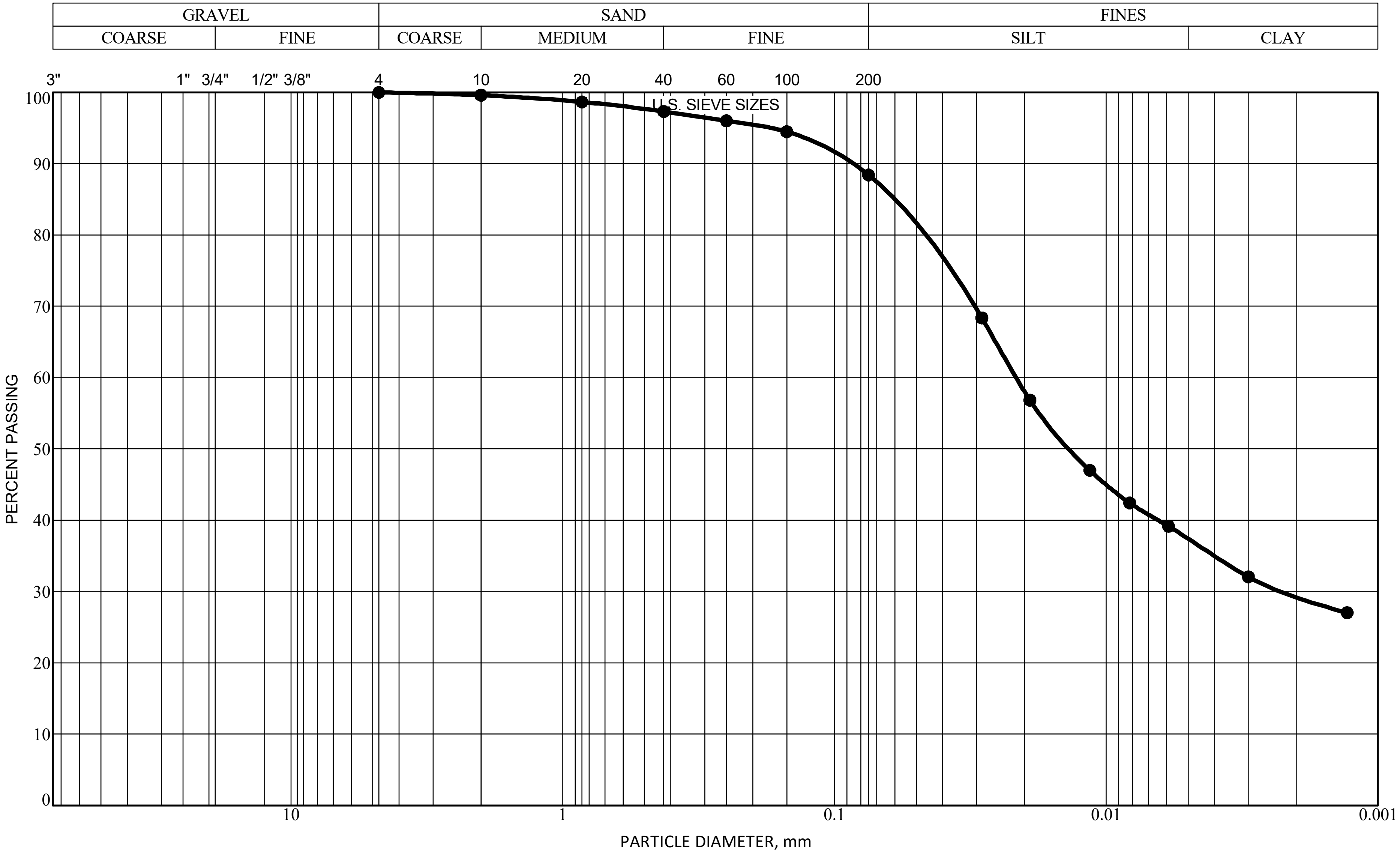
GRAVEL	2.5%
SAND	94.0%
SILT	1.6%
CLAY	1.9%

D60=0.392
D30=0.286
D10=0.183
	Cu=2.1
	Cc=1.1

CLASSIFICATION:

POORLY GRADED SAND(SP)

GRAIN SIZE ACCUMULATION CURVE (ASTM)



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Braun Project B2101436
Lower Sioux TPP Feasibility Study
Disturbed Testing - Phase 1

BORING: 21-4M SAMPLE: 1 DEPTH: 9.5'-10.0'

GRAVEL	0.0%
SAND	11.6%
SILT	51.0%
CLAY	37.4%
D60=0.021	
D30=0.002	Cu=
D10=	Cc=

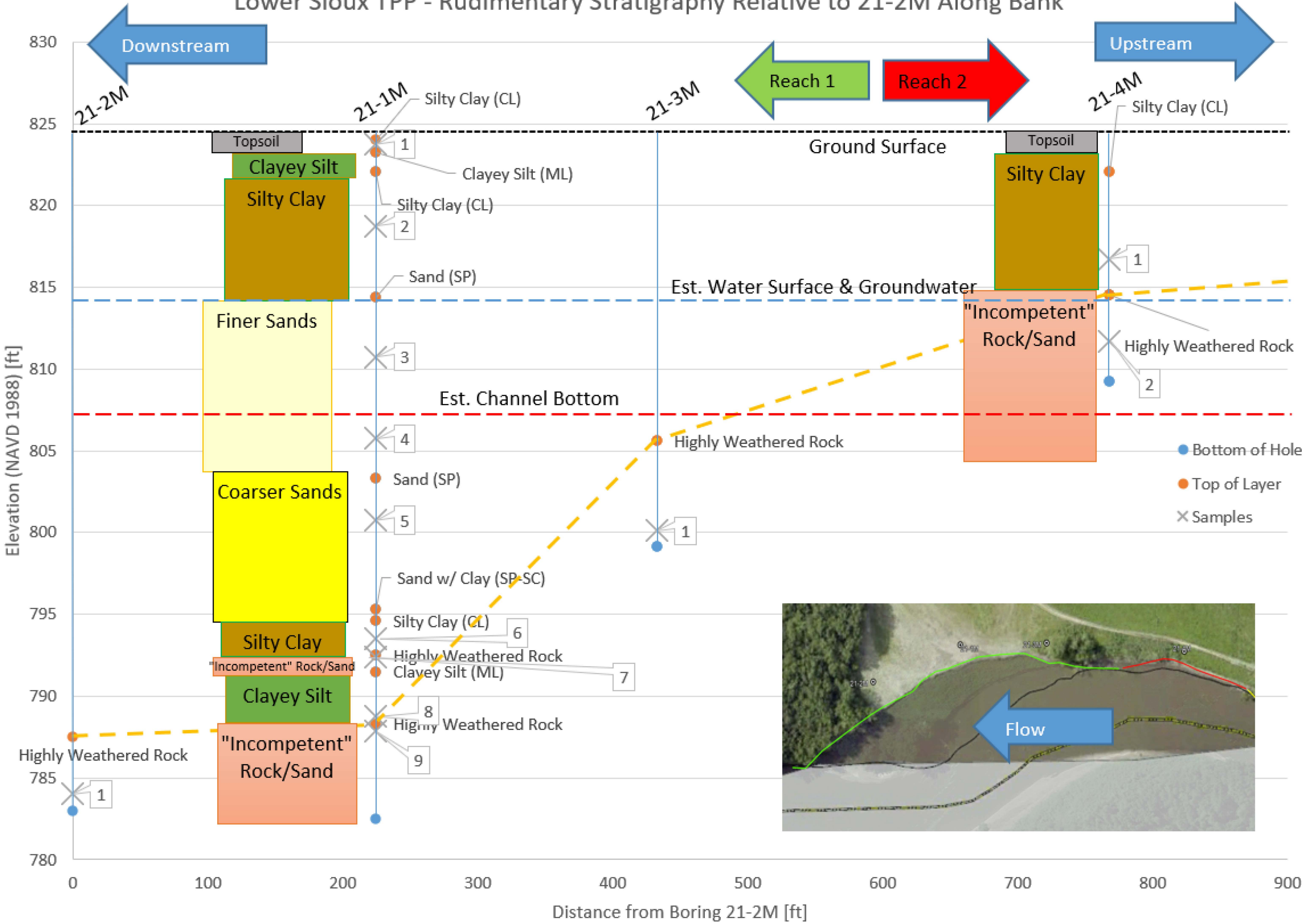
CLASSIFICATION:
LEAN CLAY(CL)

Attachment 5: Design Parameters

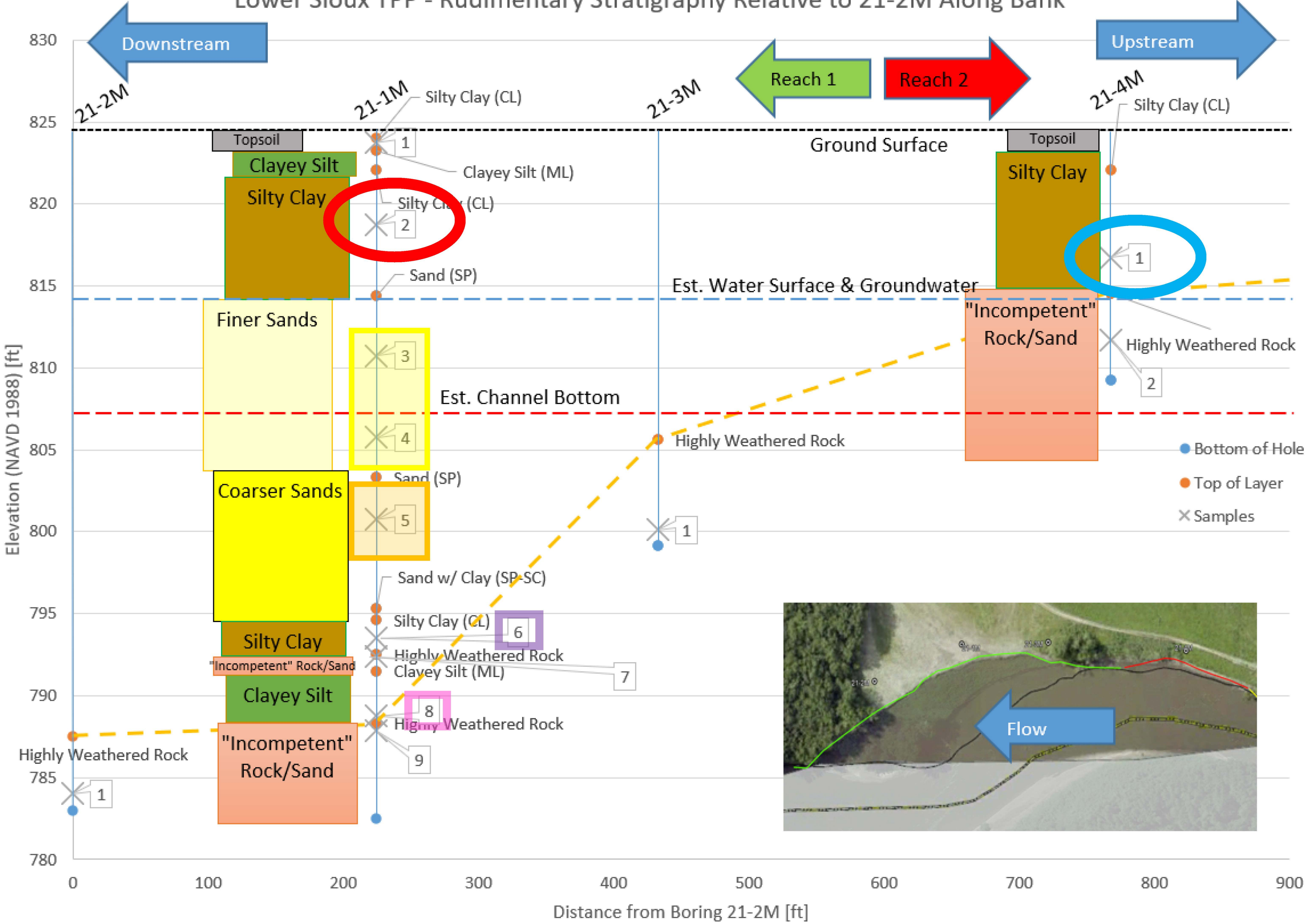
Lower Sioux TPP

Geotech Parameter Development

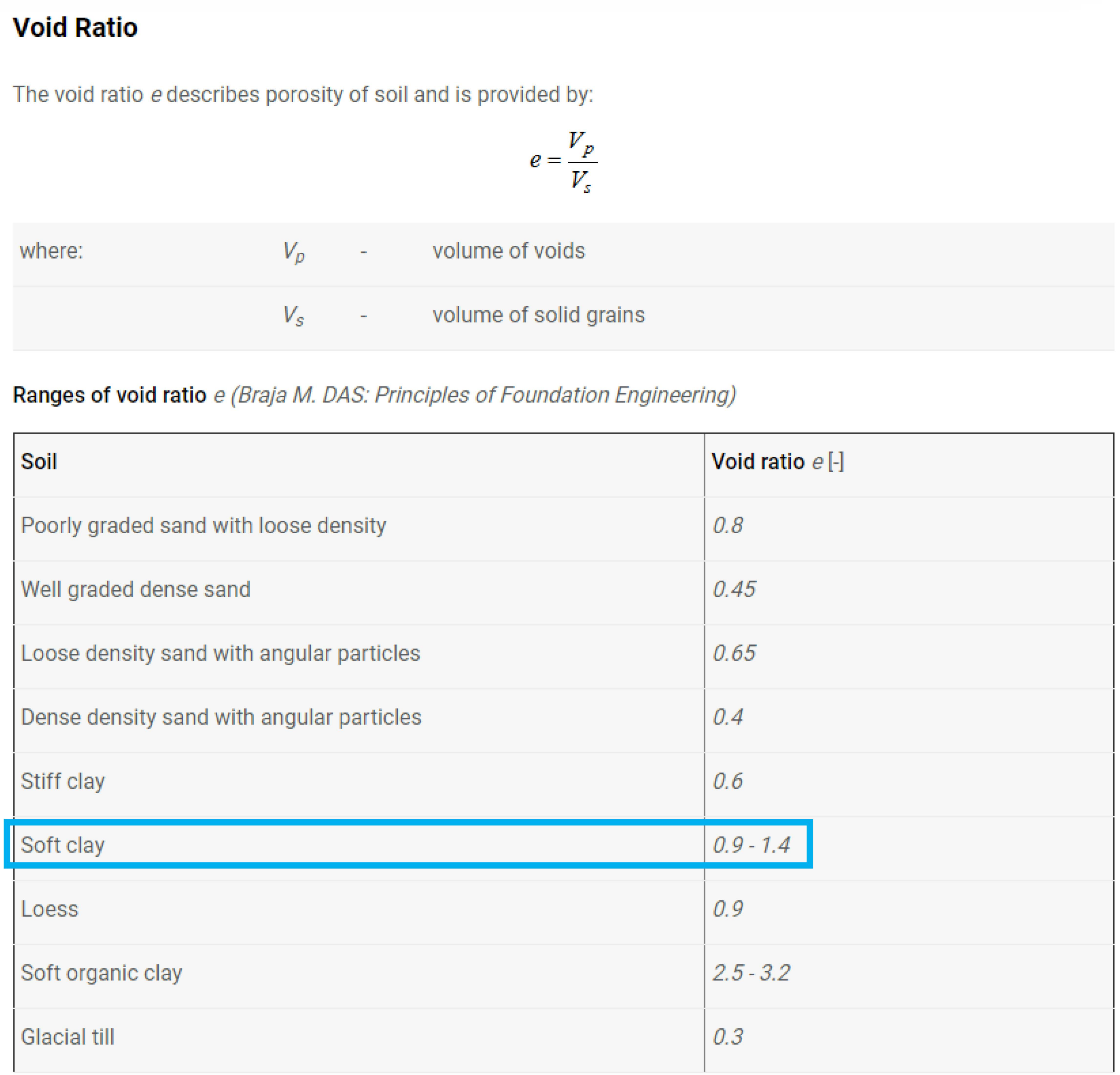
Lower Sioux TPP - Rudimentary Stratigraphy Relative to 21-2M Along Bank



Lower Sioux TPP - Rudimentary Stratigraphy Relative to 21-2M Along Bank



Unit Weights of Upper Cohesive Soils



Void Ratio

The void ratio *e* describes porosity of soil and is provided by:

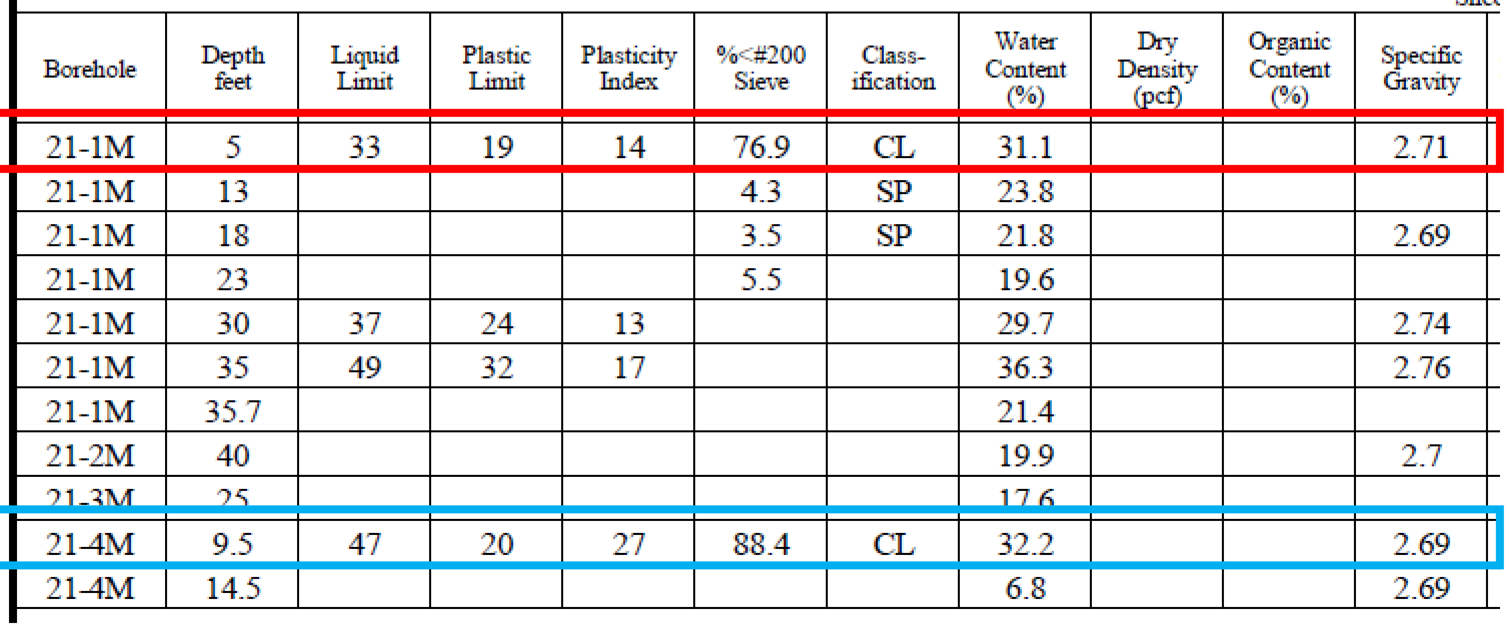
$$e = \frac{V_p}{V_s}$$

where: V_p - volume of voids

V_s - volume of solid grains

Ranges of void ratio *e (Braja M. DAS: Principles of Foundation Engineering)*

Soil	**Void ratio** *e* [-]
Poorly graded sand with loose density	*0.8*
Well graded dense sand	*0.45*
Loose density sand with angular particles	*0.65*
Dense density sand with angular particles	*0.4*
Stiff clay	*0.6*
Soft clay	*0.9 - 1.4*
Loess	*0.9*
Soft organic clay	*2.5 - 3.2*
Glacial till	*0.3*



Borehole	Depth feet	Liquid Limit	Plastic Limit	Plasticity Index	%<#200 Sieve	Class-ification	Water Content (%)	Dry Density (pcf)	Organic Content (%)	Specific Gravity
21-1M	5	33	19	14	76.9	CL	31.1			2.71
21-1M	13				4.3	SP	23.8			
21-1M	18				3.5	SP	21.8			2.69
21-1M	23				5.5		19.6			
21-1M	30	37	24	13			29.7			2.74
21-1M	35	49	32	17			36.3			2.76
21-1M	35.7						21.4			
21-2M	40						19.9			2.7
21-3M	25						17.6			
21-4M	9.5	47	20	27	88.4	CL	32.2			2.69
21-4M	14.5						6.8			2.69

Generally, 2.7 = Ws/Vs

Das, Foundation Engineering, 7th edition, pg. 10

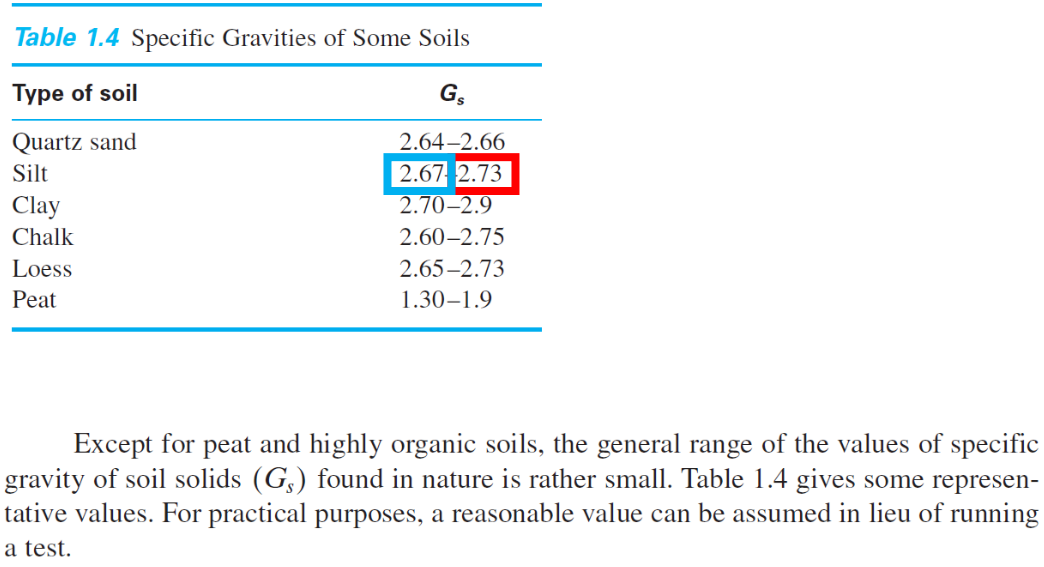
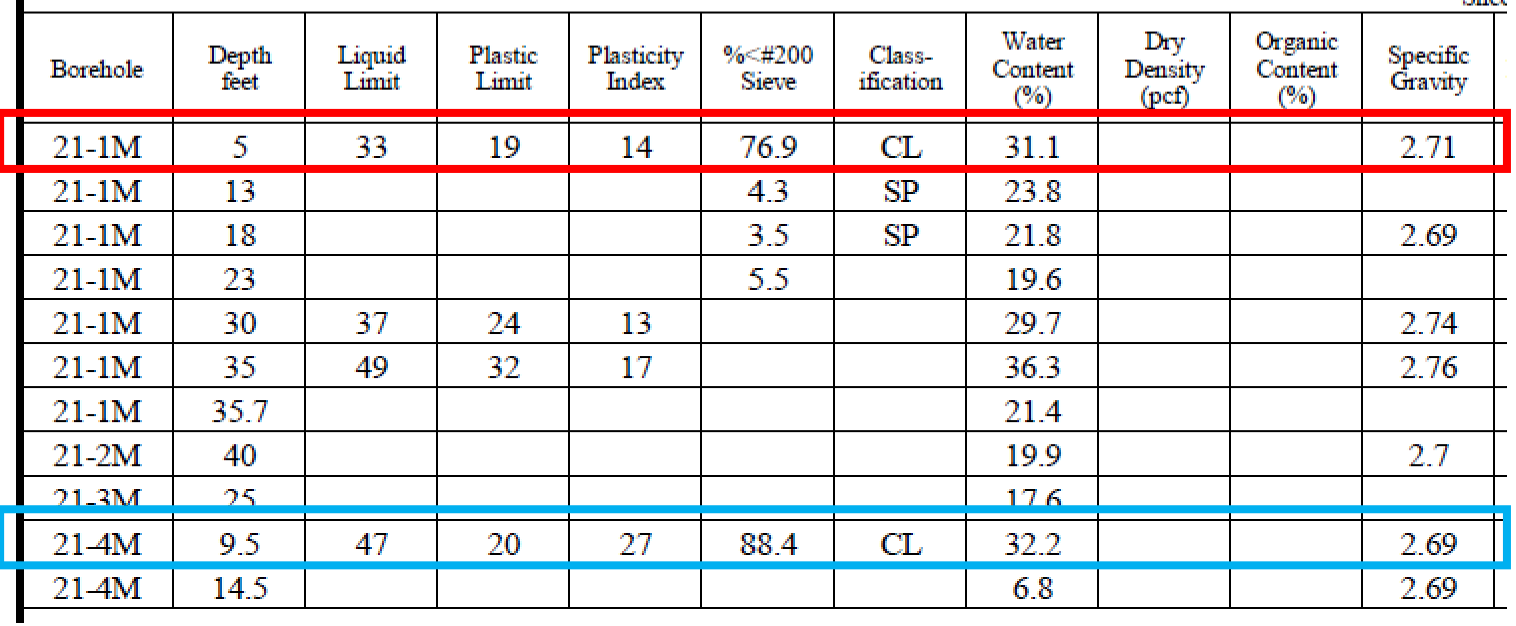


Table 1.4 Specific Gravities of Some Soils

Type of soil	G_s
Quartz sand	2.64–2.66
Silt	2.67–2.73
Clay	2.70–2.9
Chalk	2.60–2.75
Loess	2.65–2.73
Peat	1.30–1.9

Except for peat and highly organic soils, the general range of the values of specific gravity of soil solids (G_s) found in nature is rather small. Table 1.4 gives some representative values. For practical purposes, a reasonable value can be assumed in lieu of running a test.



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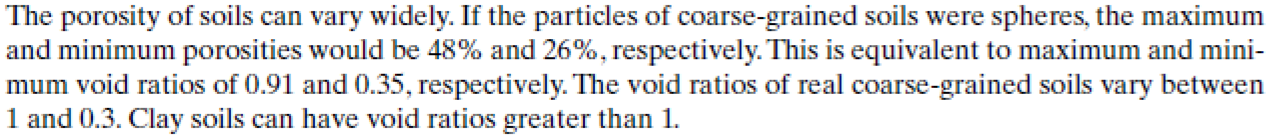


The porosity of soils can vary widely. If the particles of coarse-grained soils were spheres, the maximum and minimum porosities would be 48% and 26%, respectively. This is equivalent to maximum and minimum void ratios of 0.91 and 0.35, respectively. The void ratios of real coarse-grained soils vary between 1 and 0.3. Clay soils can have void ratios greater than 1.

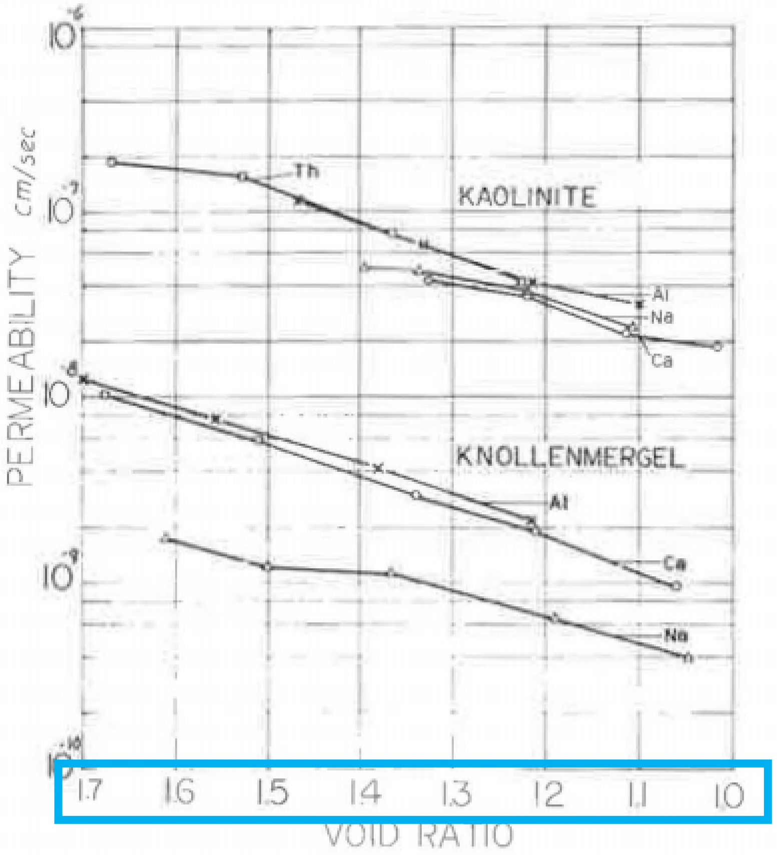
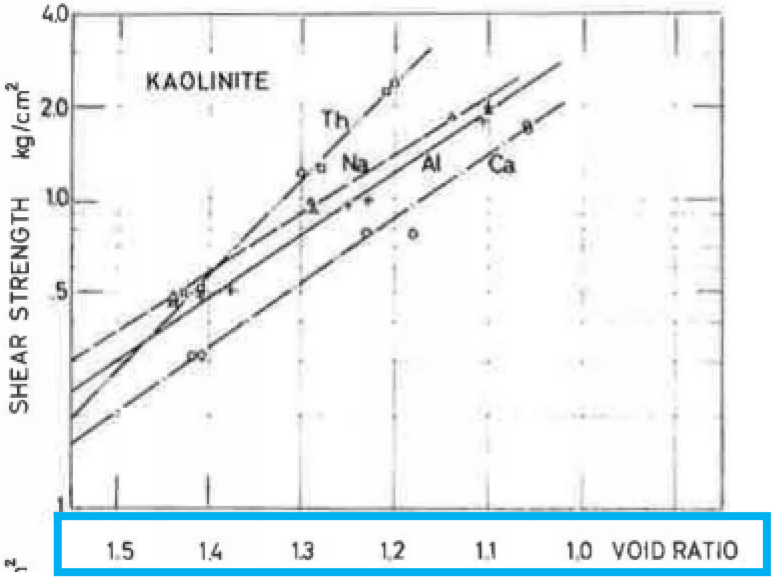


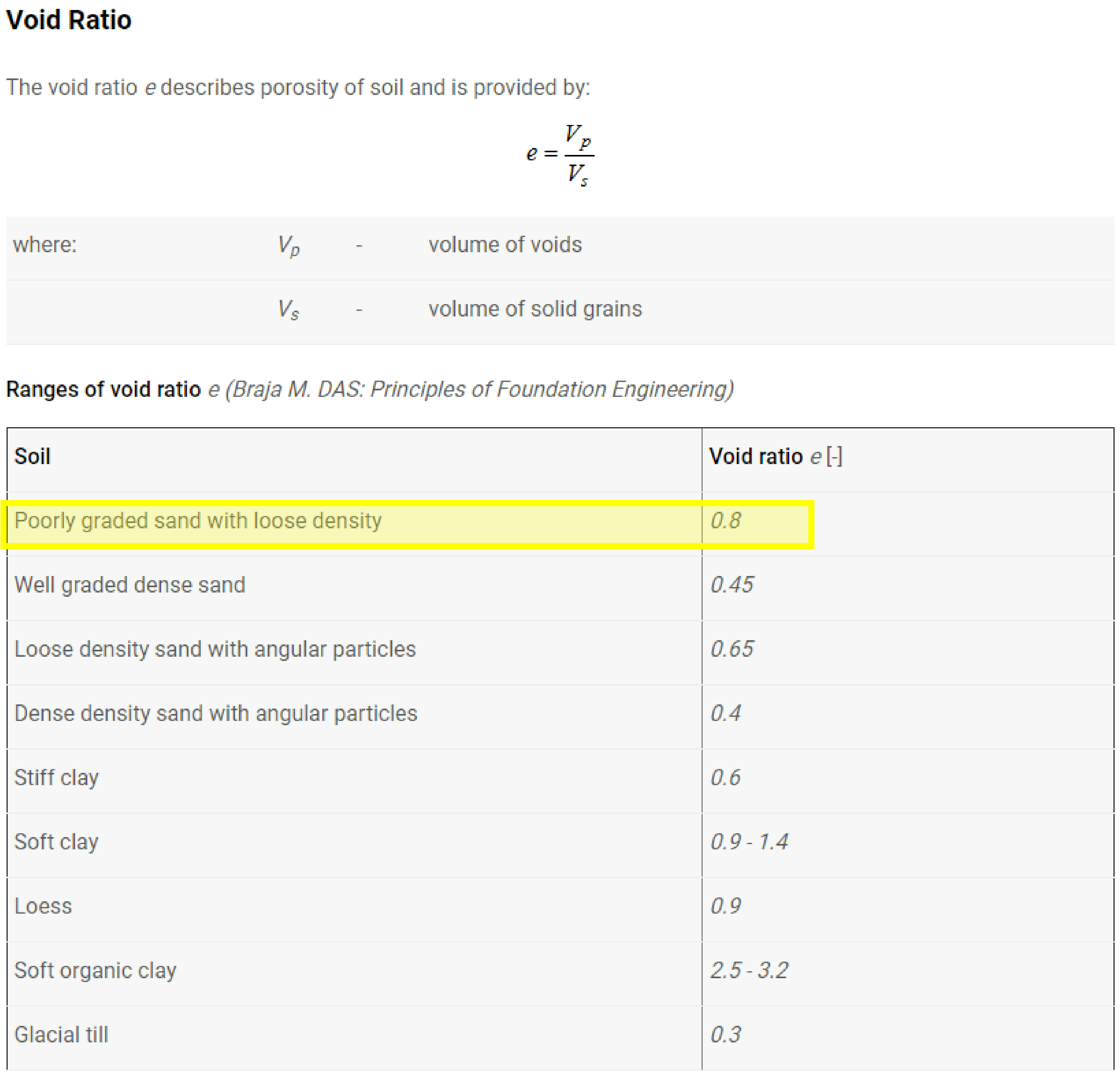
Figure 10. Permeability coefficient of attapulgite and bentonite as a function of exchange ion type and void ratio.

(See Excel Calc)

Selected 115 pcf



Unit Weights of Cohensionless Upper Soils



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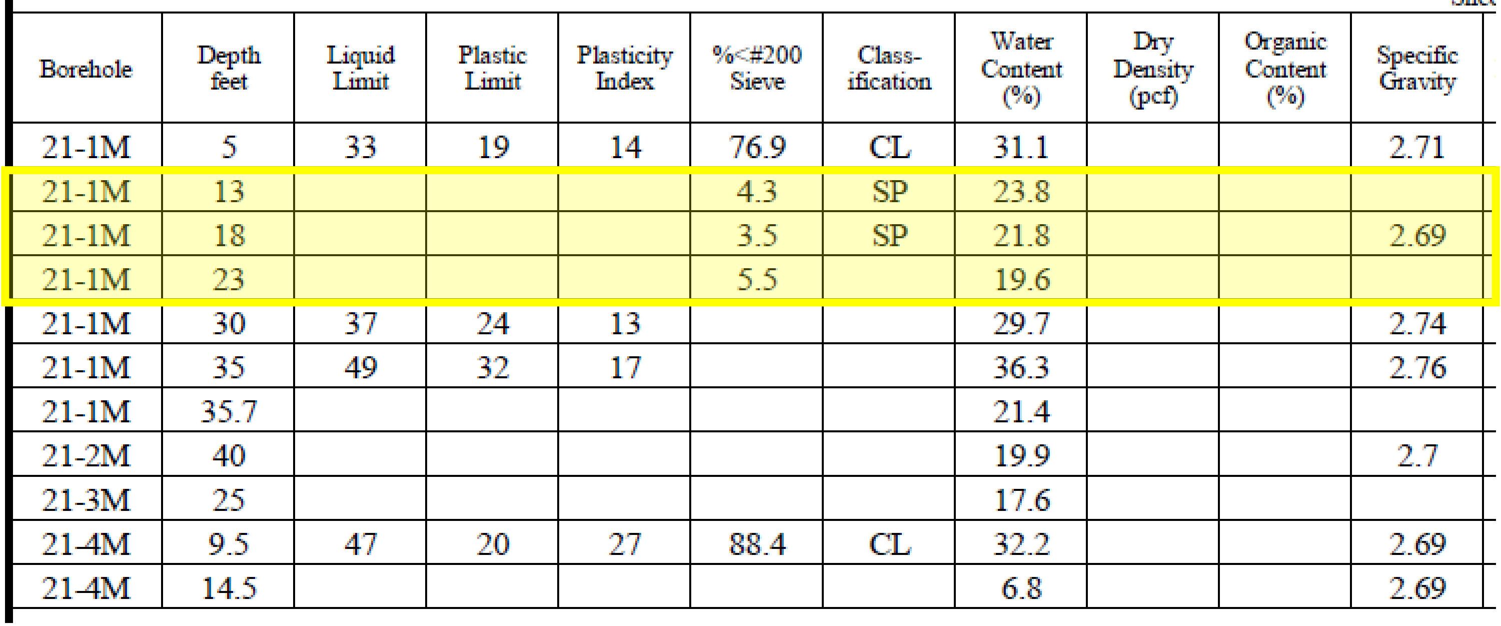
Soft clay	*0.9 - 1.4*
Loess	*0.9*
Soft organic clay	*2.5 - 3.2*
Glacial till	*0.3*



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21-1M	35.7						21.4			
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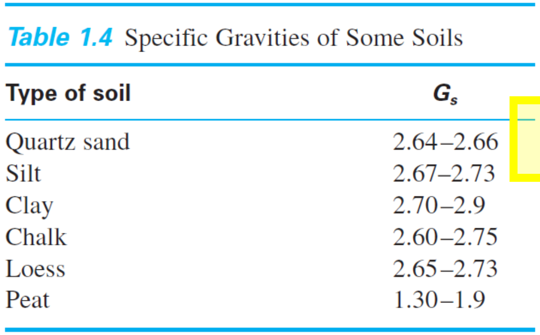
Das, Foundation Engineering, 7th edition, pg. 10



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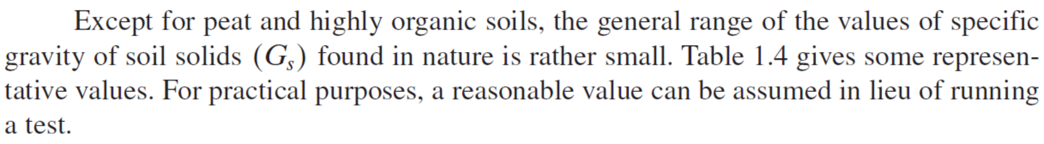
Chalk	2.60–2.75
Loess	2.65–2.73
Peat	1.30–1.9

Higher than quartz sand

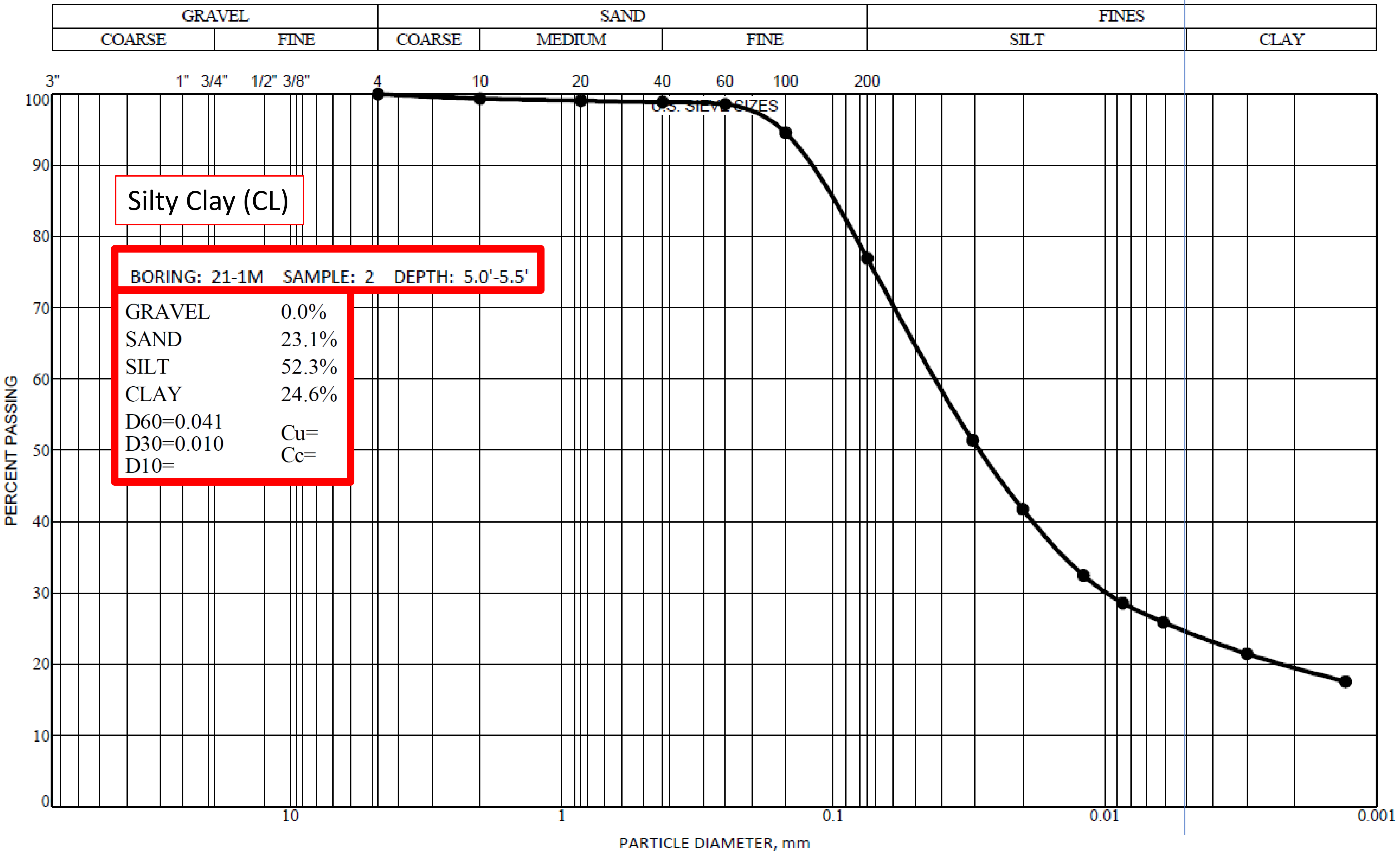
Selected 125 pcf.
See Excel Sheet.



Except for peat and highly organic soils, the general range of the values of specific gravity of soil solids (G_s) found in nature is rather small. Table 1.4 gives some representative values. For practical purposes, a reasonable value can be assumed in lieu of running a test.

Grain Size Analysis of Cohesive Upper Soils

GRAIN SIZE ACCUMULATION CURVE (ASTM)



Silty Clay (CL)

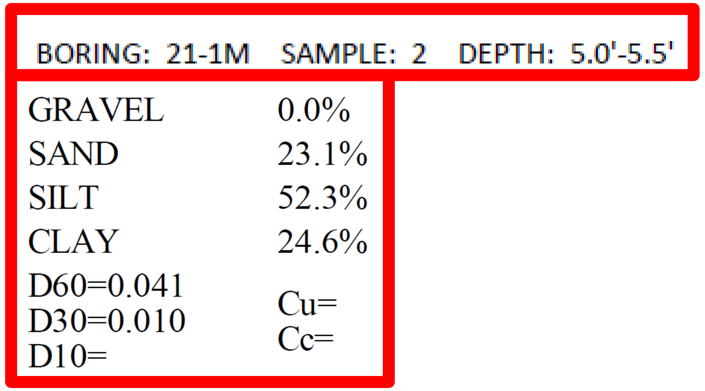
BORING: 21-1M SAMPLE: 2 DEPTH: 5.0'-5.5'

GRAVEL	0.0%
SAND	23.1%
SILT	52.3%
CLAY	24.6%

D60=0.041
D30=0.010
D10=

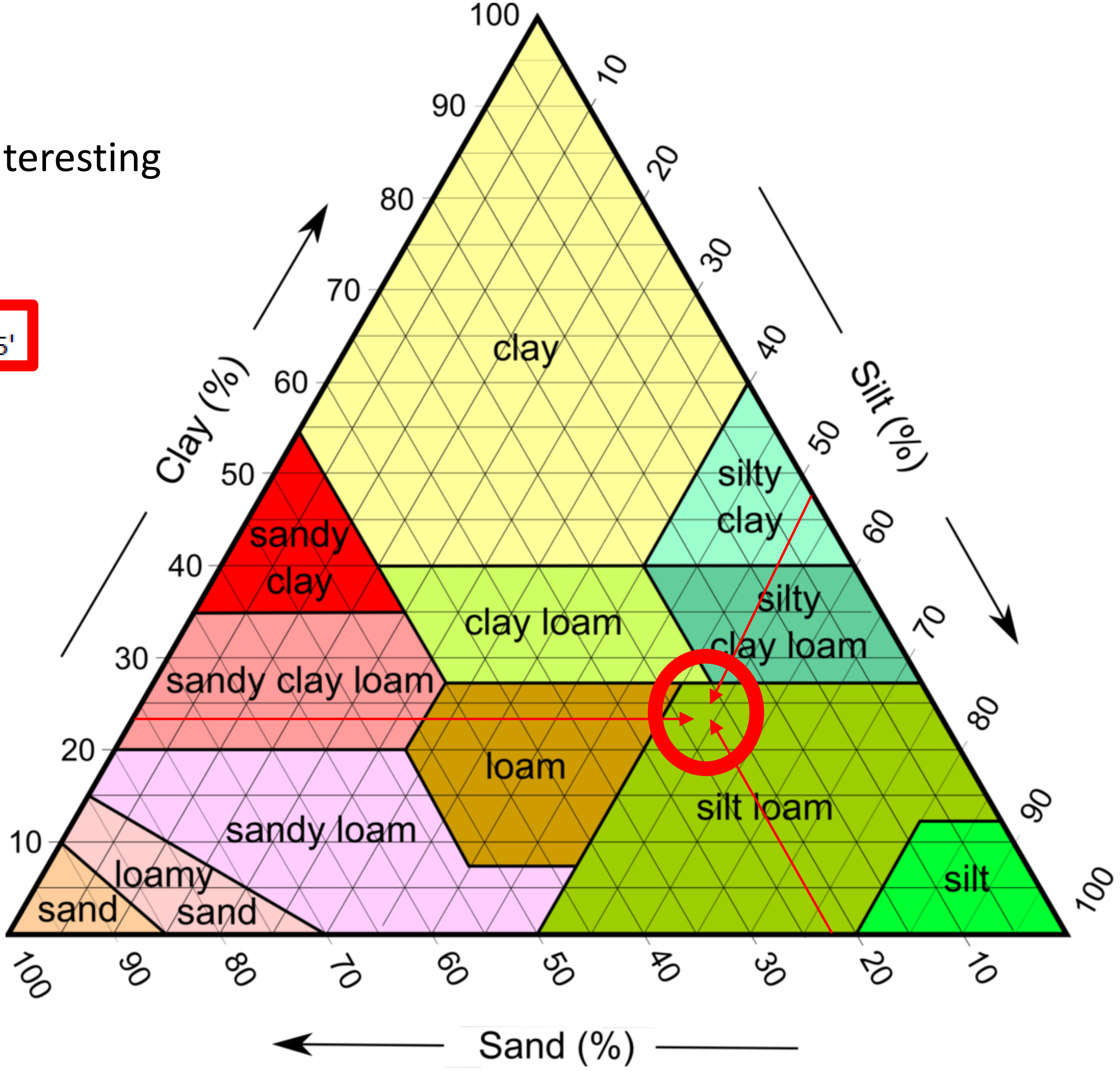
Cu=
Cc=

Textural class --- not for engineering but interesting

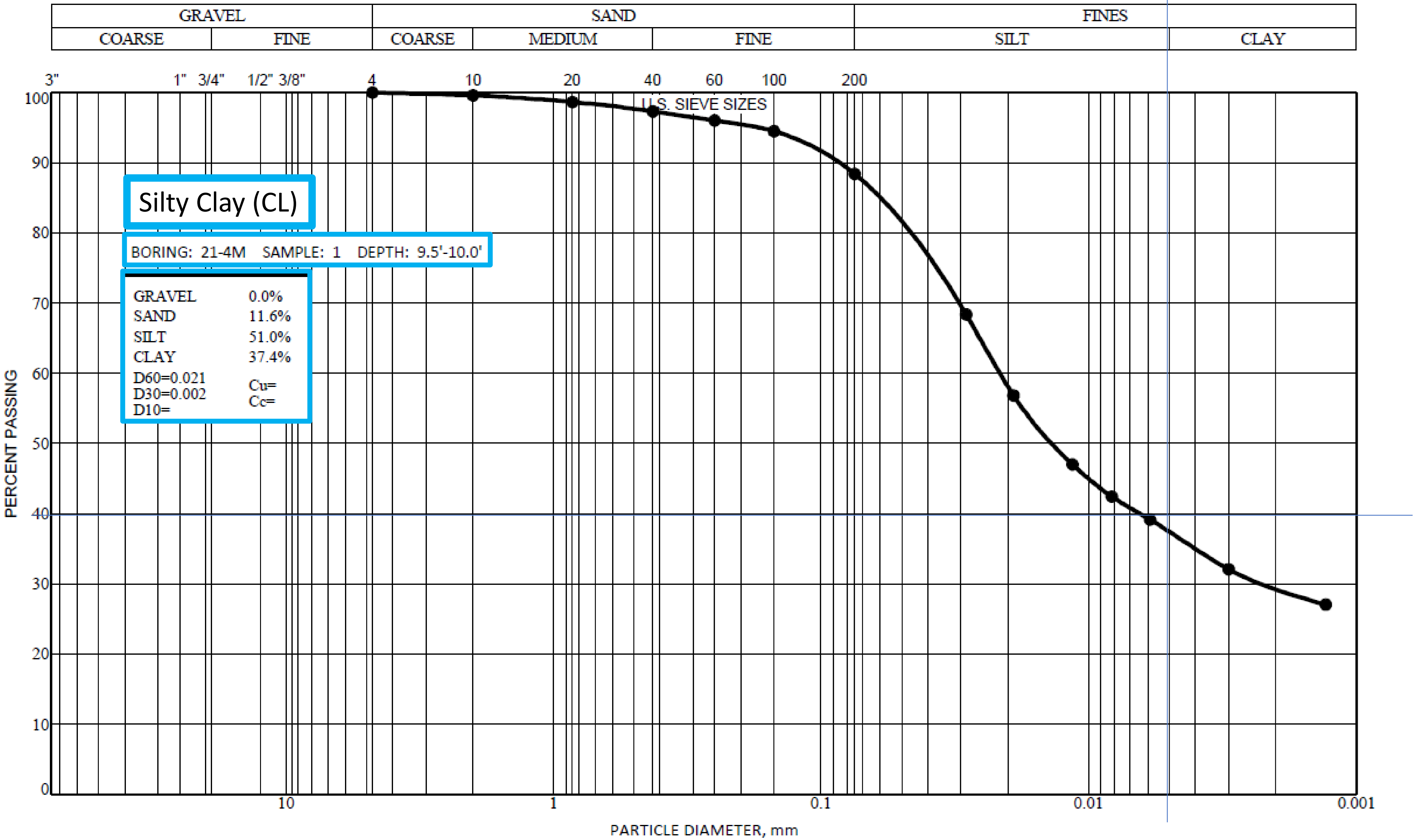


BORING: 21-1M SAMPLE: 2 DEPTH: 5.0'-5.5'

GRAVEL	0.0%
SAND	23.1%
SILT	52.3%
CLAY	24.6%
D60=0.041	Cu=
D30=0.010	Cc=
D10=	



GRAIN SIZE ACCUMULATION CURVE (ASTM)



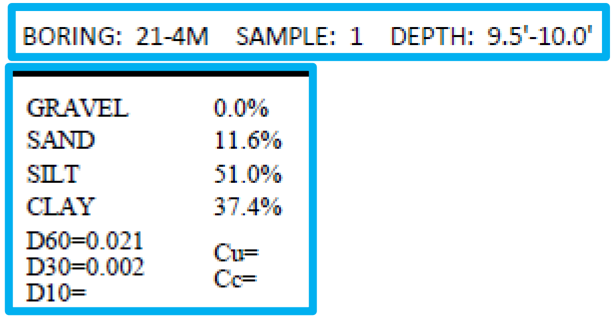
Silty Clay (CL)

BORING: 21-4M SAMPLE: 1 DEPTH: 9.5'-10.0'

GRAVEL	0.0%
SAND	11.6%
SILT	51.0%
CLAY	37.4%

D60=0.021
D30=0.002
D10=
Cu=
Cc=

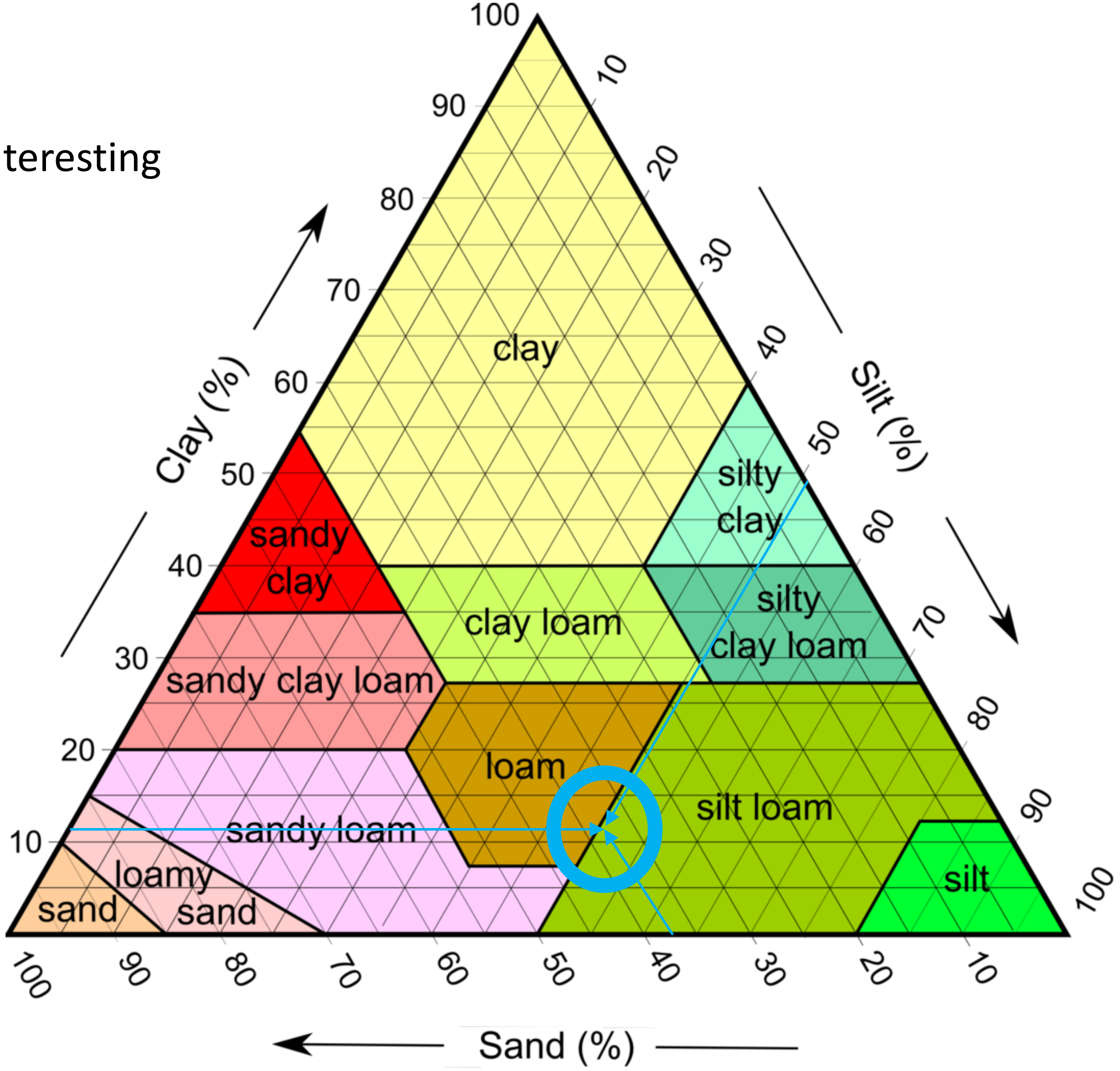
Textural class --- not for engineering but interesting



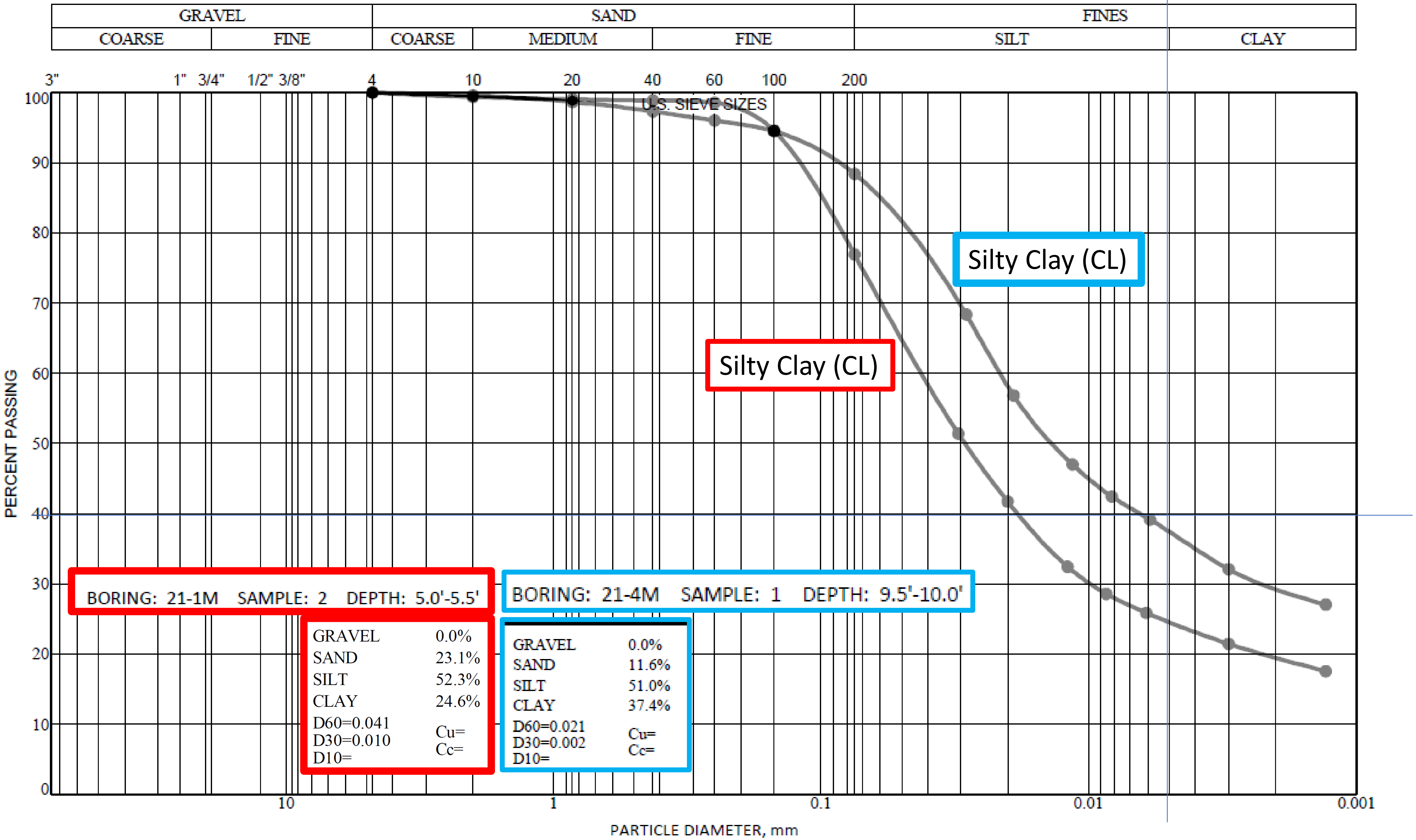
BORING: 21-4M SAMPLE: 1 DEPTH: 9.5'-10.0'

GRAVEL	0.0%
SAND	11.6%
SILT	51.0%
CLAY	37.4%

D60=0.021
D30=0.002
D10=
	Cu=
	Cc=



GRAIN SIZE ACCUMULATION CURVE (ASTM)



Silty Clay (CL)

Silty Clay (CL)

BORING: 21-1M SAMPLE: 2 DEPTH: 5.0'-5.5'

GRAVEL	0.0%	
SAND	23.1%	
SILT	52.3%	
CLAY	24.6%	
D60=0.041	Cu=	
D30=0.010	Cc=	
D10=		

BORING: 21-4M SAMPLE: 1 DEPTH: 9.5'-10.0'

GRAVEL	0.0%	
SAND	11.6%	
SILT	51.0%	
CLAY	37.4%	
D60=0.021	Cu=	
D30=0.002	Cc=	
D10=		

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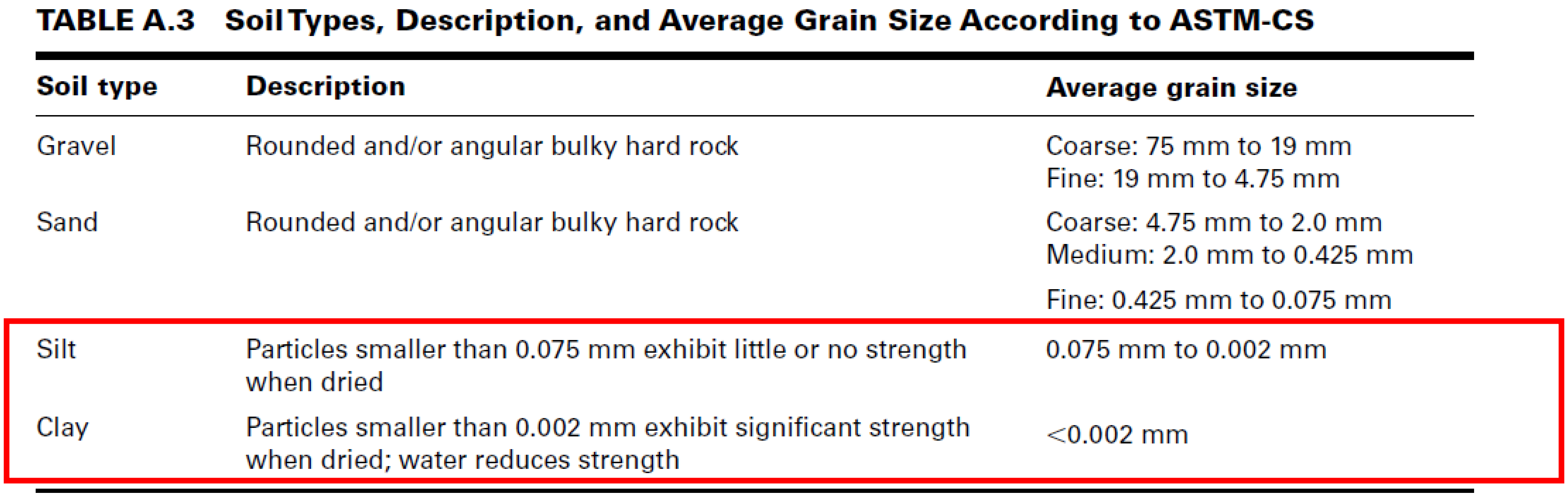
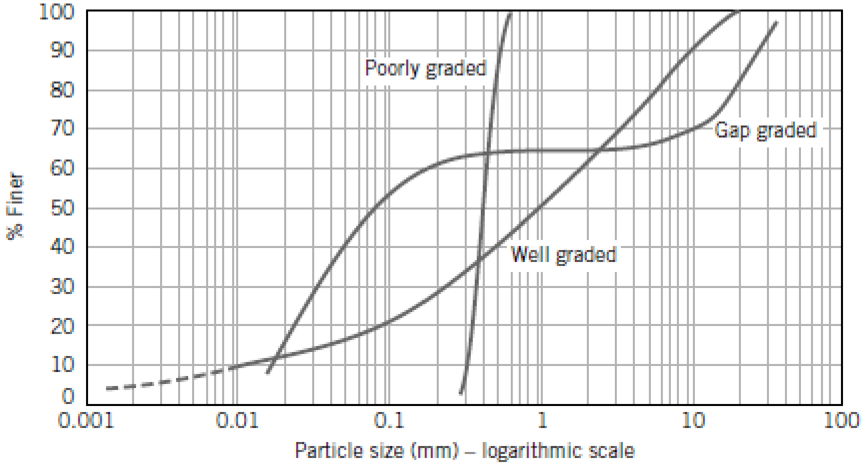


TABLE A.3 Soil Types, Description, and Average Grain Size According to ASTM-CS

Soil type	Description	Average grain size
Gravel	Rounded and/or angular bulky hard rock	Coarse: 75 mm to 19 mm Fine: 19 mm to 4.75 mm
Sand	Rounded and/or angular bulky hard rock	Coarse: 4.75 mm to 2.0 mm Medium: 2.0 mm to 0.425 mm Fine: 0.425 mm to 0.075 mm
Silt	Particles smaller than 0.075 mm exhibit little or no strength when dried	0.075 mm to 0.002 mm
Clay	Particles smaller than 0.002 mm exhibit significant strength when dried; water reduces strength	<0.002 mm

Conclusions from Grain Size Analysis on Cohesive Upper Soils

- Similarities
  - Silty Clay (CL)
  - Predominantly silt (~50%)
  - Well-Graded
- Differences
  - Higher sand content in Reach 1
  - Higher clay content in Reach 2



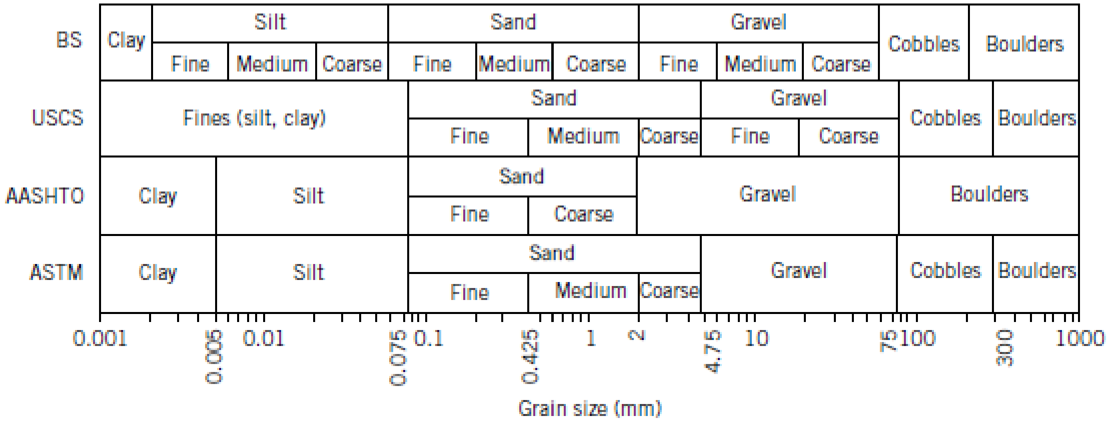


FIGURE 2.14 Comparison of four systems for describing soils based on particle size.

Grain Size Analysis of Cohesionless Upper Soils

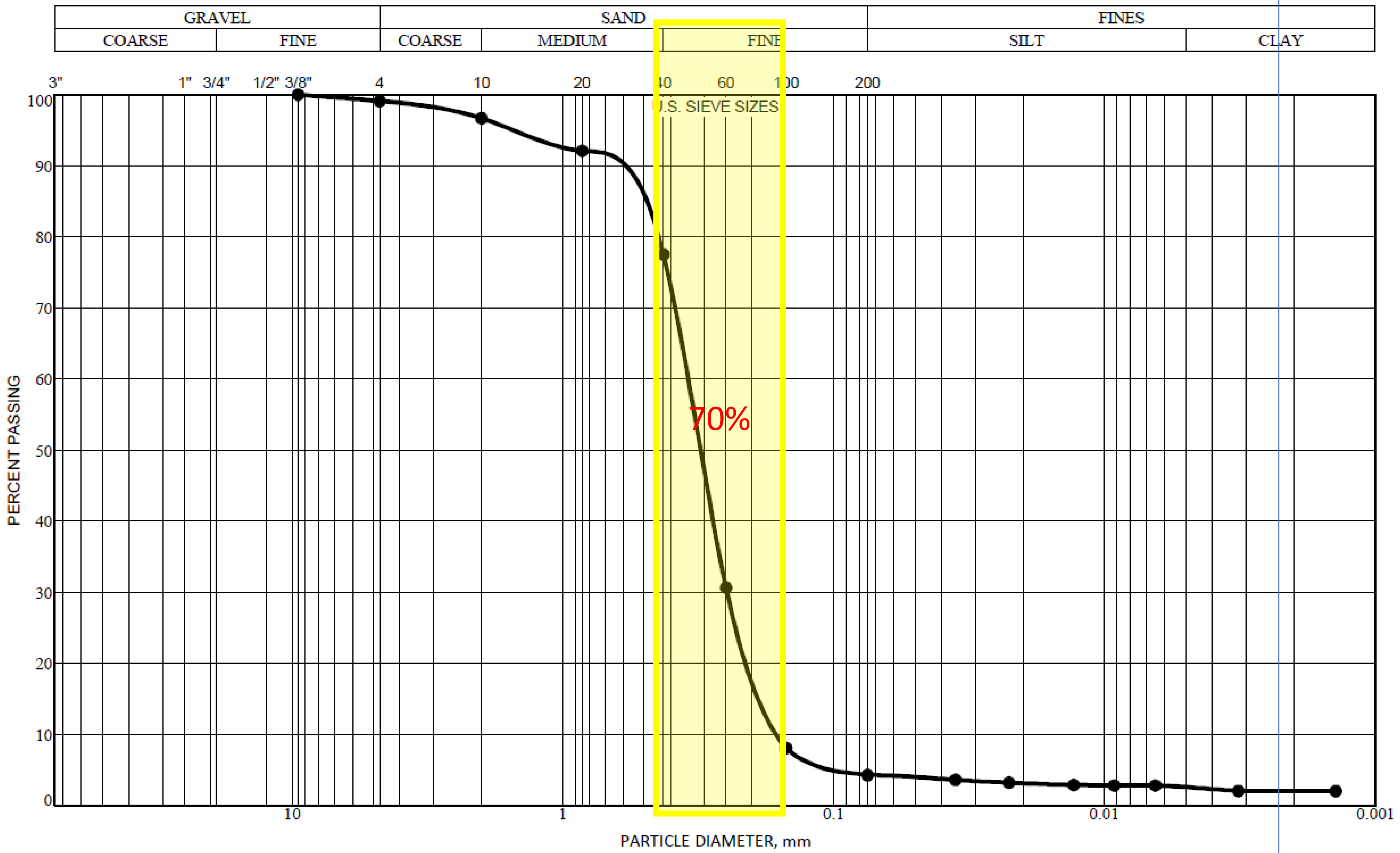
BORING: 21-1M SAMPLE: 3 DEPTH: 13.0'-13.5'

GRAIN SIZE ACCUMULATION CURVE (ASTM)

Poorly Graded Sand (SP)

GRAVEL	0.9%
SAND	94.8%
SILT	1.7%
CLAY	2.5%

D60=0.348
D30=0.246
D10=0.157
	Cu=2.2
	Cc=1.1



BRAUN℠ INTERTEC

Braun Project B2101436
Lower Sioux TPP Feasibility Study
Disturbed Testing - Phase 1

BORING: 21-1M SAMPLE: 3 DEPTH: 13.0'-13.5'

GRAVEL	0.9%
SAND	94.8%
SILT	1.7%
CLAY	2.5%

D60=0.348
D30=0.246
D10=0.157
	Cu=2.2
	Cc=1.1

CLASSIFICATION:
POORLY GRADED SAND(SP)

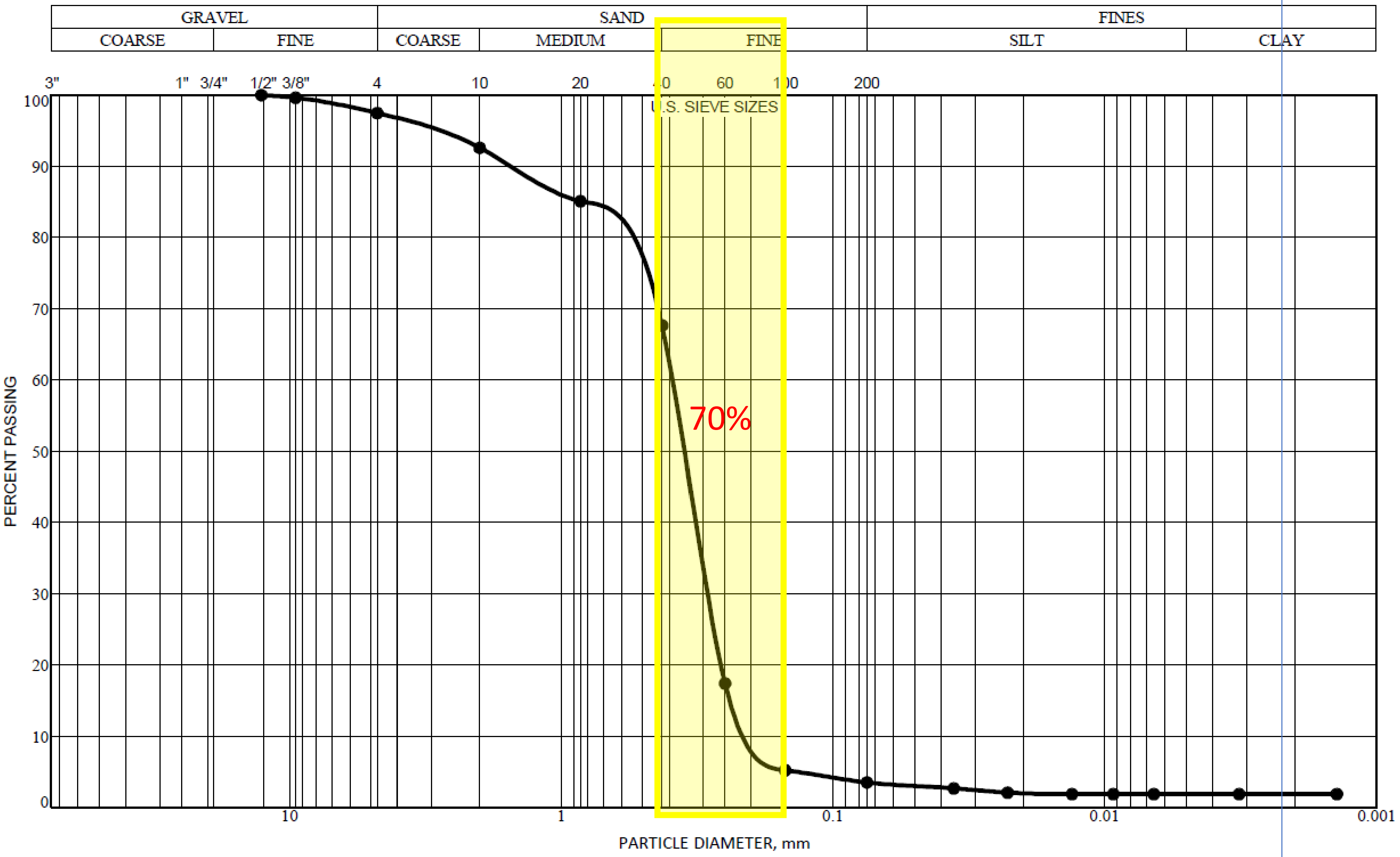
BORING: 21-1M SAMPLE: 4 DEPTH: 18.0'-18.5'

Poorly Graded Sand (SP)

GRAVEL	2.5%
SAND	94.0%
SILT	1.6%
CLAY	1.9%

D60=0.392
D30=0.286
D10=0.183
	Cu=2.1
	Cc=1.1

GRAIN SIZE ACCUMULATION CURVE (ASTM)



BRAUN INTERTEC

Braun Project B2101436
Lower Sioux TPP Feasibility Study
Disturbed Testing - Phase 1

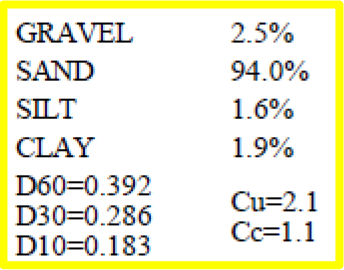
BORING: 21-1M SAMPLE: 4 DEPTH: 18.0'-18.5'

GRAVEL	2.5%
SAND	94.0%
SILT	1.6%
CLAY	1.9%

D60=0.392
D30=0.286
D10=0.183
	Cu=2.1
	Cc=1.1

CLASSIFICATION:
POORLY GRADED SAND(SP)

Textural class --- not for engineering but interesting



GRAVEL	2.5%
SAND	94.0%
SILT	1.6%
CLAY	1.9%

D60=0.392
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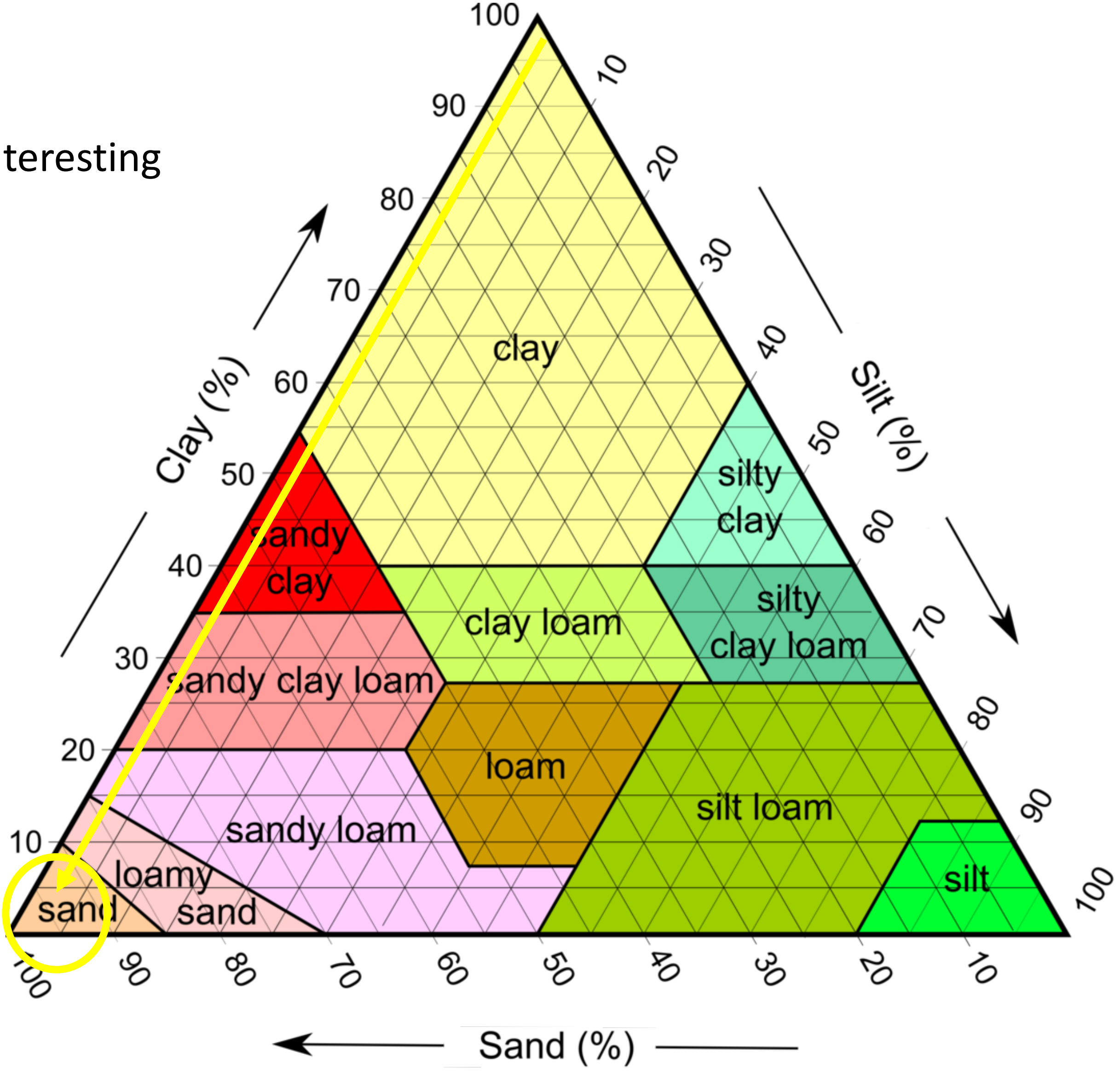
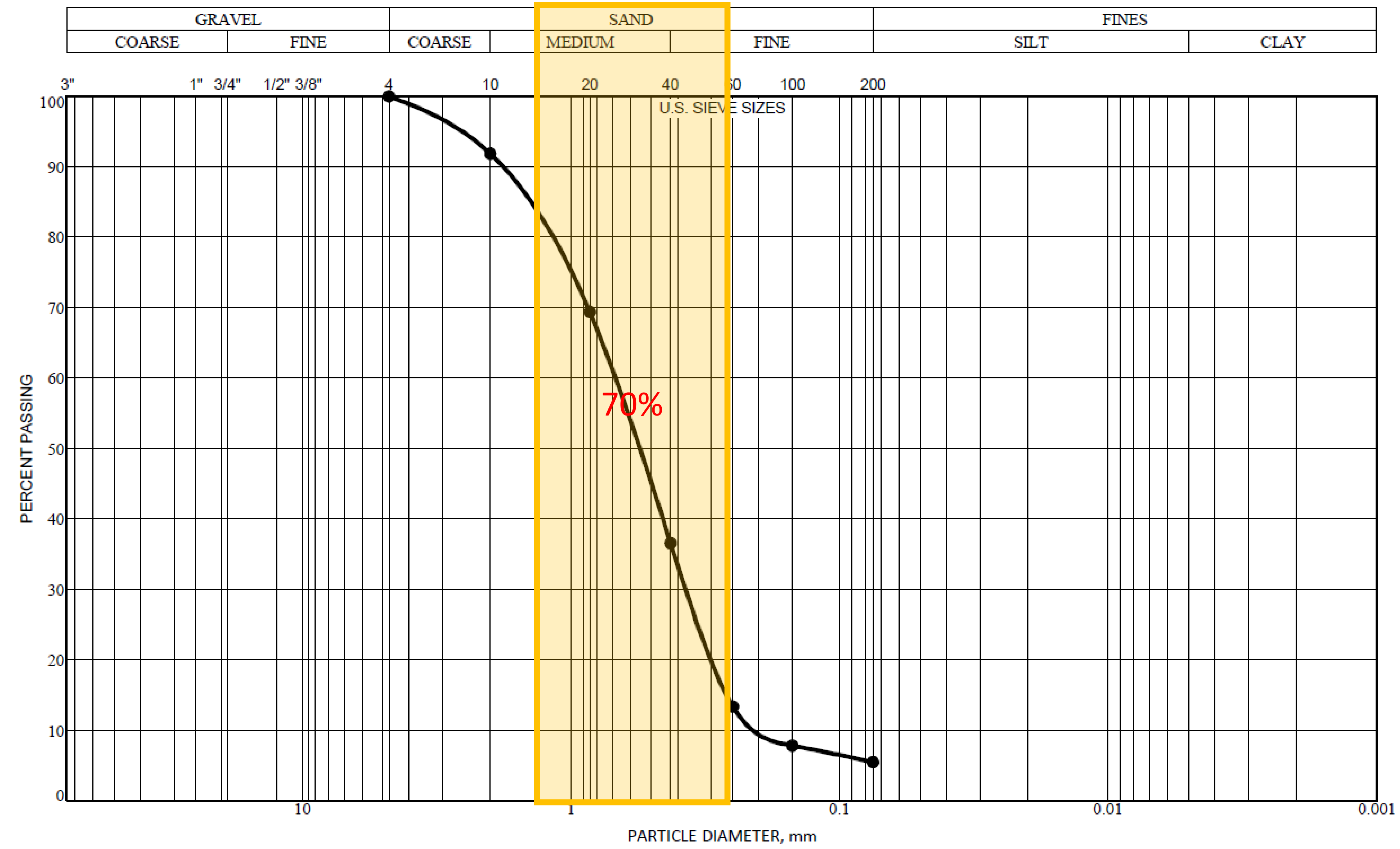


Poorly Graded Sand w/ Silt (SP-SM)
Borderline SP/SP-SM

GRAIN SIZE ACCUMULATION CURVE (ASTM)



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INTERTEC

Braun Project B2101436
Lower Sioux TPP Feasibility Study
Disturbed Testing - Phase 1

BORING: 21-1M SAMPLE: 5 DEPTH: 23.0'-23.5'

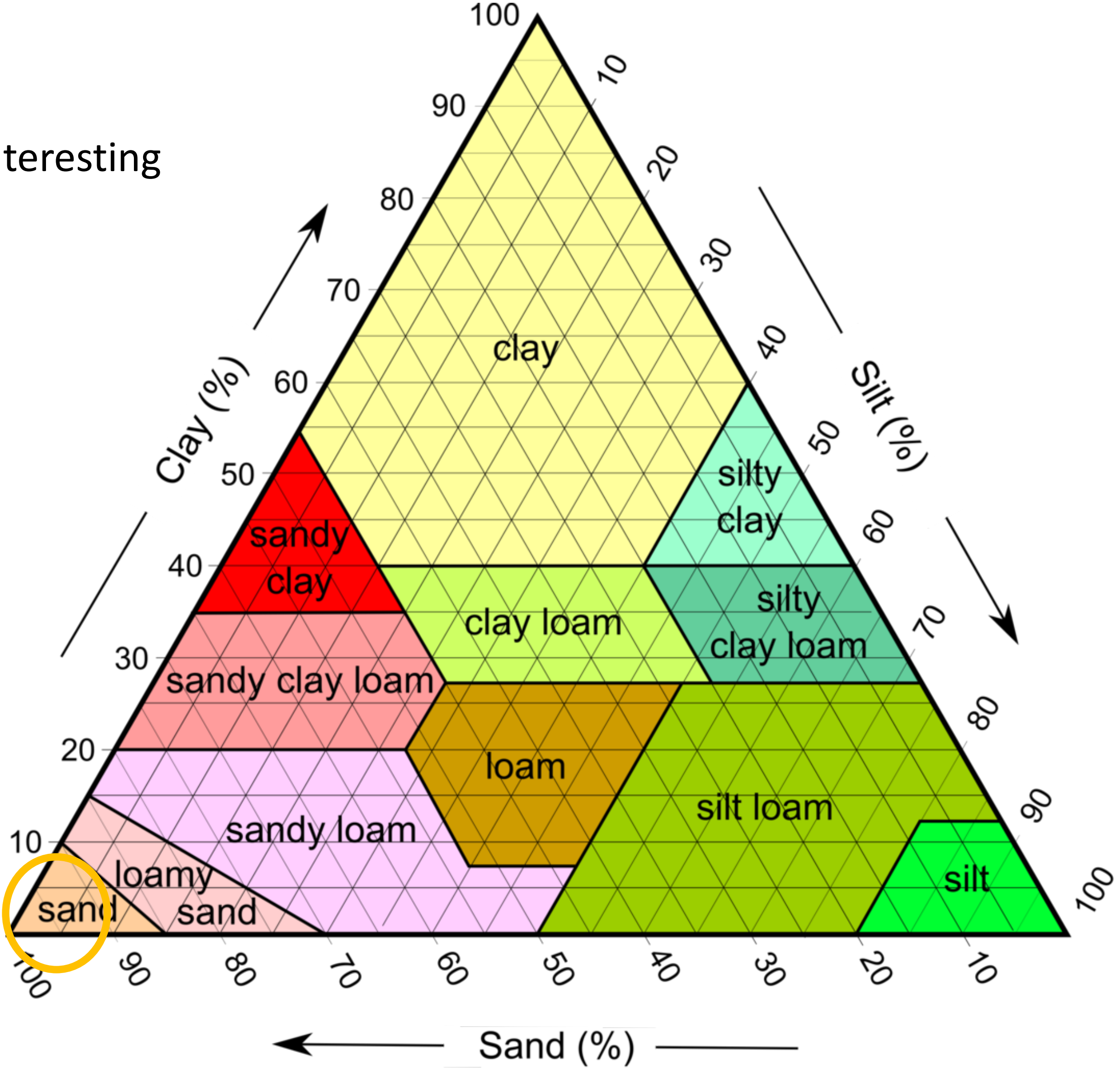
GRAVEL	0.0%
SAND	94.5%
FINES	5.5%

D60=0.698
D30=0.366
D10=0.183

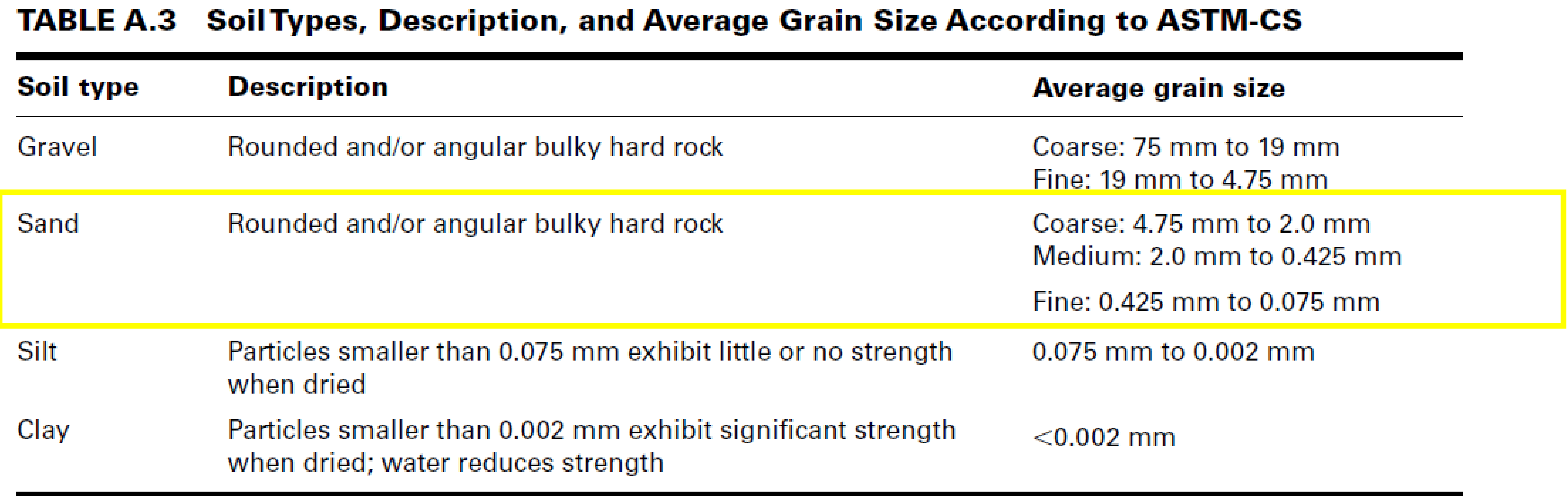
Cu=3.8
Cc=1.0

CLASSIFICATION:
POORLY GRADED SAND with SILT(SP-SM)

Textural class --- not for engineering but interesting



Budhu, pg. 723



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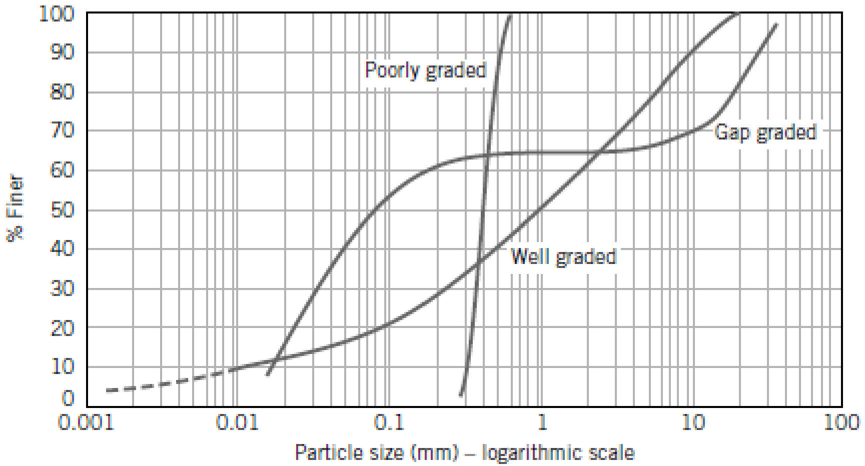
Conclusions from Grain Size Analysis on Cohesionless Upper Soils

- Similarities
  - SP
  - Poorly Graded
  - Clean

- Differences
  - Finer Sands higher up
  - Coarser Sands lower down



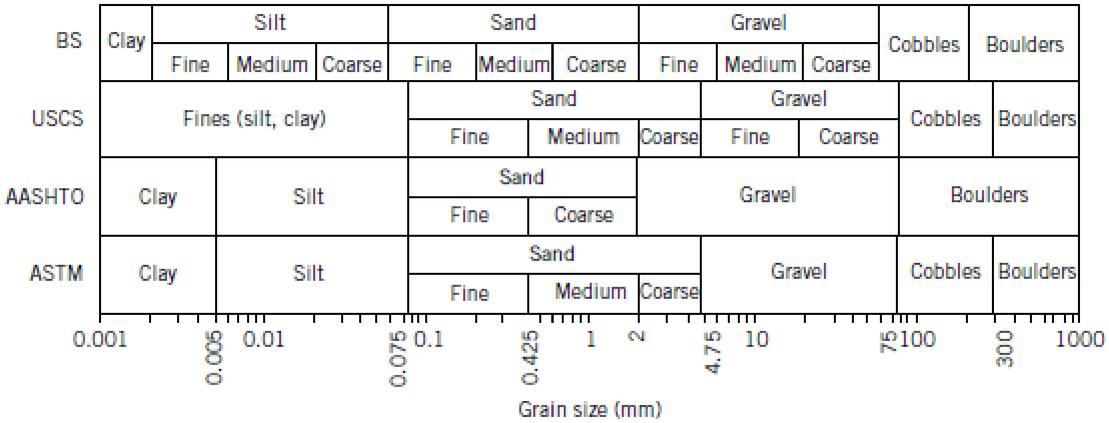
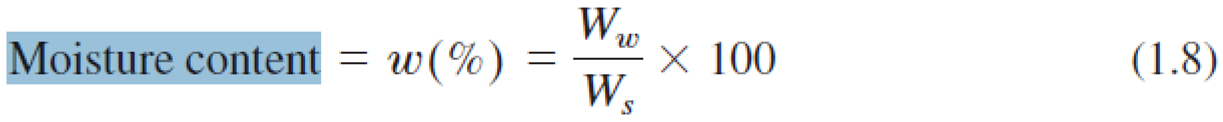
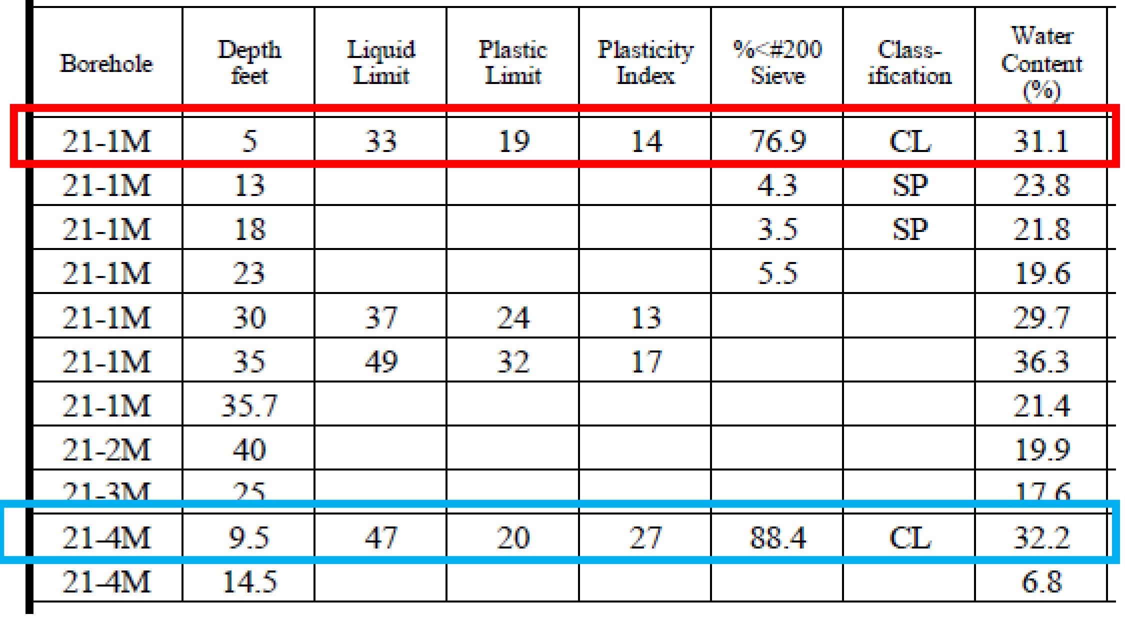


FIGURE 2.14 Comparison of four systems for describing soils based on particle size.

Moisture Content of Cohesive Upper Soils



$$\text{Moisture content} = w(\%) = \frac{W_w}{W_s} \times 100 \qquad (1.8)$$



Borehole	Depth feet	Liquid Limit	Plastic Limit	Plasticity Index	%<#200 Sieve	Class-ification	Water Content (%)
21-1M	5	33	19	14	76.9	CL	31.1
21-1M	13				4.3	SP	23.8
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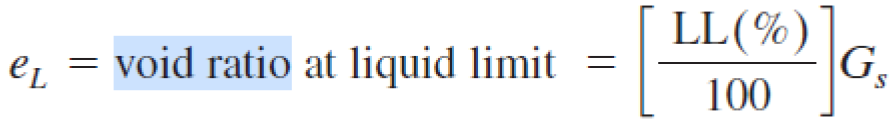
21-1M	30	37	24	13			29.7
21-1M	35	49	32	17			36.3
21-1M	35.7						21.4
21-2M	40						19.9
21-3M	25						17.6
21-4M	9.5	47	20	27	88.4	CL	32.2
21-4M	14.5						6.8

Both ~32%

One just shy of LL!

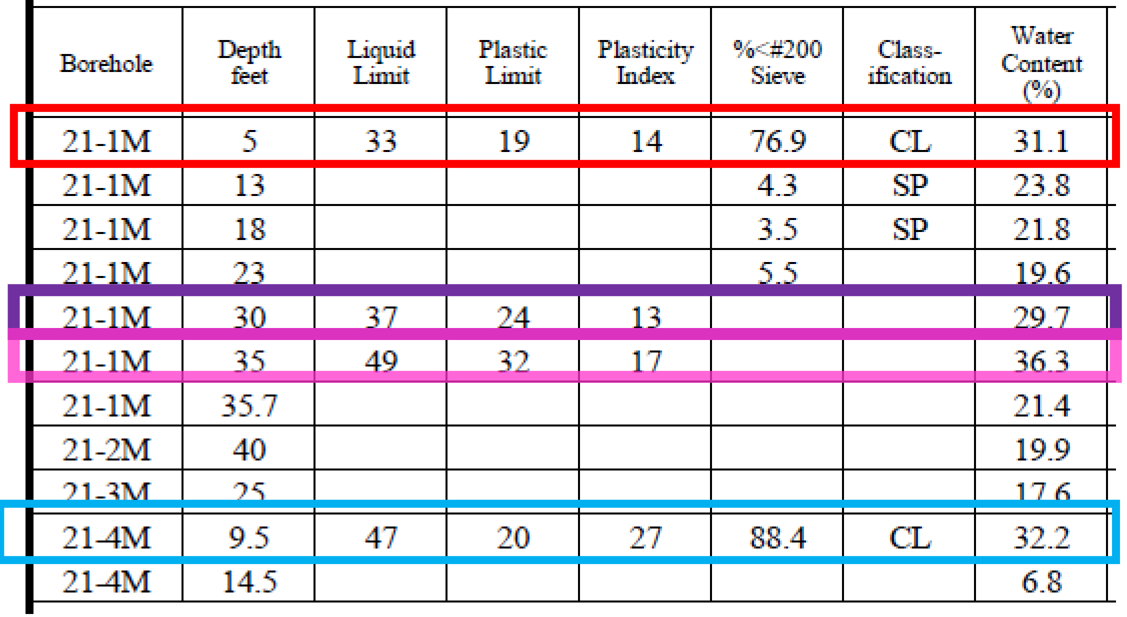


$$e_L = \text{void ratio at liquid limit} = \left[\frac{\text{LL}(\%)}{100}\right] G_s$$

e_L = 33/100*2.71 = 0.8943

e_L = 47/100*2.69 = 1.2643

These would be upper limit of void ratio.
Since Reach 1 is saturated basically, then reasonable to assume 0.8 void ratio and unit weight of around 115 to 120 pcf.



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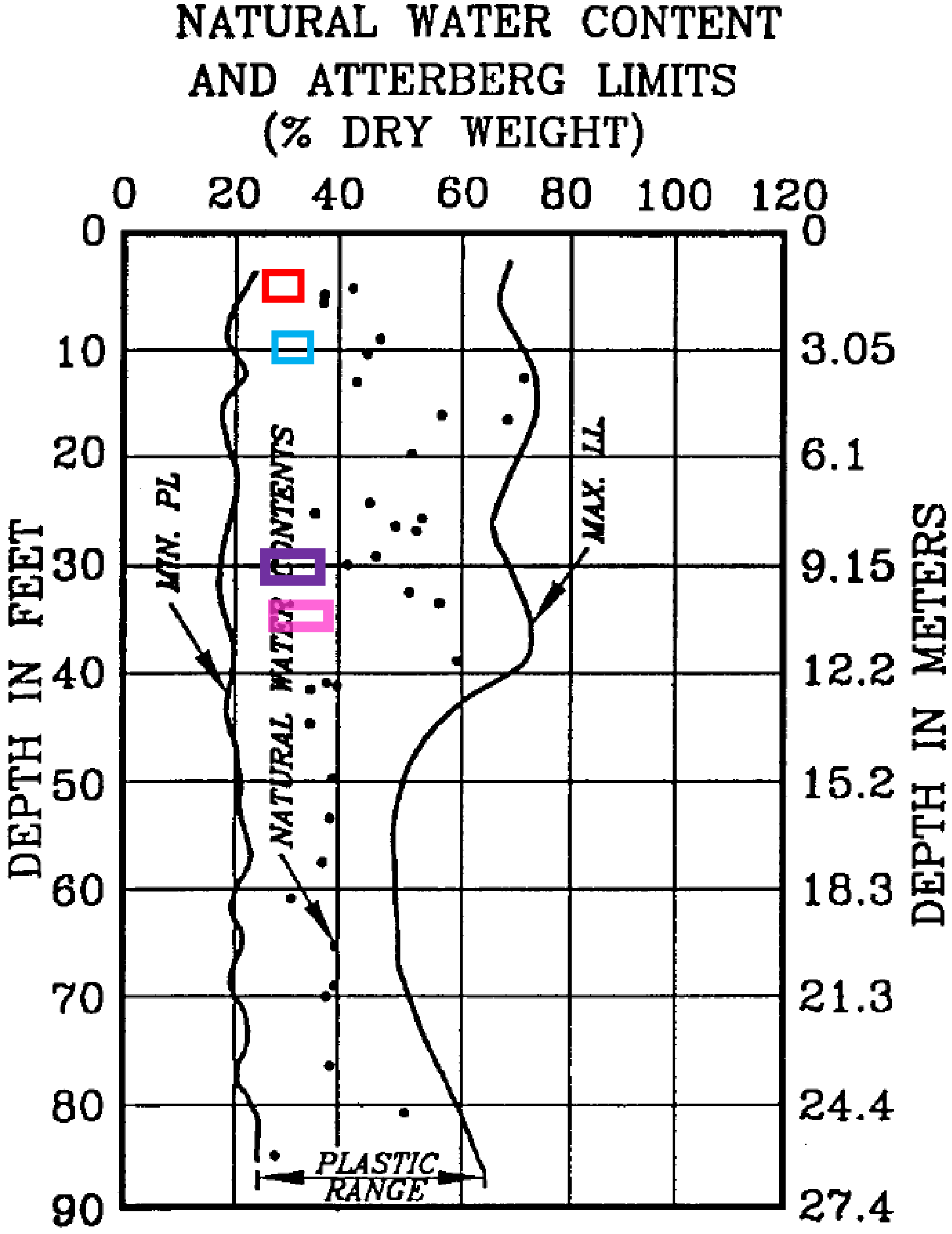
21-1M	30	37	24	13			29.7
21-1M	35	49	32	17			36.3
21-1M	35.7						21.4
21-2M	40						19.9
21-3M	25						17.6
21-4M	9.5	47	20	27	88.4	CL	32.2
21-4M	14.5						6.8

LI = (MC-PL)/(LL-PL) = (MC-PL)/(PI) = (31.1-19)/14 =0.86

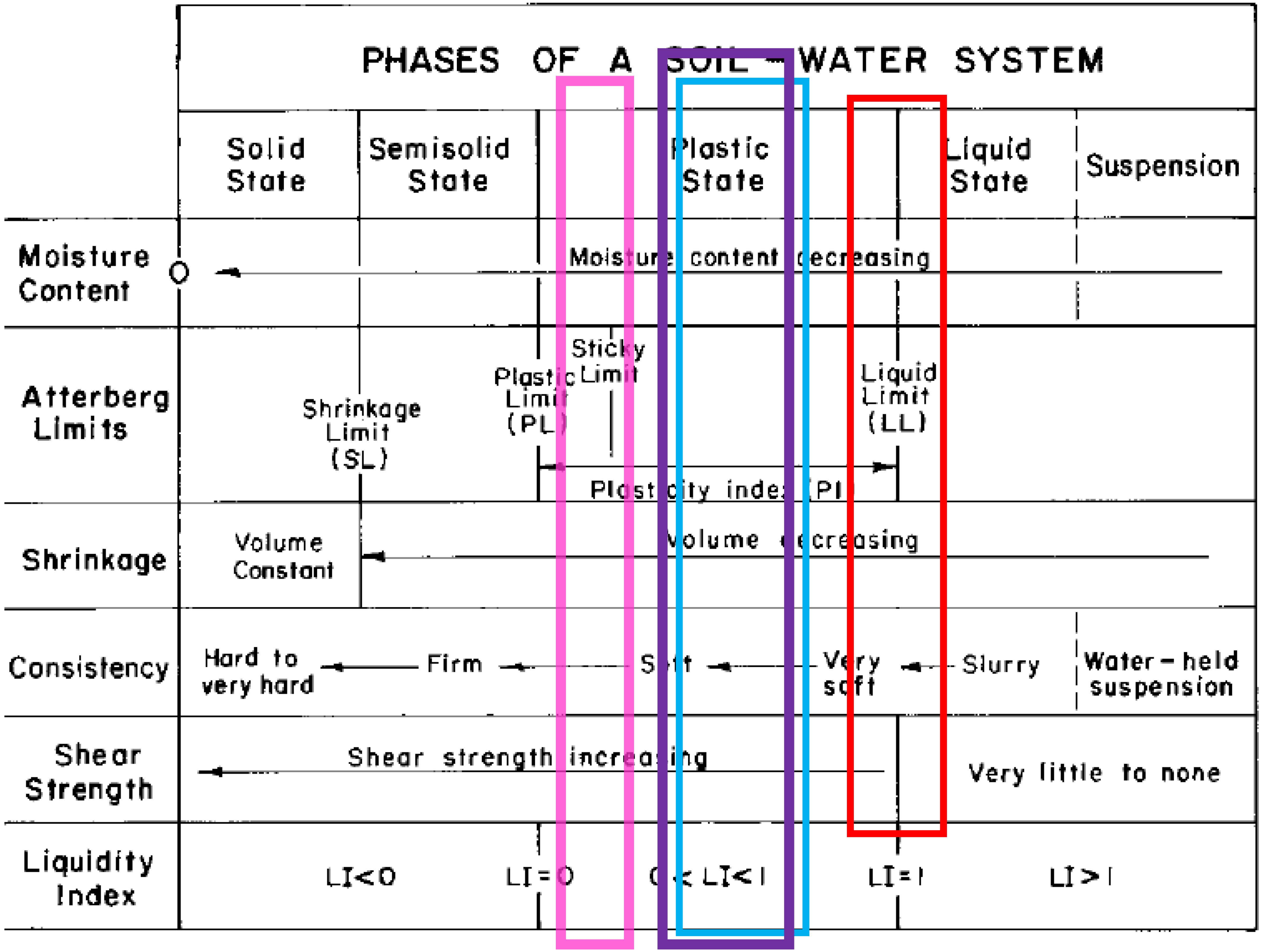
LI = (32.2-20)/27 = 0.45

LI = (29.7-24)/13 =0.44

LI = (36.3 – 32)/17 = 0.25



Atterberg Limits Analysis of Cohesive Soils



PHASES OF A SOIL – WATER SYSTEM

	Solid State	Semisolid State	Plastic State	Liquid State	Suspension
Moisture Content	0 ← Moisture content decreasing				
Atterberg Limits	Shrinkage Limit (SL)	Plastic Limit (PL)	Sticky Limit ← Plasticity index (PI) →	Liquid Limit (LL)	
Shrinkage	Volume Constant	← Volume decreasing			
Consistency	Hard to very hard ←	Firm ←	Soft ← Very soft ←	Slurry	Water-held suspension
Shear Strength	← Shear strength increasing			Very little to none	
Liquidity Index	LI<0	LI=0	0<LI<1	LI=1	LI>1

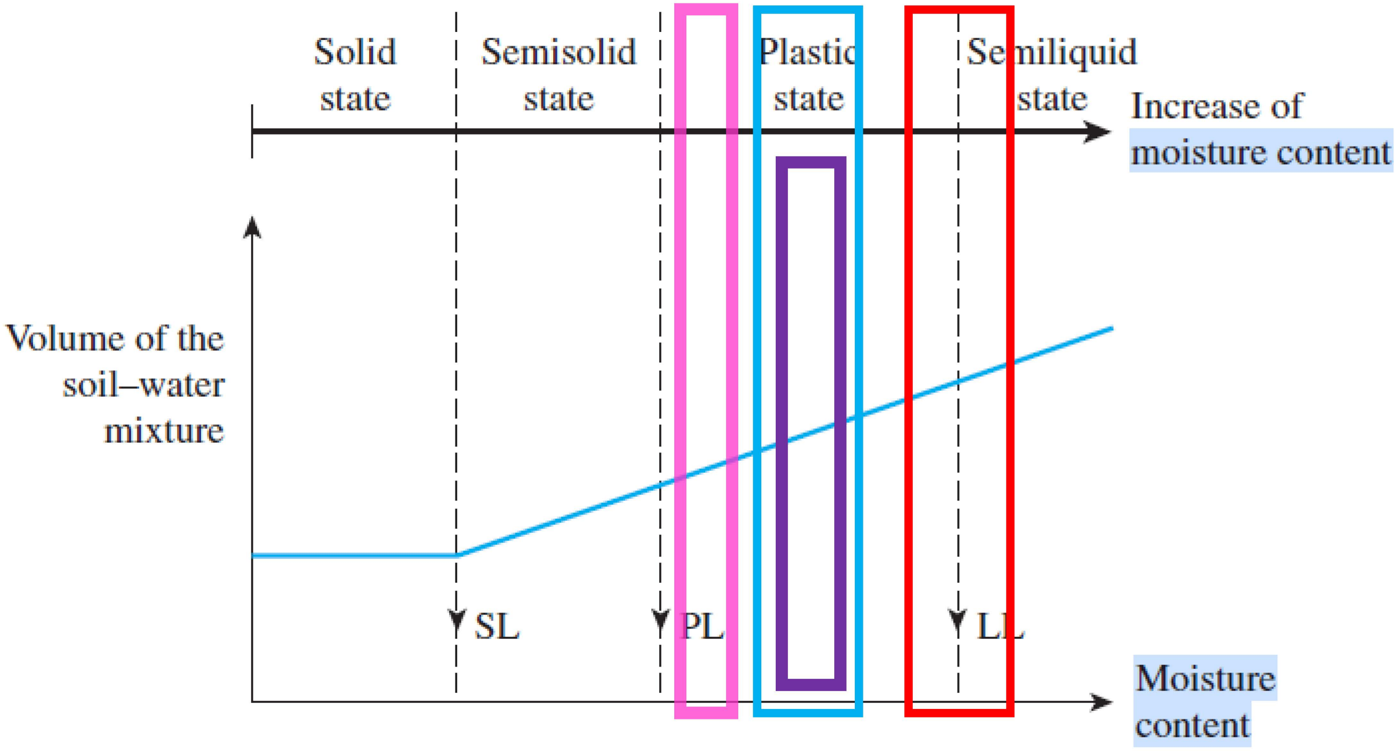
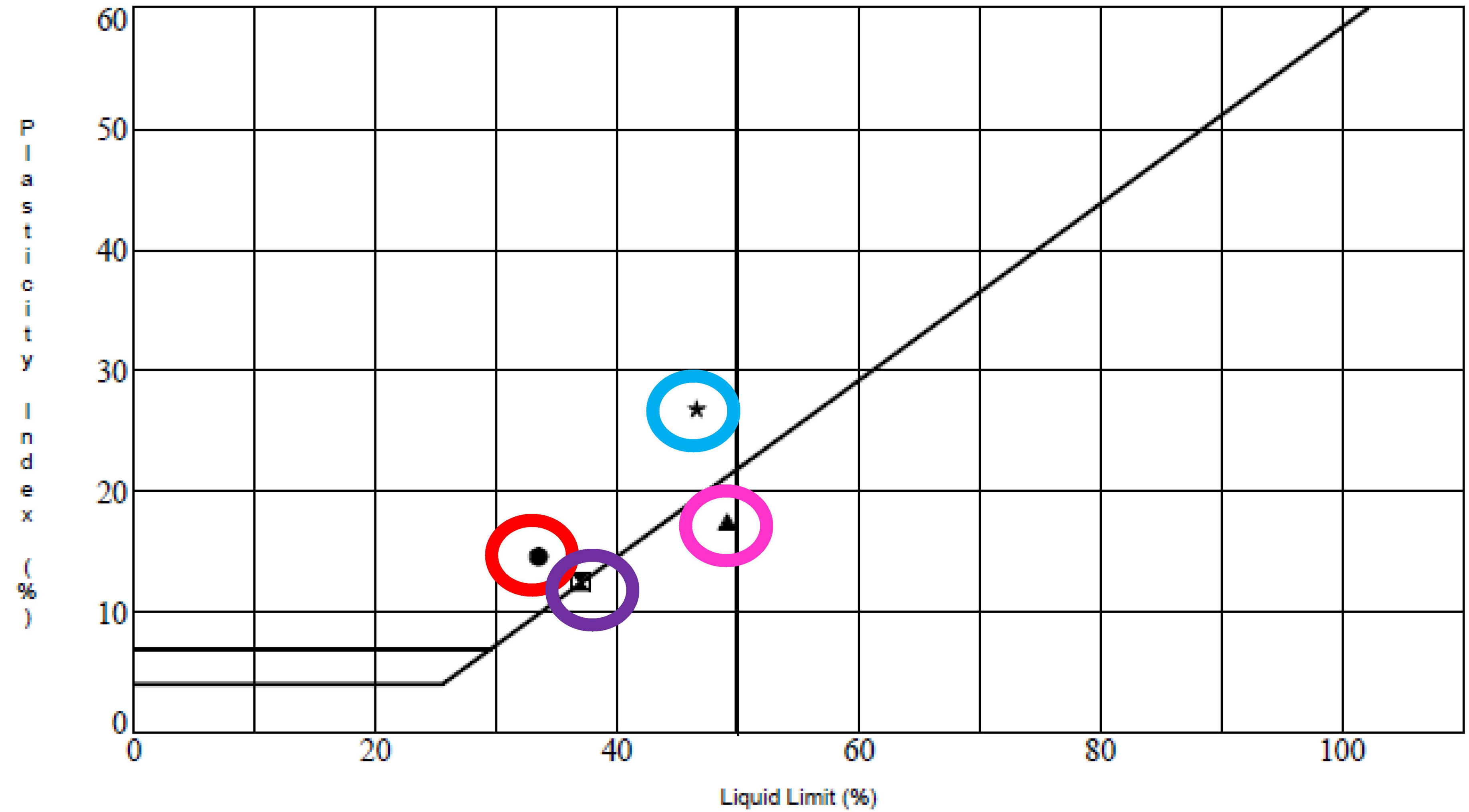


Figure 1.4 Definition of Atterberg limits



	Specimen Identification		LL	PL	PI	Fines	Classification
●	21-1M	5.0'-5.5'	33	19	14	77	LEAN CLAY with SAND(CL)
⧗	21-1M	30.0'-31.0'	37	24	13		
▲	21-1M	35.0'-35.5'	49	32	17		
★	21-4M	9.5'-10.0'	47	20	27	88	LEAN CLAY(CL)

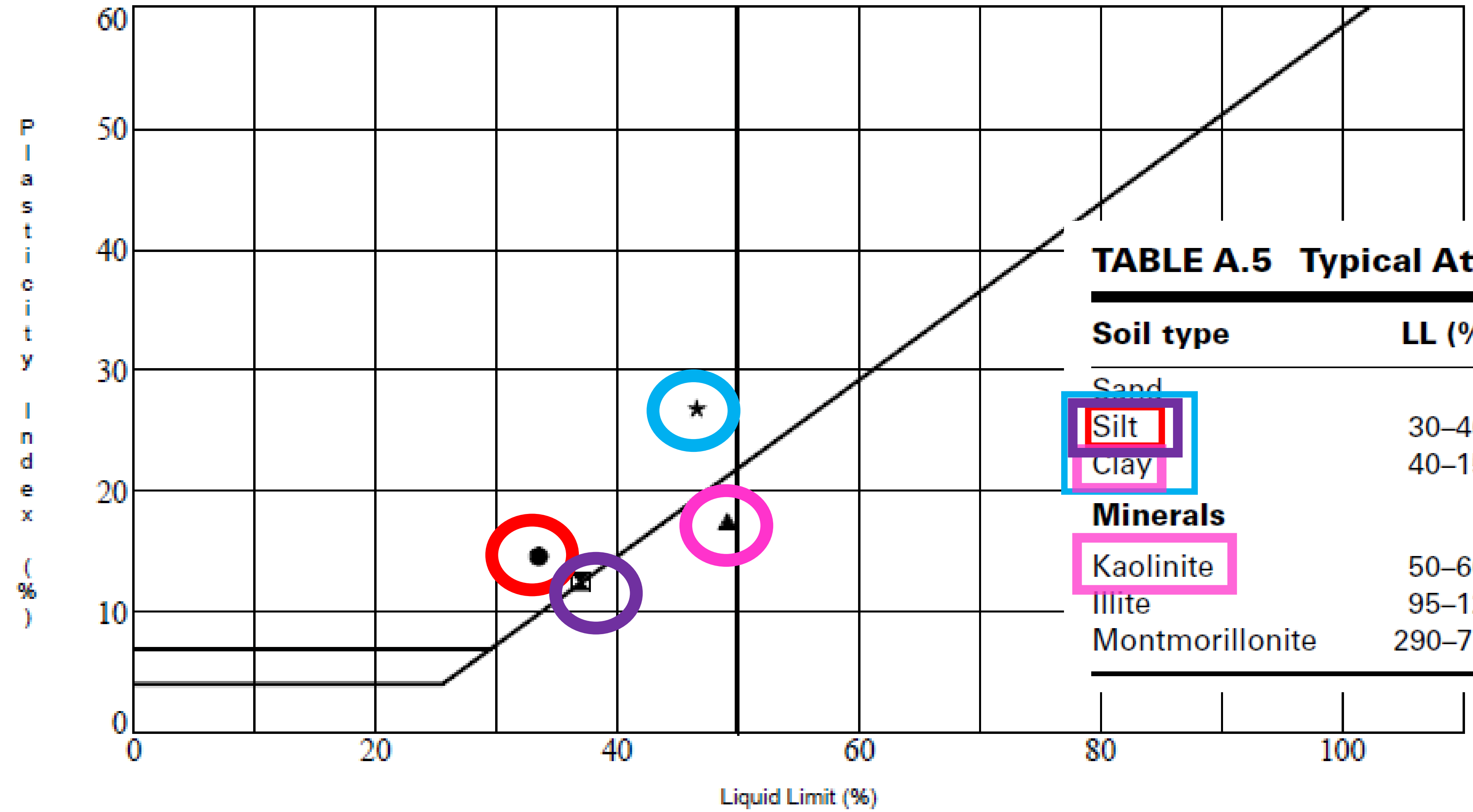


TABLE A.5 Typical Atterberg Limits for Soils

Soil type	LL (%)	PL (%)	PI (%)
Sand		Nonplastic	
Silt	30–40	20–25	10–15
Clay	40–150	25–50	15–100
Minerals			
Kaolinite	50–60	30–40	10–25
Illite	95–120	50–60	50–70
Montmorillonite	290–710	50–100	200–660

	Specimen Identification		LL	PL	PI	Fines	Classification
●	**21-1M**	**5.0'-5.5'**	**33**	**19**	**14**	**77**	**LEAN CLAY with SAND(CL)**
⧗	**21-1M**	**30.0'-31.0'**	**37**	**24**	**13**		
▲	**21-1M**	**35.0'-35.5'**	**49**	**32**	**17**		
★	**21-4M**	**9.5'-10.0'**	**47**	**20**	**27**	**88**	**LEAN CLAY(CL)**

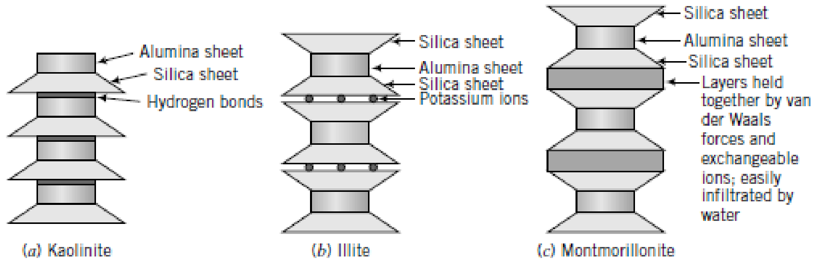
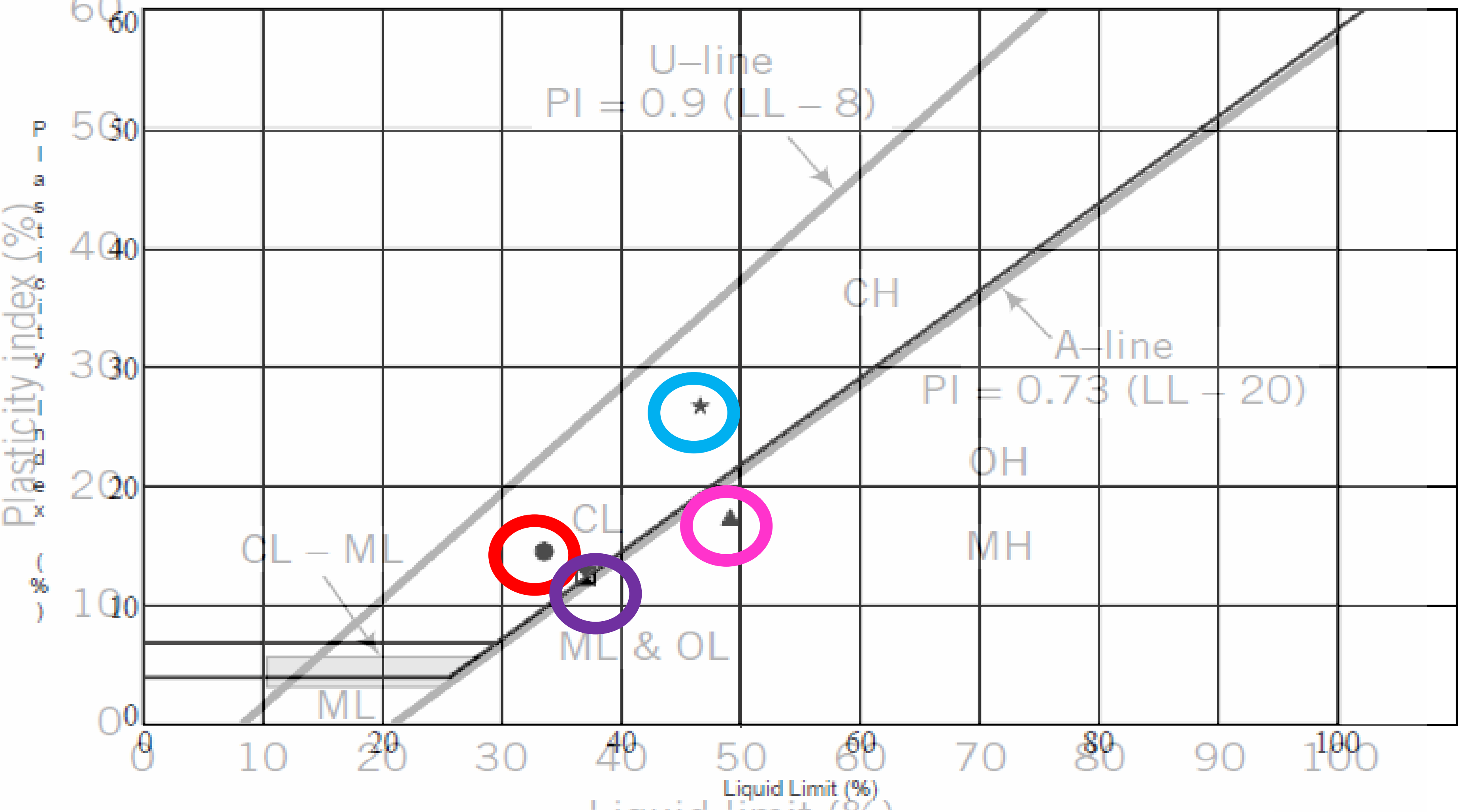
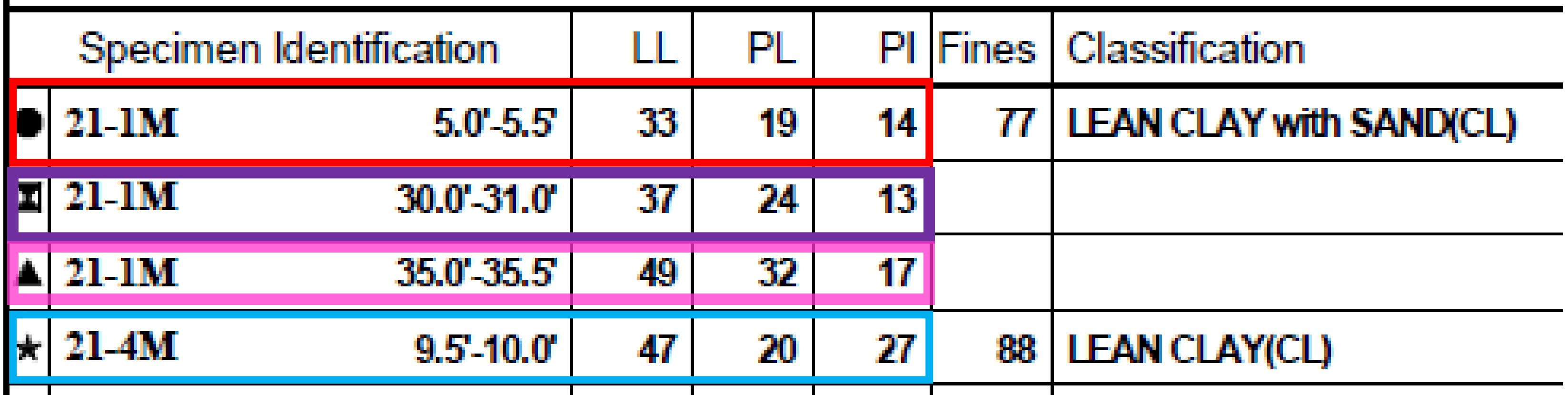


FIGURE 2.7 Structure of kaolinite, illite, and montmorillonite.



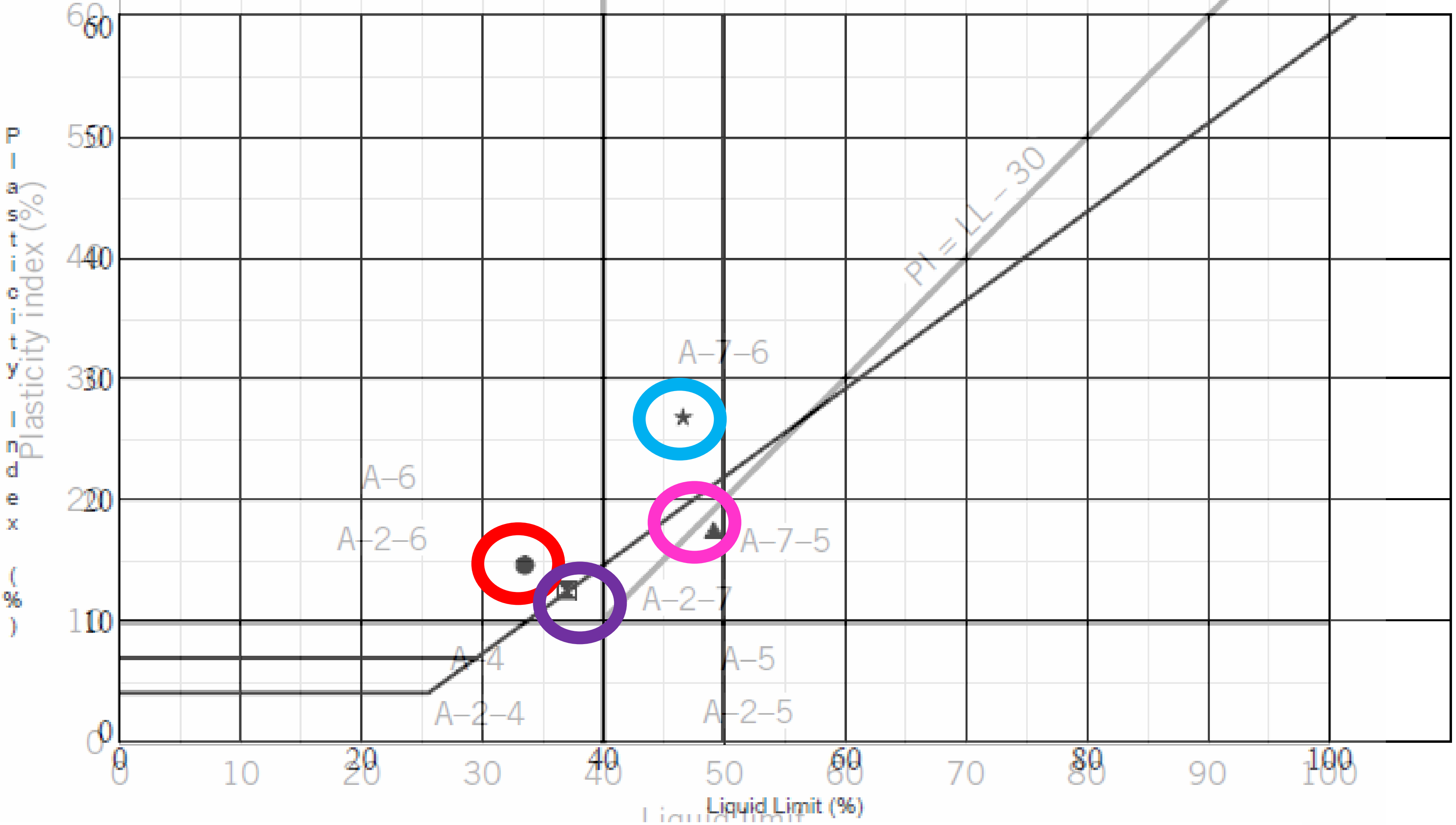


Specimen Identification			LL	PL	PI	Fines	Classification
●	21-1M	5.0'-5.5'	33	19	14	77	LEAN CLAY with SAND(CL)
⊠	21-1M	30.0'-31.0'	37	24	13		
▲	21-1M	35.0'-35.5'	49	32	17		
★	21-4M	9.5'-10.0'	47	20	27	88	LEAN CLAY(CL)

USCS: CL

v.

ML



	Specimen Identification		LL	PL	PI	Fines	Classification
●	21-1M	5.0'-5.5'	33	19	14	77	LEAN CLAY with SAND(CL)
⊠	21-1M	30.0'-31.0'	37	24	13		
▲	21-1M	35.0'-35.5'	49	32	17		
★	21-4M	9.5'-10.0'	47	20	27	88	LEAN CLAY(CL)

AASHTO: A-2-6

v. A-7-6

v. A-7-5

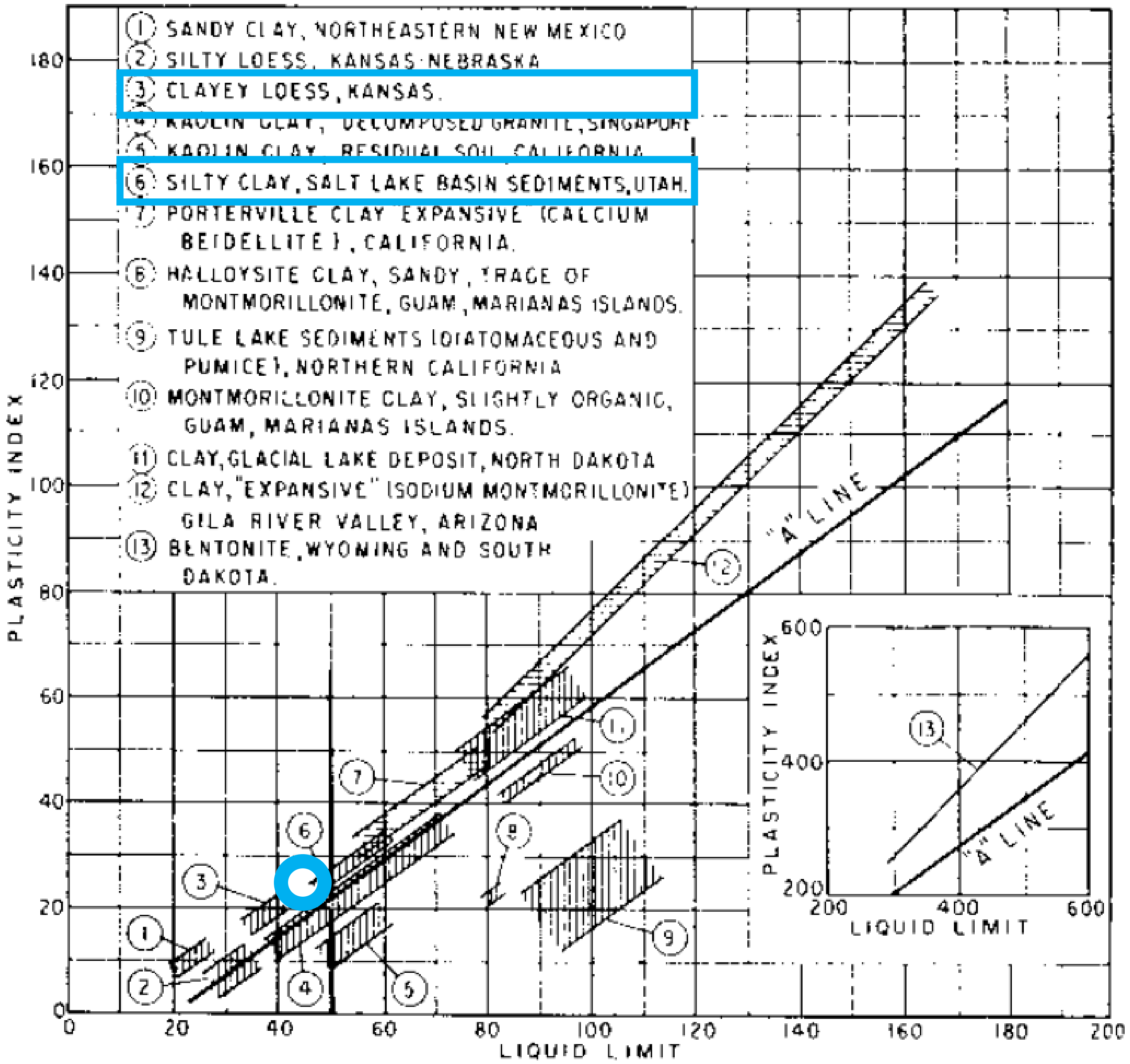


Figure 1-8.—Typical relationships between the liquid limit and the plasticity index for various soils.

EARTH MANUAL

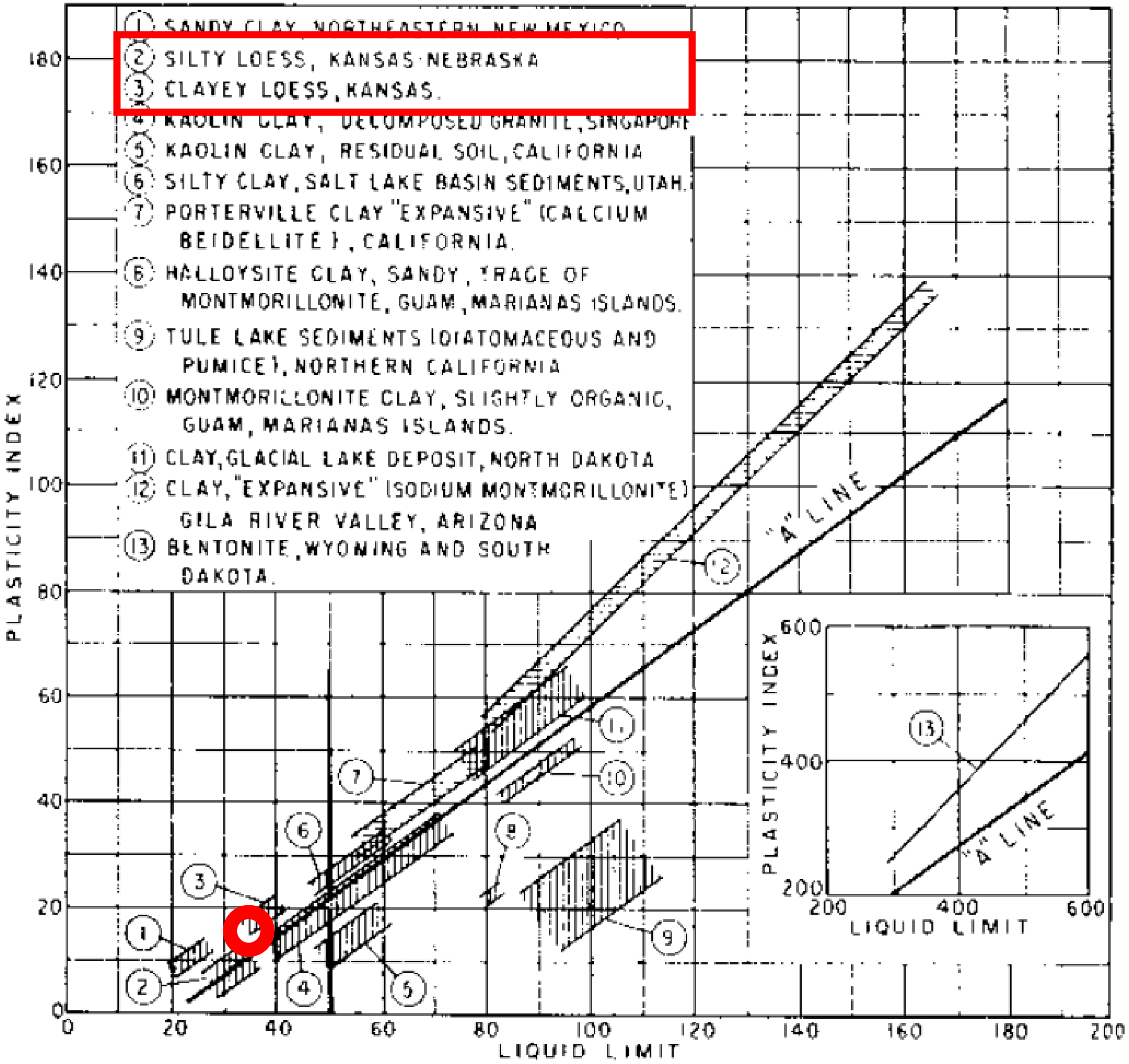


Figure 1-8.—Typical relationships between the liquid limit and the plasticity index for various soils.

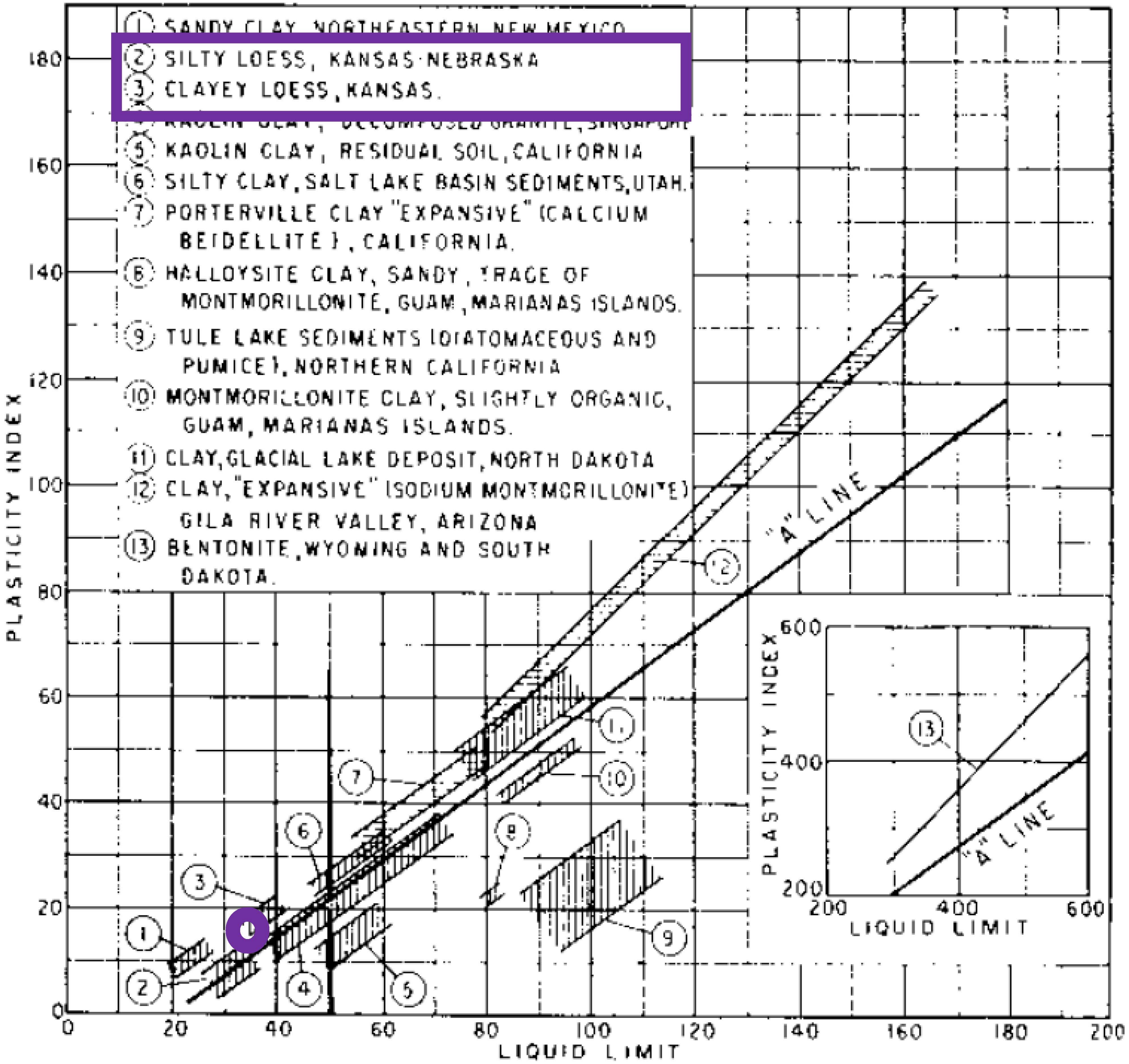


Figure 1-8.—Typical relationships between the liquid limit and the plasticity index for various soils.

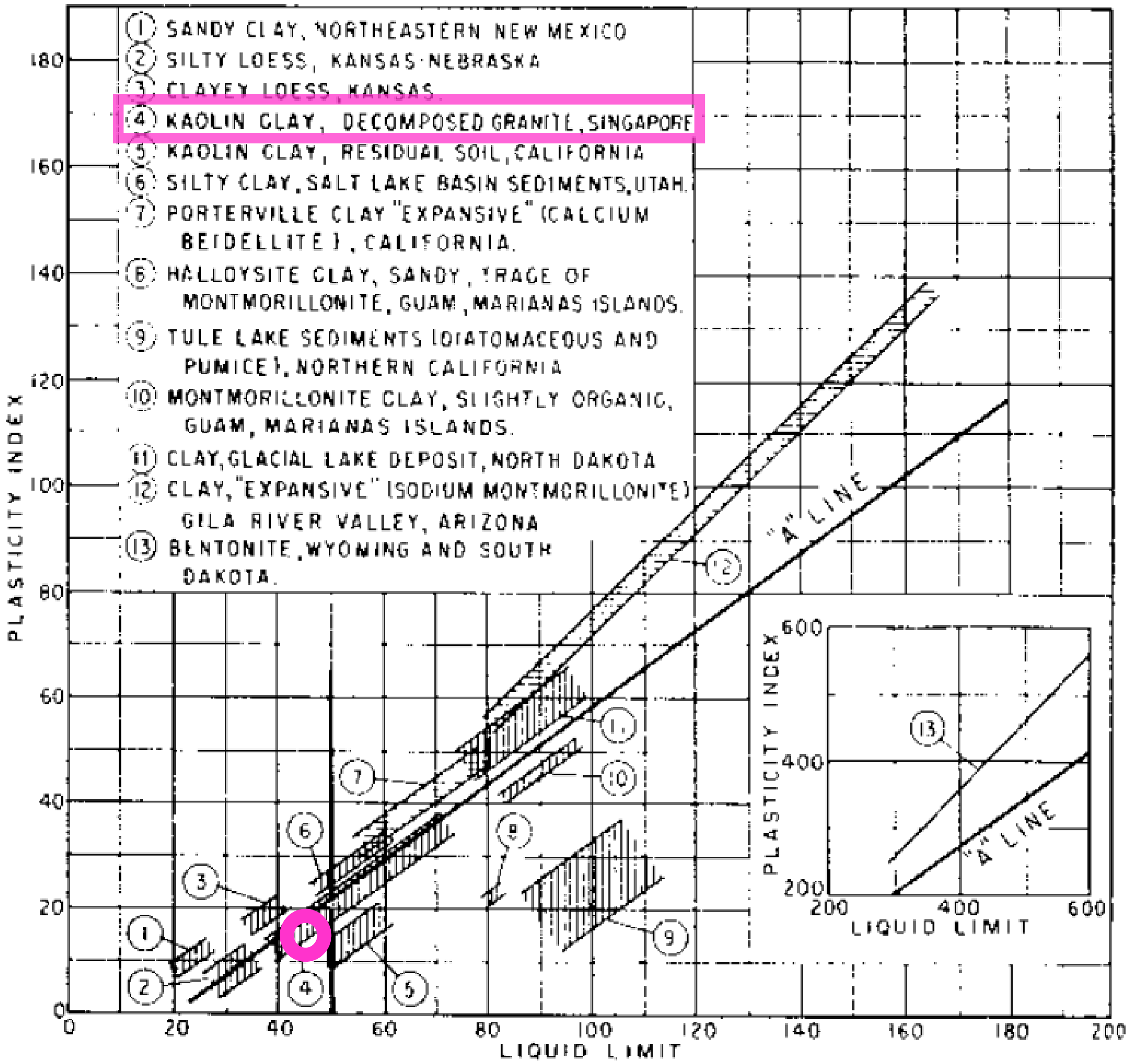


Figure 1-8.—Typical relationships between the liquid limit and the plasticity index for various soils.

Swell/Activity of Cohesive Upper Soils

$$A = \frac{\text{PI}}{(\text{\% of clay-size fraction, by weight})} \qquad (1.27)$$

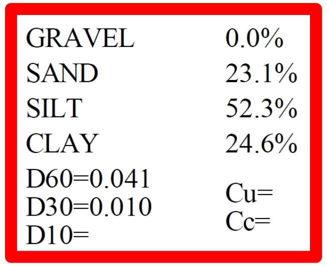
Activity is used as an index for identifying the swelling potential of clay soils. Typical values of activities for various clay minerals are given in Table 1.6.

Table 1.6 Activities of Clay Minerals

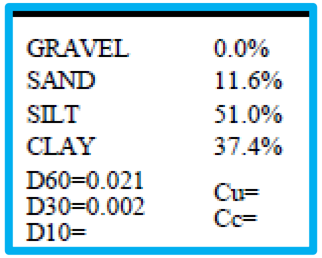
Mineral	**Activity (*A*)**
Smectites	1–7
Illite	0.5–1
Kaolinite	0.5
Halloysite ($4H_2O$)	0.5
Halloysite ($2H_2O$)	0.1
Attapulgite	0.5–1.2
Allophane	0.5–1.2

A= 14/24.6=0.569

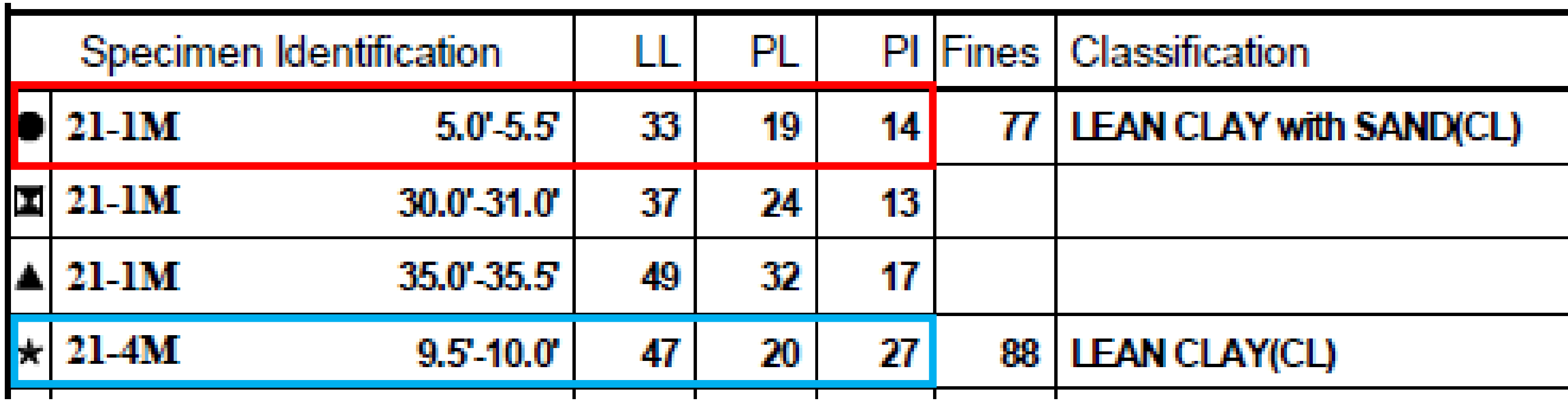
A= 27/37.4=0.722



GRAVEL	0.0%		
SAND	23.1%		
SILT	52.3%		
CLAY	24.6%		
D60=0.041		Cu=	
D30=0.010		Cc=	
D10=			

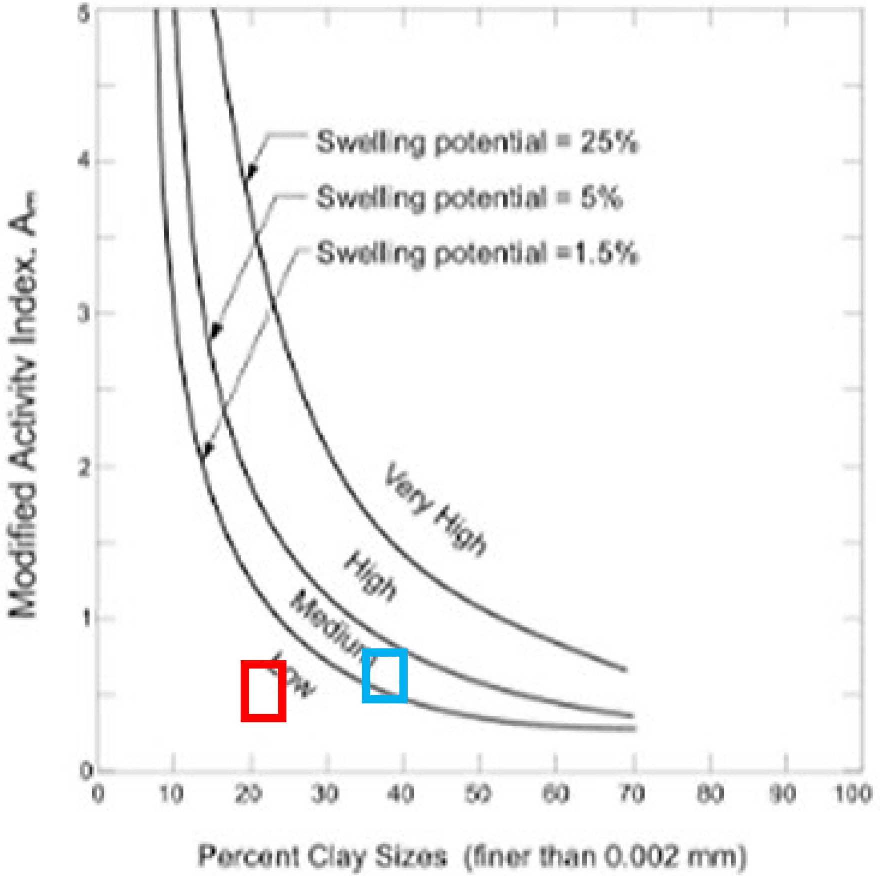


GRAVEL	0.0%		
SAND	11.6%		
SILT	51.0%		
CLAY	37.4%		
D60=0.021		Cu=	
D30=0.002		Cc=	
D10=			



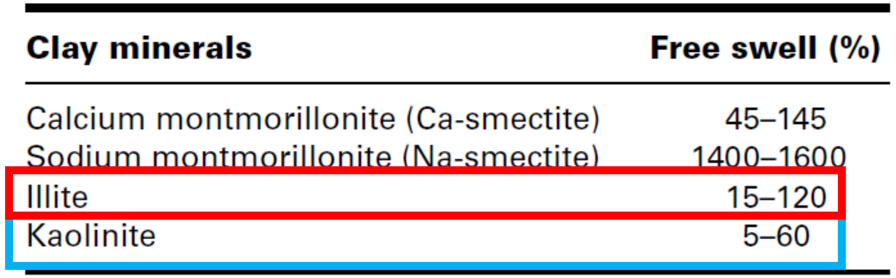
	Specimen Identification		LL	PL	PI	Fines	Classification
●	21-1M	5.0'-5.5'	33	19	14	77	LEAN CLAY with SAND(CL)
⊠	21-1M	30.0'-31.0'	37	24	13		
▲	21-1M	35.0'-35.5'	49	32	17		
★	21-4M	9.5'-10.0'	47	20	27	88	LEAN CLAY(CL)

Classification of swell potential for soils



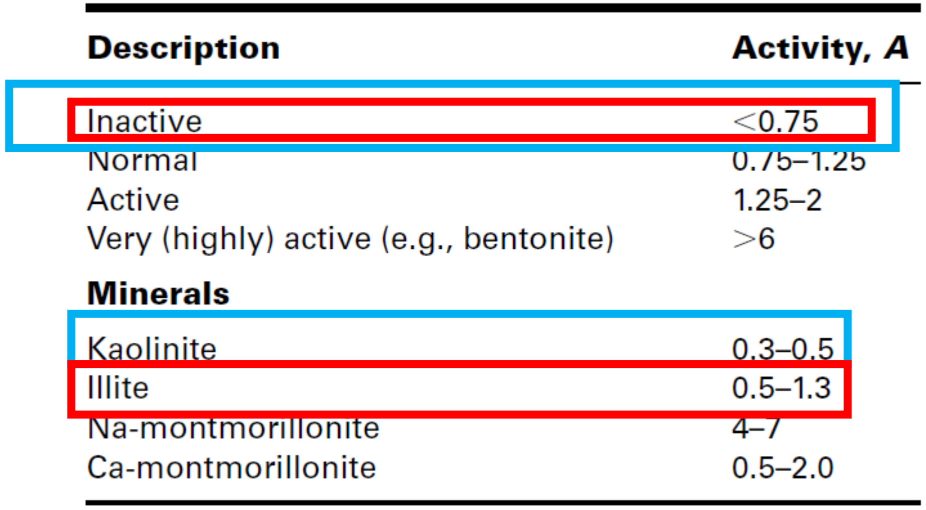
From FHWA NHI-06-088, *Soils and Foundations Reference Manual—Volume I*, Fig. 5-27, © 2006, U.S. Department of Transportation Federal Highway Administration.

TABLE A.15 Ranges of Free Swell for Some Clay Minerals



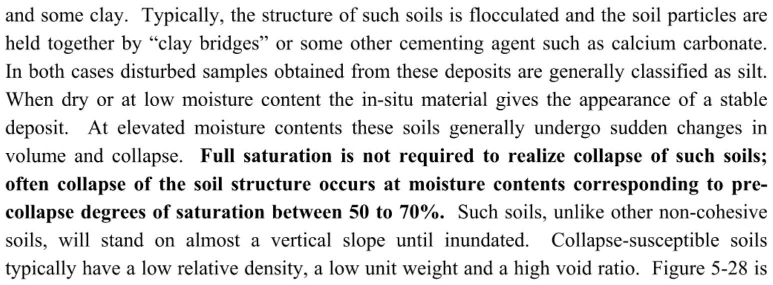
Clay minerals	Free swell (%)
Calcium montmorillonite (Ca-smectite)	45–145
Sodium montmorillonite (Na-smectite)	1400–1600
Illite	15–120
Kaolinite	5–60

TABLE A.16 Activity of Clay-Rich Soils



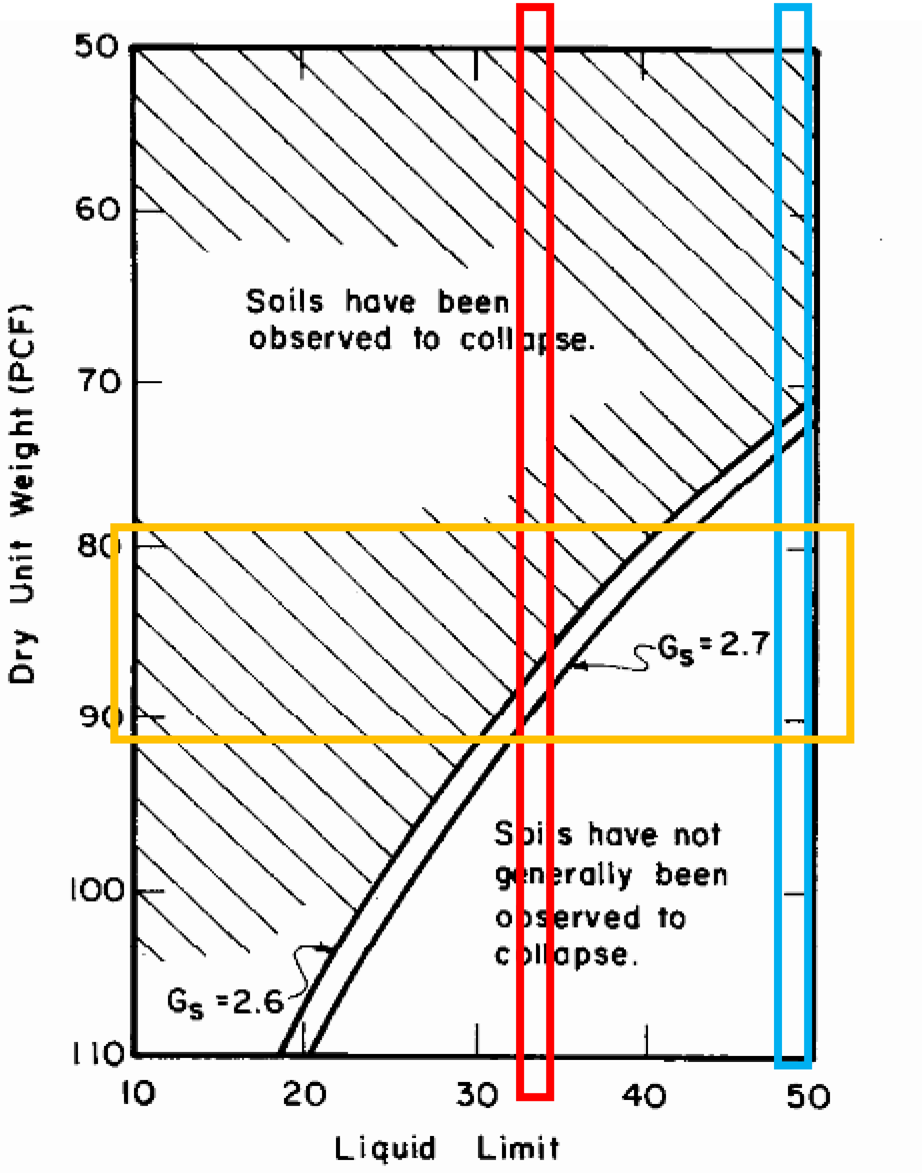
Description	Activity, *A*
Inactive	<0.75
Normal	0.75–1.25
Active	1.25–2
Very (highly) active (e.g., bentonite)	>6
Minerals	
Kaolinite	0.3–0.5
Illite	0.5–1.3
Na-montmorillonite	4–7
Ca-montmorillonite	0.5–2.0

Collapse Potential of Cohesive Upper Soils



and some clay. Typically, the structure of such soils is flocculated and the soil particles are held together by "clay bridges" or some other cementing agent such as calcium carbonate. In both cases disturbed samples obtained from these deposits are generally classified as silt. When dry or at low moisture content the in-situ material gives the appearance of a stable deposit. At elevated moisture contents these soils generally undergo sudden changes in volume and collapse. **Full saturation is not required to realize collapse of such soils; often collapse of the soil structure occurs at moisture contents corresponding to pre-collapse degrees of saturation between 50 to 70%.** Such soils, unlike other non-cohesive soils, will stand on almost a vertical slope until inundated. Collapse-susceptible soils typically have a low relative density, a low unit weight and a high void ratio. Figure 5-28 is

FHWA_NHI-06-088_Soils&FoundationsReferenceManual_Vol_I



Potential for collapsible soils exists in upper layers.

Figure 5-28. Chart for evaluation of collapsible soils (after Holtz and Hilf, 1961).

Hydraulic Conductivity

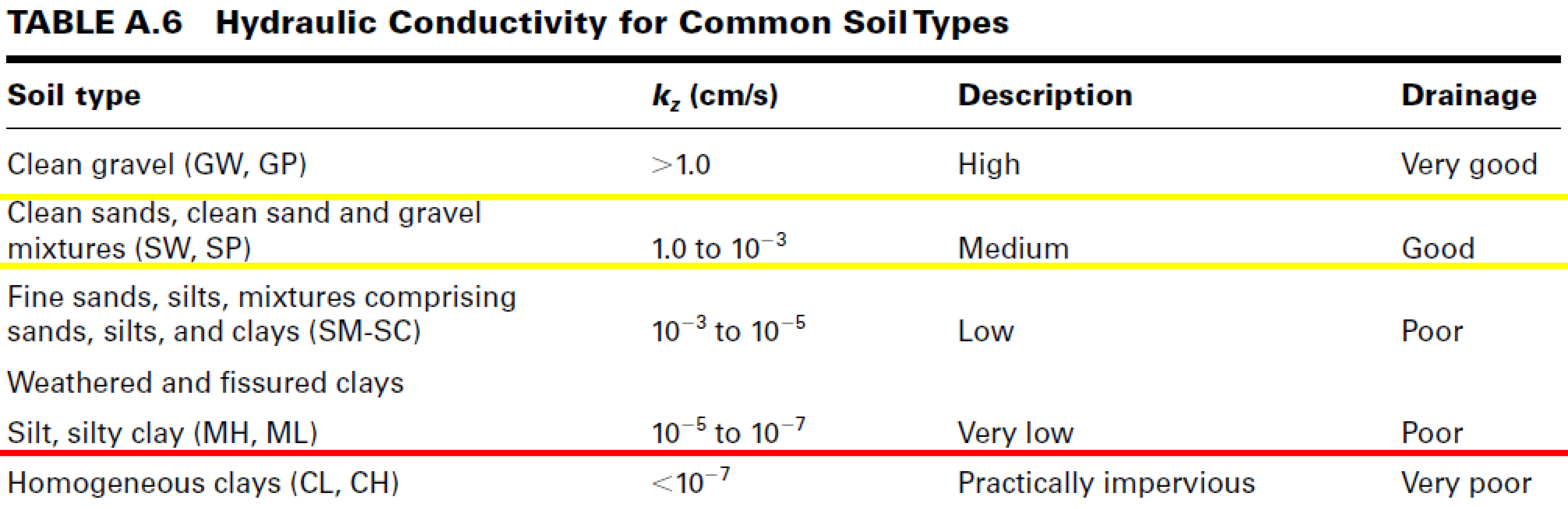
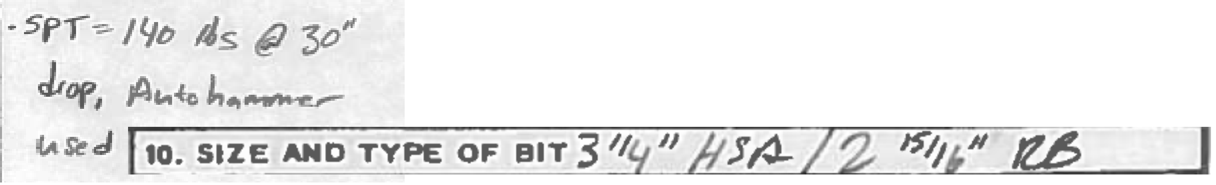


TABLE A.6 Hydraulic Conductivity for Common Soil Types

Soil type	k_z (cm/s)	Description	Drainage
Clean gravel (GW, GP)	>1.0	High	Very good
Clean sands, clean sand and gravel mixtures (SW, SP)	1.0 to 10^{-3}	Medium	Good
Fine sands, silts, mixtures comprising sands, silts, and clays (SM-SC)	10^{-3} to 10^{-5}	Low	Poor
Weathered and fissured clays			
Silt, silty clay (MH, ML)	10^{-5} to 10^{-7}	Very low	Poor
Homogeneous clays (CL, CH)	$<10^{-7}$	Practically impervious	Very poor

Undrained Strengths of Cohesive Upper Soils



- SPT = 140 lbs @ 30" drop, Auto hammer used

10. SIZE AND TYPE OF BIT 3¼" HSA / 2 15/16" RB

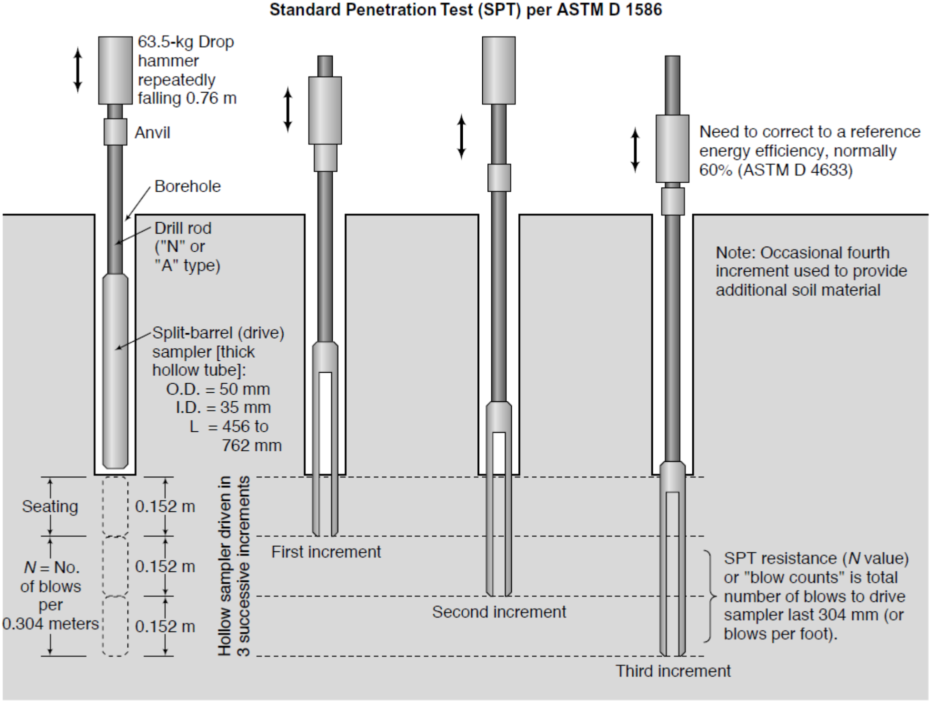
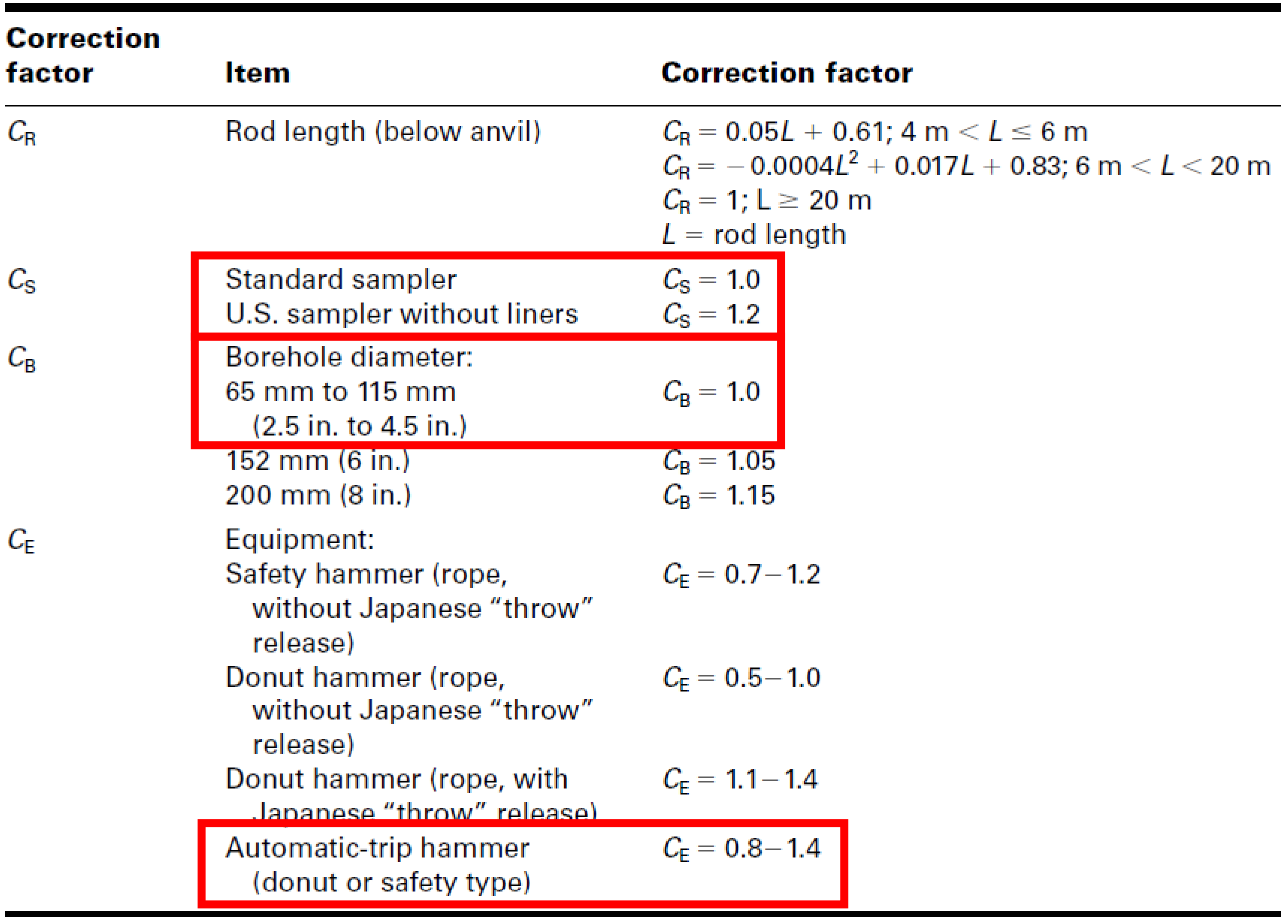

Standard Penetration Test (SPT) per ASTM D 1586
63.5-kg Drop hammer repeatedly falling 0.76 m
Anvil
Borehole
Drill rod ("N" or "A" type)
Split-barrel (drive) sampler [thick hollow tube]: O.D. = 50 mm I.D. = 35 mm L = 456 to 762 mm
Need to correct to a reference energy efficiency, normally 60% (ASTM D 4633)
Note: Occasional fourth increment used to provide additional soil material
Seating
N = No. of blows per 0.304 meters
0.152 m
0.152 m
0.152 m
Hollow sampler driven in 3 successive increments
First increment
Second increment
Third increment
SPT resistance (N value) or "blow counts" is total number of blows to drive sampler last 304 mm (or blows per foot).

FIGURE 3.7 Driving sequence in an SPT test. (Source: Professor Paul Mayne, Georgia Tech.)

TABLE 3.4 Correction Factors for Rod Length, Sampler Type, and Borehole Size



Correction factor	Item	Correction factor
C_R	Rod length (below anvil)	$C_R = 0.05L + 0.61$; 4 m $< L \le$ 6 m $C_R = -0.0004L^2 + 0.017L + 0.83$; 6 m $< L <$ 20 m $C_R = 1$; $L \ge$ 20 m L = rod length
C_S	Standard sampler	$C_S = 1.0$
	U.S. sampler without liners	$C_S = 1.2$
C_B	Borehole diameter:	
	65 mm to 115 mm (2.5 in. to 4.5 in.)	$C_B = 1.0$
	152 mm (6 in.)	$C_B = 1.05$
	200 mm (8 in.)	$C_B = 1.15$
C_E	Equipment:	
	Safety hammer (rope, without Japanese "throw" release)	$C_E = 0.7 - 1.2$
	Donut hammer (rope, without Japanese "throw" release)	$C_E = 0.5 - 1.0$
	Donut hammer (rope, with Japanese "throw" release)	$C_E = 1.1 - 1.4$
	Automatic-trip hammer (donut or safety type)	$C_E = 0.8 - 1.4$

SOURCE: Youd et al. (2001) and Seed et al. (2003).

$$N_{60} = N\left(\frac{ER_r}{60}\right) = NC_E$$

$$N_{cor} = C_{RSBE}N$$

$$C_{RSBE} = C_R C_S C_B C_E$$

where C_R, C_S, C_B, and C_E are correction factors for rod length, sampler type, bore hole diameter, and rod energy correction, respectively.

3.0

4.0

5.0

CL

6.0

Low-No Plast.
Brown
Laminated
100% fines
Trace f Sand

Silty Clay (CL)

Soft
Dry-Wet
Med. Plast.
Dark Brown
Occ. Jumbled texture
100% fines
Trace f. Sand

R 2.
T 3.0

SPT
1
1
1
1
R 0.2
T 5.0

2+2½
P
O

SN 2
$\frac{5.0}{5.5}$

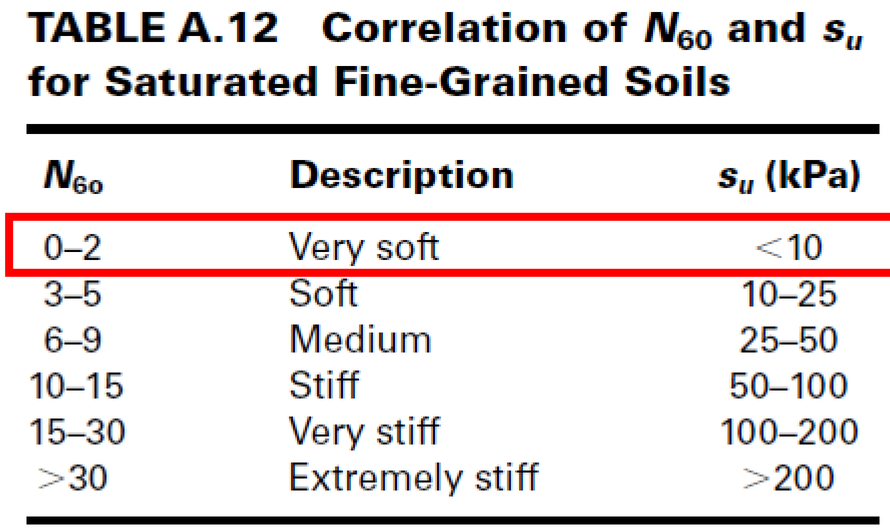


TABLE A.12 Correlation of N_{60} and s_u for Saturated Fine-Grained Soils

N_{60}	Description	s_u (kPa)
0–2	Very soft	<10
3–5	Soft	10–25
6–9	Medium	25–50
10–15	Stiff	50–100
15–30	Very stiff	100–200
>30	Extremely stiff	>200

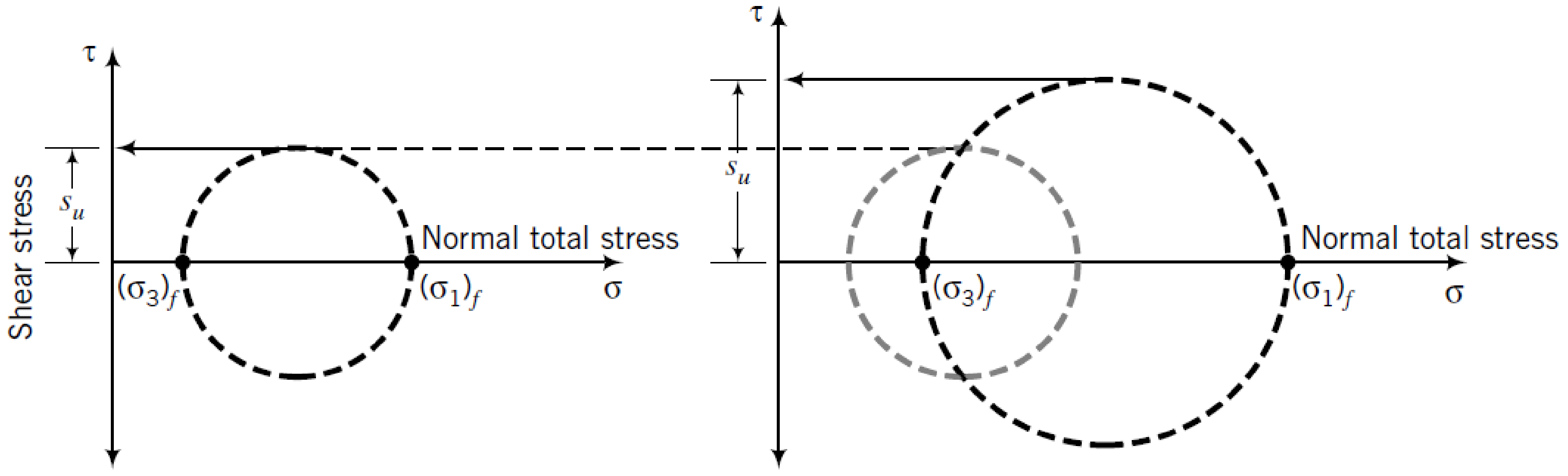
<~200 psf

1 kPa = 20.89 psf.

Could functionally assume some cohesiveness given existence of tension cracks.

Seems like high moisture content near LL for Reach 1 sample would mean lower end of strength range.

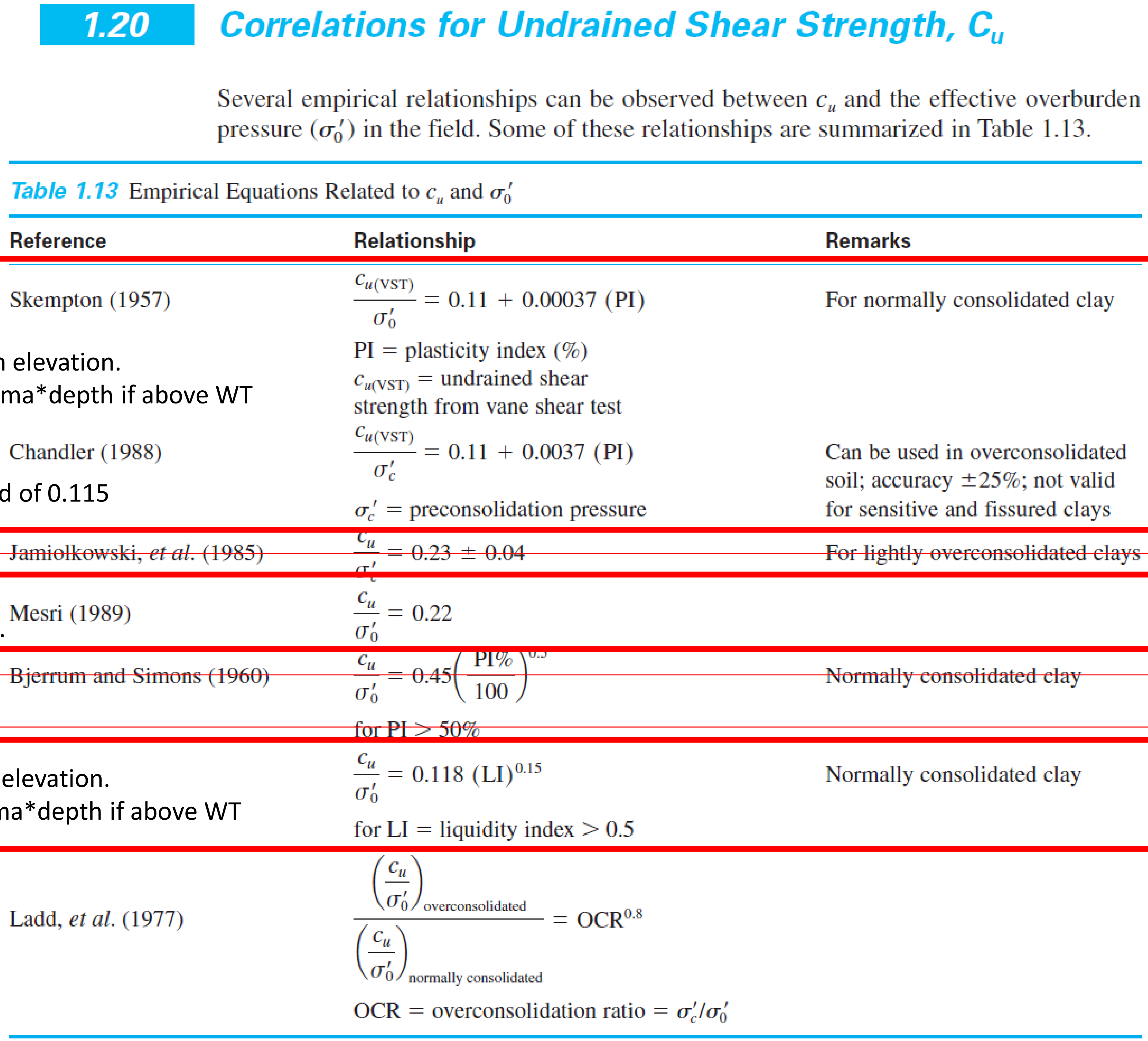
***Undrained shear strength* (s_u)** is the shear strength of a soil when sheared at constant volume.



(*a*) Undrained shear strength

(*b*) Increase in undrained shear strength from increase in confining pressure

FIGURE 10.15 Mohr's circles for undrained conditions.



1.20 Correlations for Undrained Shear Strength, C_u

Several empirical relationships can be observed between c_u and the effective overburden pressure (σ'_0) in the field. Some of these relationships are summarized in Table 1.13.

Table 1.13 Empirical Equations Related to c_u and σ'_0

Reference	**Relationship**	**Remarks**
Skempton (1957)	$\frac{c_{u(\text{VST})}}{\sigma'_0} = 0.11 + 0.00037\,(\text{PI})$ PI = plasticity index (%) $c_{u(\text{VST})}$ = undrained shear strength from vane shear test	For normally consolidated clay
Chandler (1988)	$\frac{c_{u(\text{VST})}}{\sigma'_c} = 0.11 + 0.0037\,(\text{PI})$ σ'_c = preconsolidation pressure	Can be used in overconsolidated soil; accuracy ±25%; not valid for sensitive and fissured clays
~~Jamiolkowski, *et al.* (1985)~~	~~$\frac{c_u}{\sigma'_c} = 0.23 \pm 0.04$~~	~~For lightly overconsolidated clays~~
Mesri (1989)	$\frac{c_u}{\sigma'_0} = 0.22$	
~~Bjerrum and Simons (1960)~~	~~$\frac{c_u}{\sigma'_0} = 0.45\left(\frac{\text{PI\%}}{100}\right)^{0.5}$~~ ~~for PI > 50%~~	~~Normally consolidated clay~~
	$\frac{c_u}{\sigma'_0} = 0.118\,(\text{LI})^{0.15}$ for LI = liquidity index > 0.5	Normally consolidated clay
Ladd, *et al.* (1977)	$\frac{\left(\frac{c_u}{\sigma'_0}\right)_{\text{overconsolidated}}}{\left(\frac{c_u}{\sigma'_0}\right)_{\text{normally consolidated}}} = \text{OCR}^{0.8}$ OCR = overconsolidation ratio = σ'_c/σ'_0	

Yields a function based on elevation.
Basically, Cu = 0.115*gamma*depth if above WT

Same except 0.116 instead of 0.115

Behling recommends.
Sets to 200 psf as conservative.

Yields a function based on elevation.
Basically, Cu = 0.115*gamma*depth if above WT

TABLE A.13 Empirical Soil Strength Relationships

Soil type	Equation	Reference
Normally consolidated clays	$\left(\frac{s_u}{\sigma'_z}\right)_{nc} = 0.11 + 0.0037\,\mathrm{PI}$	Skempton (1957)
	$\left(\frac{s_u}{\sigma'_{zo}}\right) = 0.22$	Mesri (1975)
~~Overconsolidated clays~~	~~$\frac{(s_u/\sigma'_z)_{oc}}{(s_u/\sigma'_z)_{nc}} = (\mathrm{OCR})^{0.8}$ See Note 1.~~	~~Ladd et al. (1977)~~
	~~$\frac{s_u}{\sigma'_z} = (0.23 \pm 0.04)\mathrm{OCR}^{0.8}$ See Note 1.~~	~~Jamiolkowski et al. (1985)~~
~~Clean quartz sand~~	~~$\phi'_p = \phi'_{cs} + 3D_r(10 - \ln p'_f) - 3$, where p'_f is~~ the mean effective stress at failure (in kPa) and D_r is relative density. This equation should only be used if $12 > (\phi'_p - \phi'_{cs}) > 0$.	~~Bolton (1986)~~

Note 1: These are applicable to direct simple shear tests. The estimated undrained shear strength from triaxial compression tests would be about 1.4 times greater.

Drained Strengths of Cohesive and Cohesionless Upper Soils

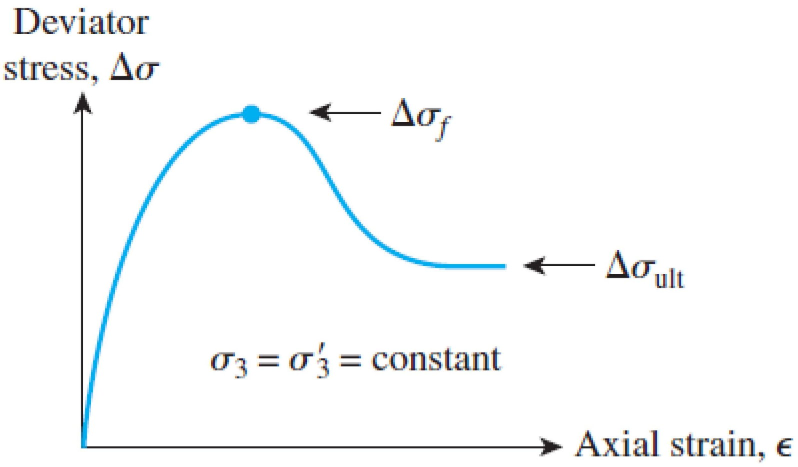


Figure 1.31 Plot of deviator stress versus axial strain–drained triaxial test

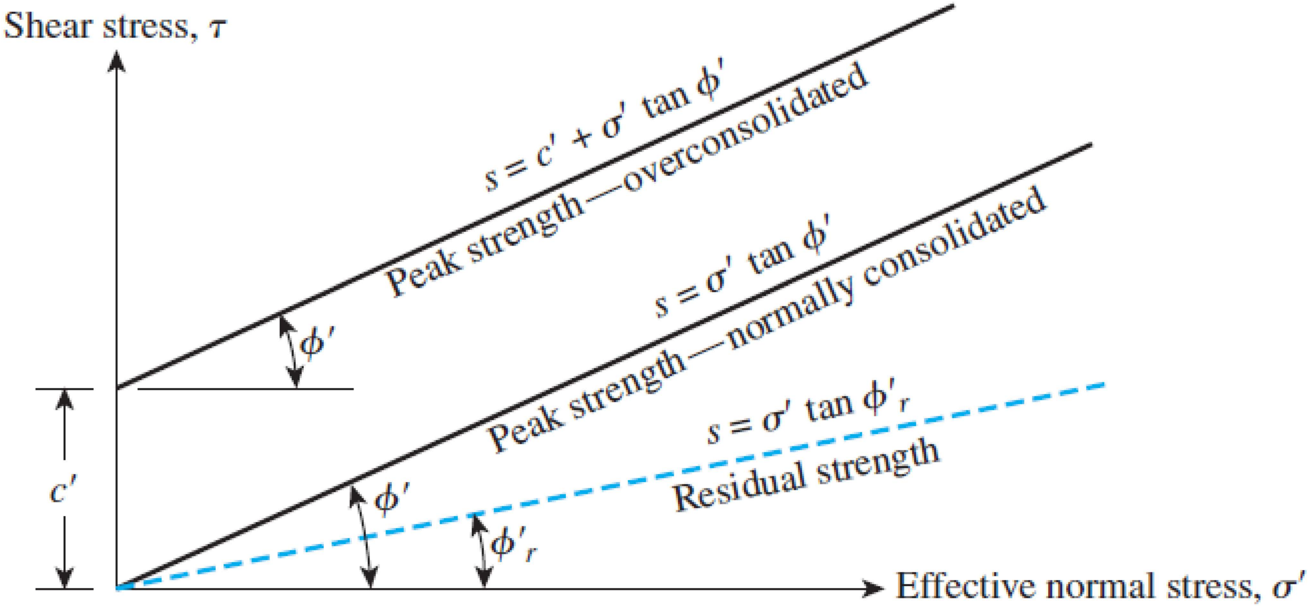

Shear stress, τ
$s = c' + \sigma' \tan\phi'$
Peak strength—overconsolidated
ϕ'
$s = \sigma' \tan\phi'$
Peak strength—normally consolidated
$s = \sigma' \tan\phi'_r$
Residual strength
c'
ϕ'
ϕ'_r
Effective normal stress, σ'

Figure 1.32 Peak- and residual-strength envelopes for clay

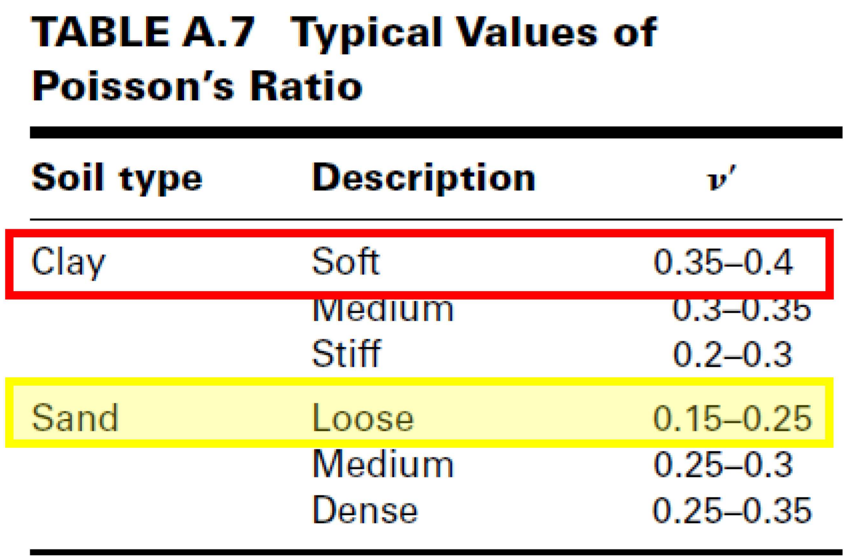


TABLE A.7 Typical Values of Poisson's Ratio

Soil type	Description	ν'
Clay	Soft	0.35–0.4
	Medium	0.3–0.35
	Stiff	0.2–0.3
Sand	Loose	0.15–0.25
	Medium	0.25–0.3
	Dense	0.25–0.35

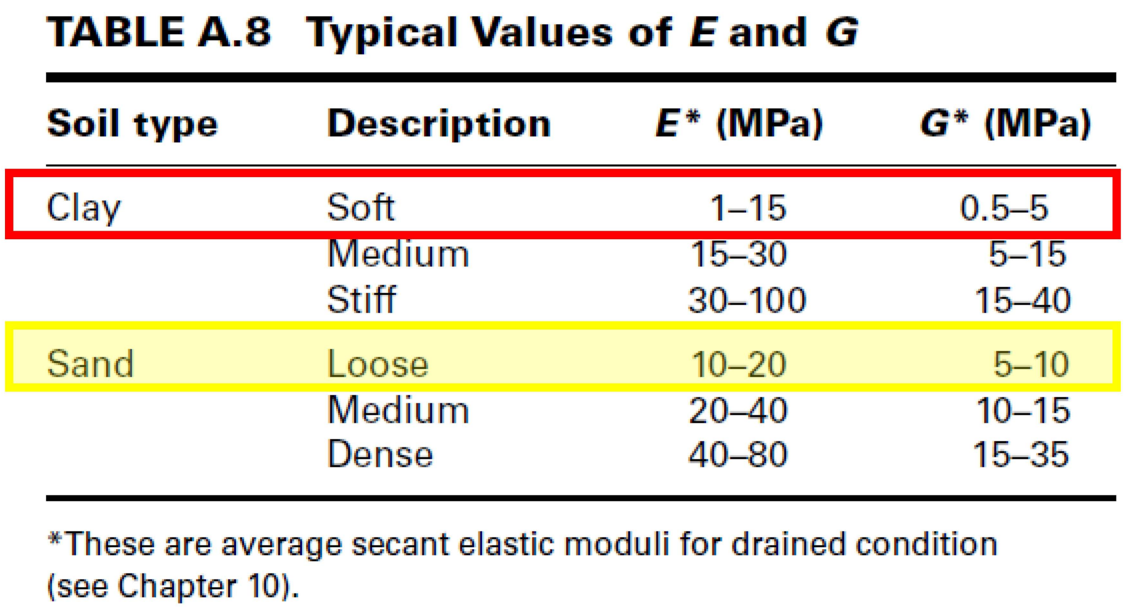


TABLE A.8 Typical Values of *E* and *G*

Soil type	Description	E* (MPa)	G* (MPa)
Clay	Soft	1–15	0.5–5
	Medium	15–30	5–15
	Stiff	30–100	15–40
Sand	Loose	10–20	5–10
	Medium	20–40	10–15
	Dense	40–80	15–35

*These are average secant elastic moduli for drained condition (see Chapter 10).

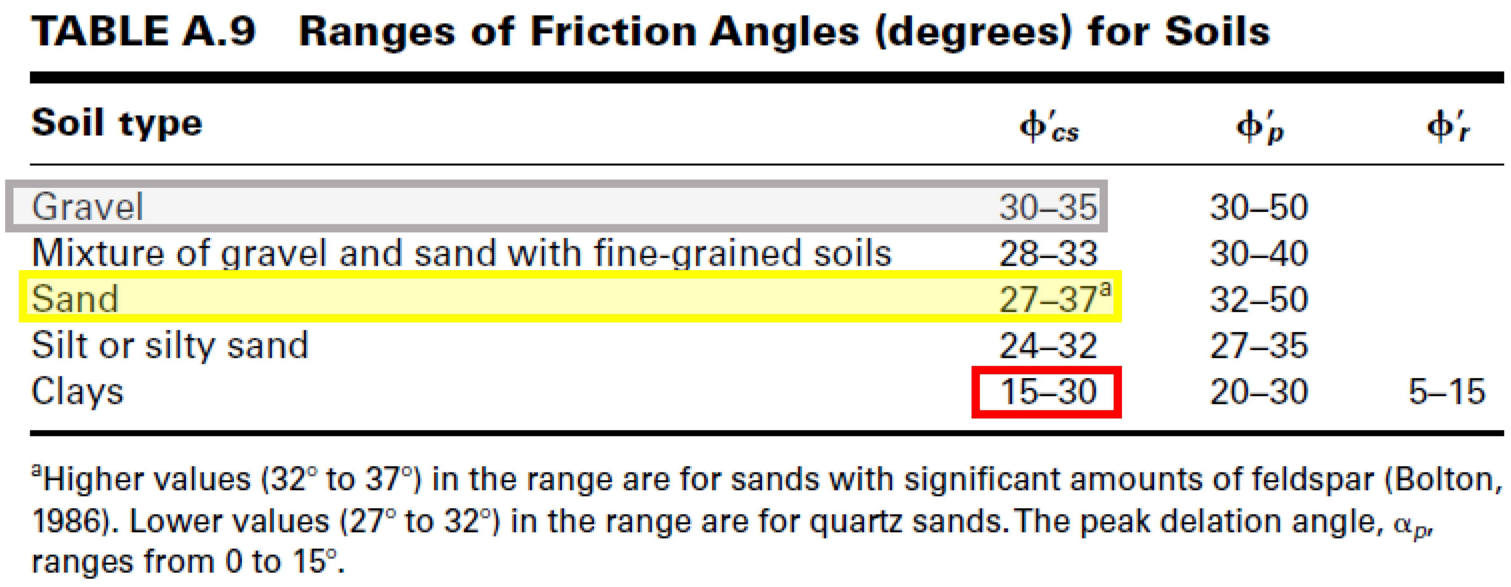
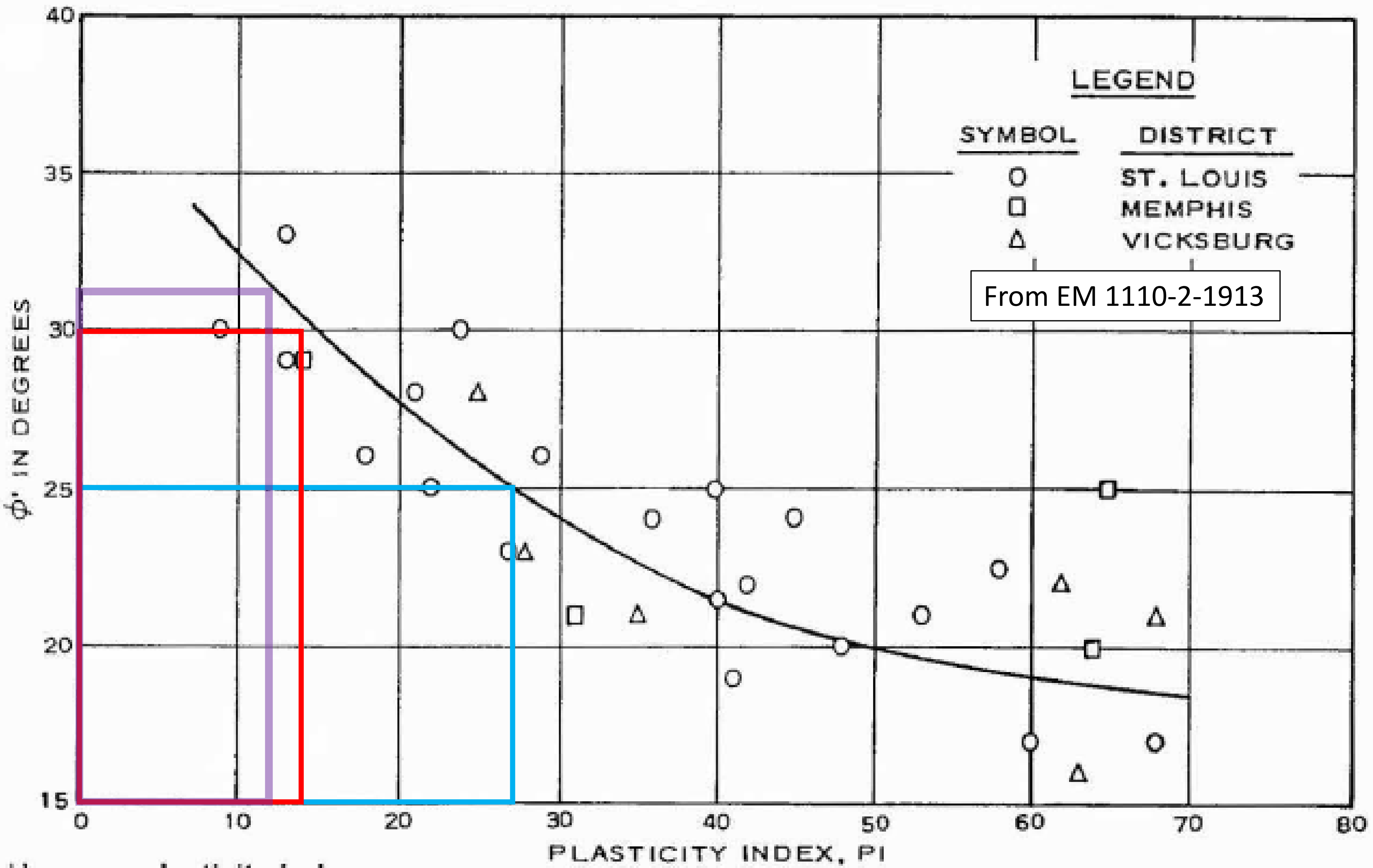


TABLE A.9 Ranges of Friction Angles (degrees) for Soils

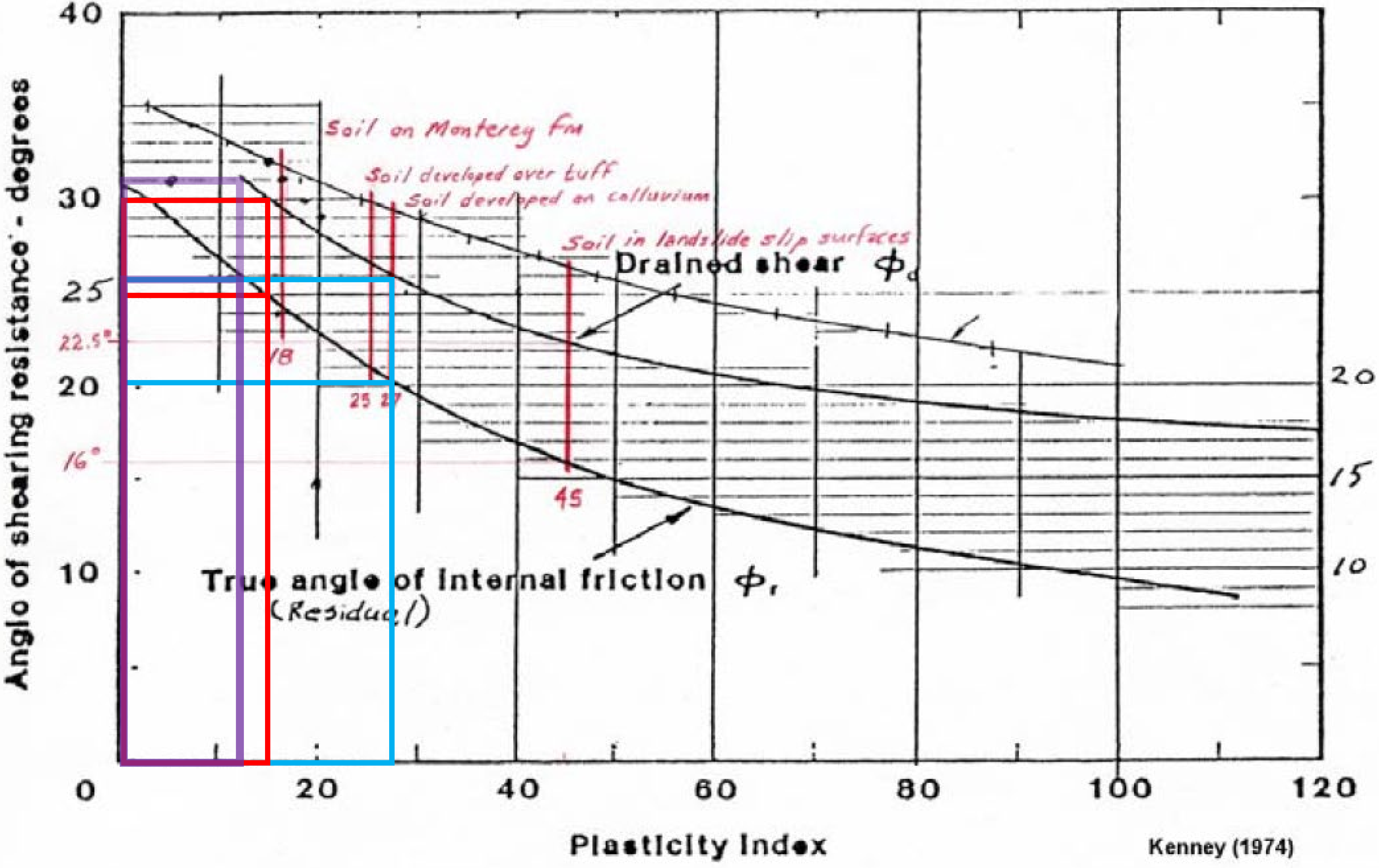
Soil type	ϕ'_{cs}	ϕ'_{p}	ϕ'_{r}
Gravel	30–35	30–50	
Mixture of gravel and sand with fine-grained soils	28–33	30–40	
Sand	27–37[a]	32–50	
Silt or silty sand	24–32	27–35	
Clays	15–30	20–30	5–15

[a] Higher values (32° to 37°) in the range are for sands with significant amounts of feldspar (Bolton, 1986). Lower values (27° to 32°) in the range are for quartz sands. The peak delation angle, α_p, ranges from 0 to 15°.

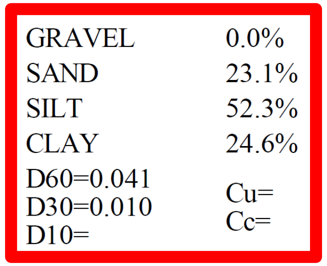


From EM 1110-2-1913

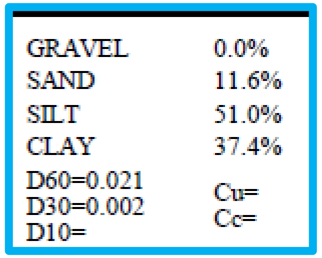
c. ϕ' versus plasticity index


40
30
25
22.5°
20
16°
10
0
20
15
10
20
40
60
80
100
120
Angle of shearing resistance - degrees
Plasticity Index
Soil on Monterey Fm
Soil developed over tuff
Soil developed on colluvium
Soil in landslide slip surfaces
Drained shear ϕ_d
True angle of internal friction ϕ_r
(Residual)
18
25
27
45

Kenney (1974)



GRAVEL	0.0%
SAND	23.1%
SILT	52.3%
CLAY	24.6%
D60=0.041	Cu=
D30=0.010	Cc=
D10=	



GRAVEL	0.0%
SAND	11.6%
SILT	51.0%
CLAY	37.4%
D60=0.021	Cu=
D30=0.002	Cc=
D10=	

1. If CF is less than about 15%, then ϕ'_r is greater than about 25°.
2. For CF > about 50%, ϕ'_r is entirely governed by the sliding of clay minerals and may be in the range of about 10 to 15°.
3. For kaolinite, illite, and montmorillonite, ϕ'_r is about 15°, 10°, and 5°, respectively.

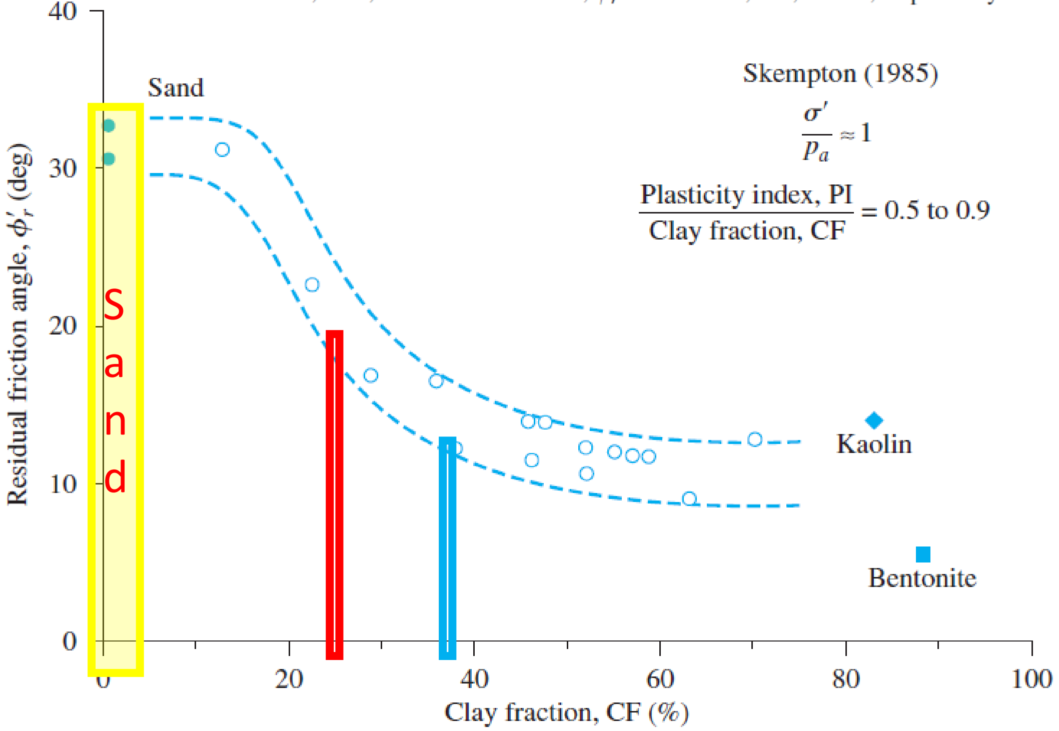


Figure 1.33 Variation of ϕ'_r with CF (*Note:* p_a = atmospheric pressure)

Reasonable Values for clay residual friction based on CF in this graph: 20° to 14°

Sand: 30°

Effective Stress Friction Angle of Cohesive Soils

Figure 1.30 shows the variation of effective stress friction angle, ϕ', for several normally consolidated clays (Bjerrum and Simons, 1960; Kenney, 1959). It can be seen from the figure that, in general, the friction angle ϕ' decreases with the increase in plasticity index. The value of ϕ' generally decreases from about 37 to 38° with a plasticity index of about 10 to about 25° or less with a plasticity index of about 100. The consolidated undrained friction angle (ϕ) of normally consolidated saturated clays generally ranges from 5 to 20°.

$$\sin(\phi') = 0.5$$
$$\phi' = 30^\circ$$

Range of 0.6 to 0.4 is
36.8° to 23.6° respectively

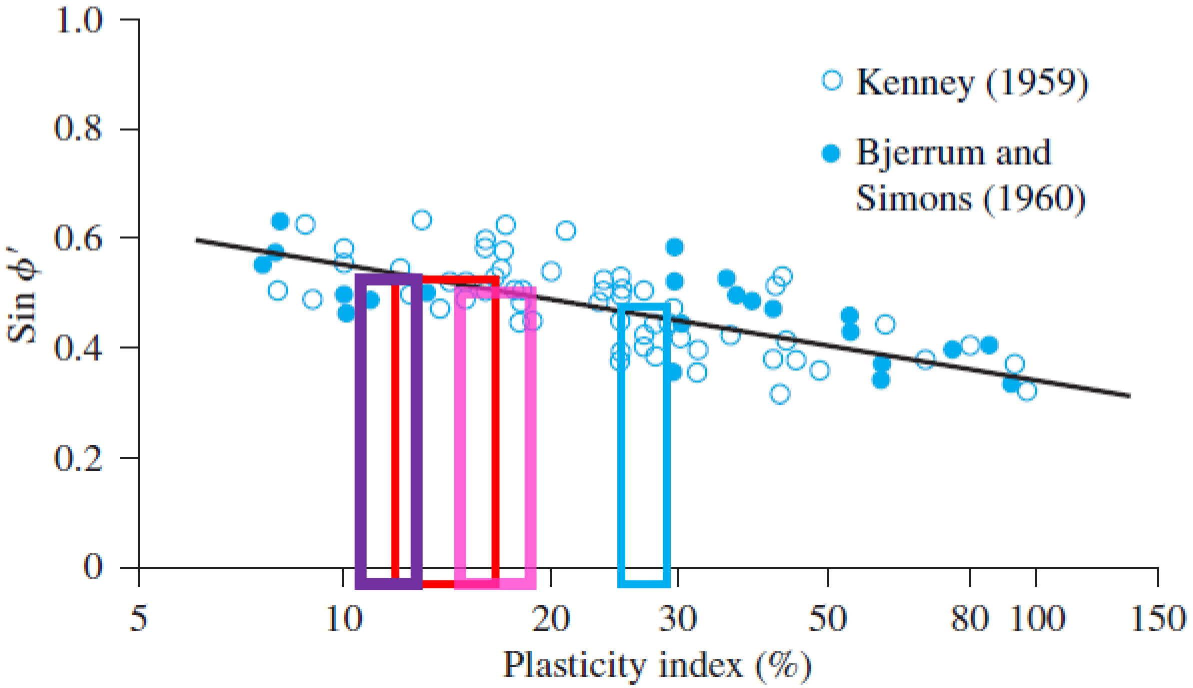


Figure 1.30 Variation of sin ϕ' with plasticity index (PI) for several normally consolidated clays

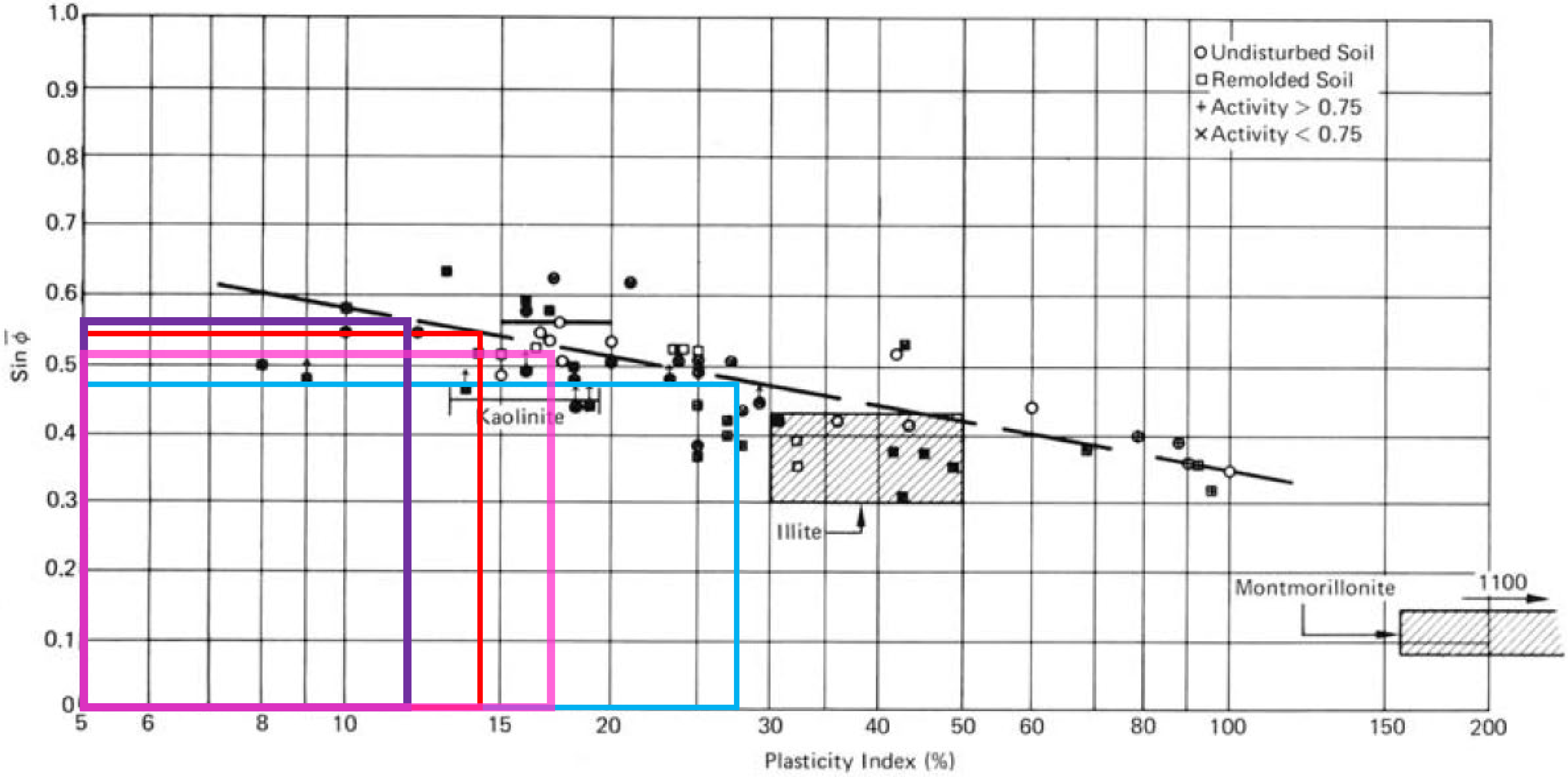
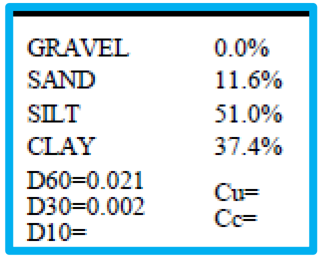
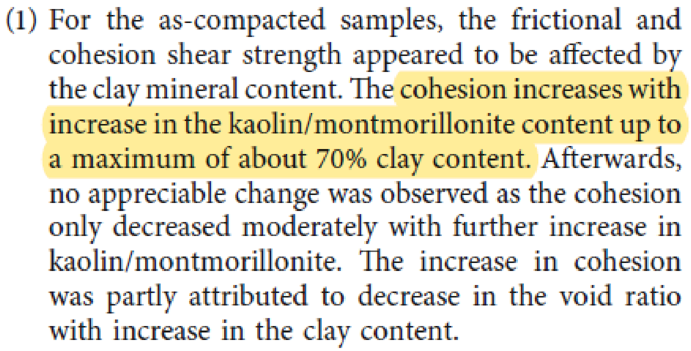


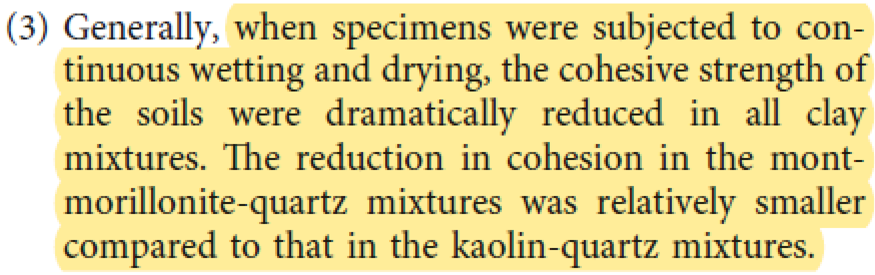
Figure 8 – *Relationship between sin Ø‘ and plasticity index for normally consolidated soils, using data from Kenney (1959) and Olson (1974). Note how montmorillonitic clay plots off the chart to right.*



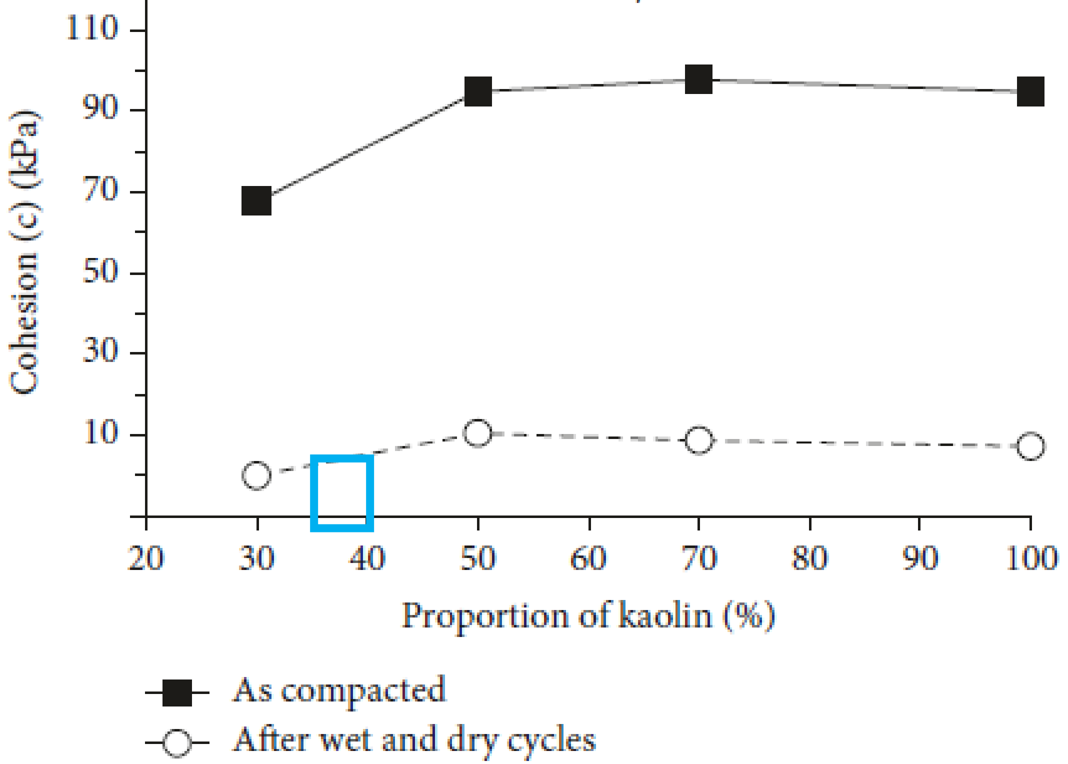
GRAVEL	0.0%
SAND	11.6%
SILT	51.0%
CLAY	37.4%
D60=0.021	Cu=
D30=0.002	Cc=
D10=	

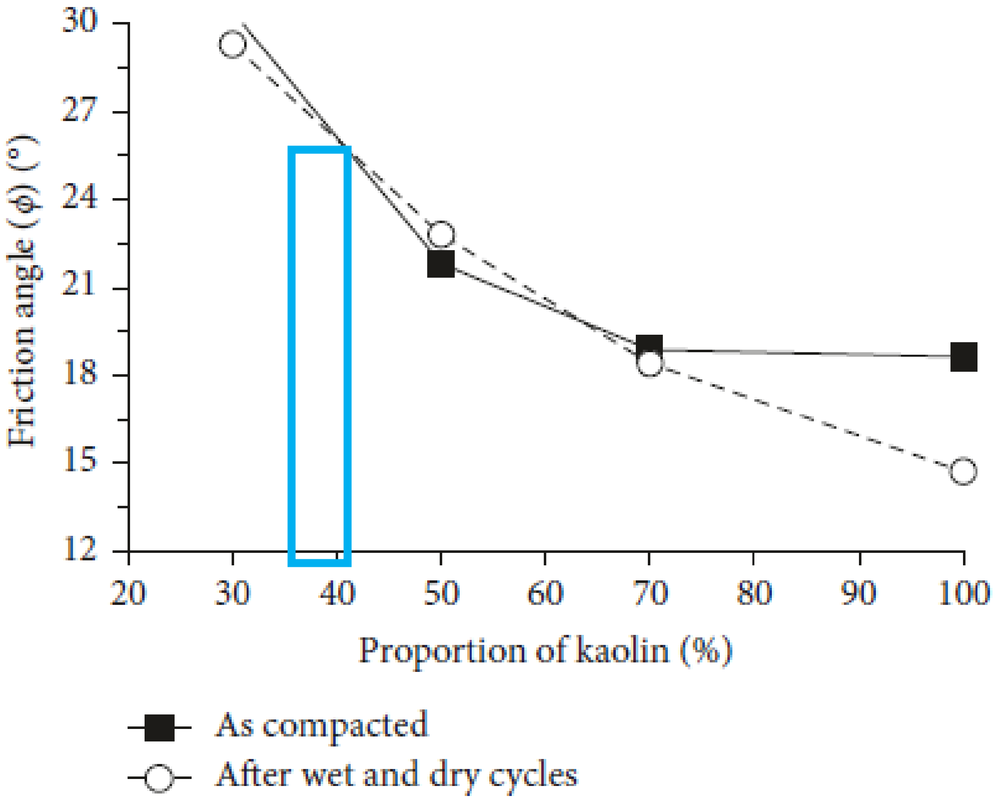


(1) For the as-compacted samples, the frictional and cohesion shear strength appeared to be affected by the clay mineral content. The cohesion increases with increase in the kaolin/montmorillonite content up to a maximum of about 70% clay content. Afterwards, no appreciable change was observed as the cohesion only decreased moderately with further increase in kaolin/montmorillonite. The increase in cohesion was partly attributed to decrease in the void ratio with increase in the clay content.



(3) Generally, when specimens were subjected to continuous wetting and drying, the cohesive strength of the soils were dramatically reduced in all clay mixtures. The reduction in cohesion in the montmorillonite-quartz mixtures was relatively smaller compared to that in the kaolin-quartz mixtures.





Implying ~100 psf (5 kPa) would be reasonable for cohesion…

…but a friction angle of ~25° if clays 100% kaolin…

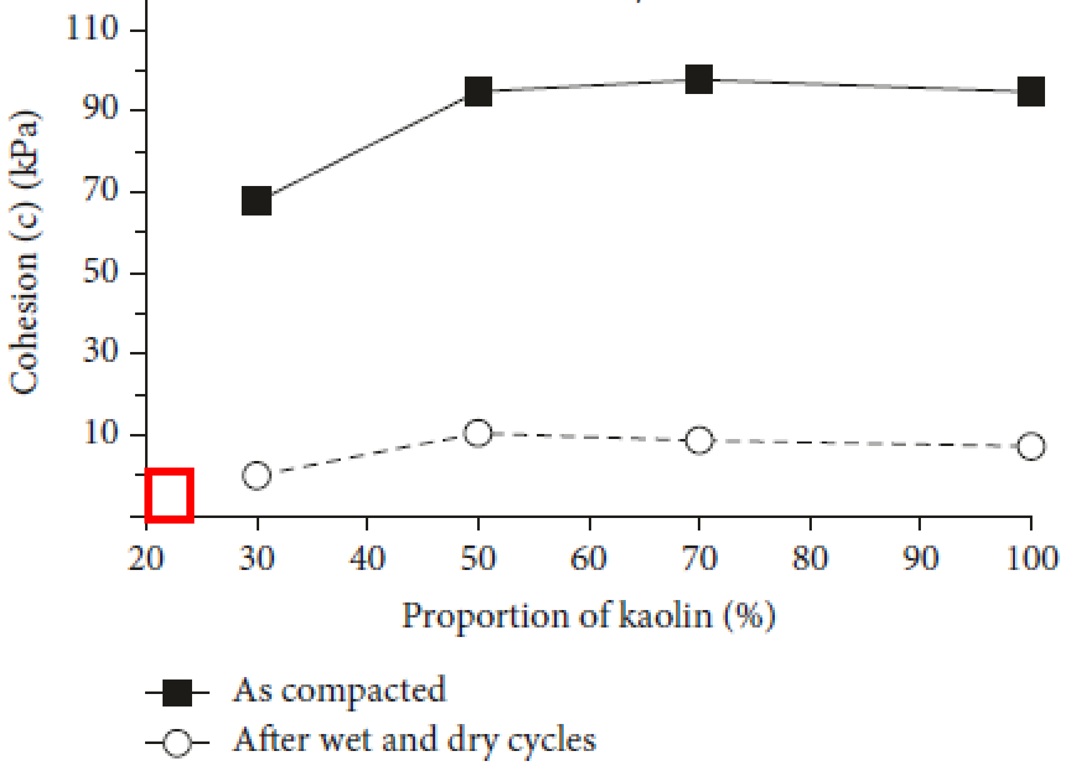
GRAVEL	0.0%
SAND	23.1%
SILT	52.3%
CLAY	24.6%

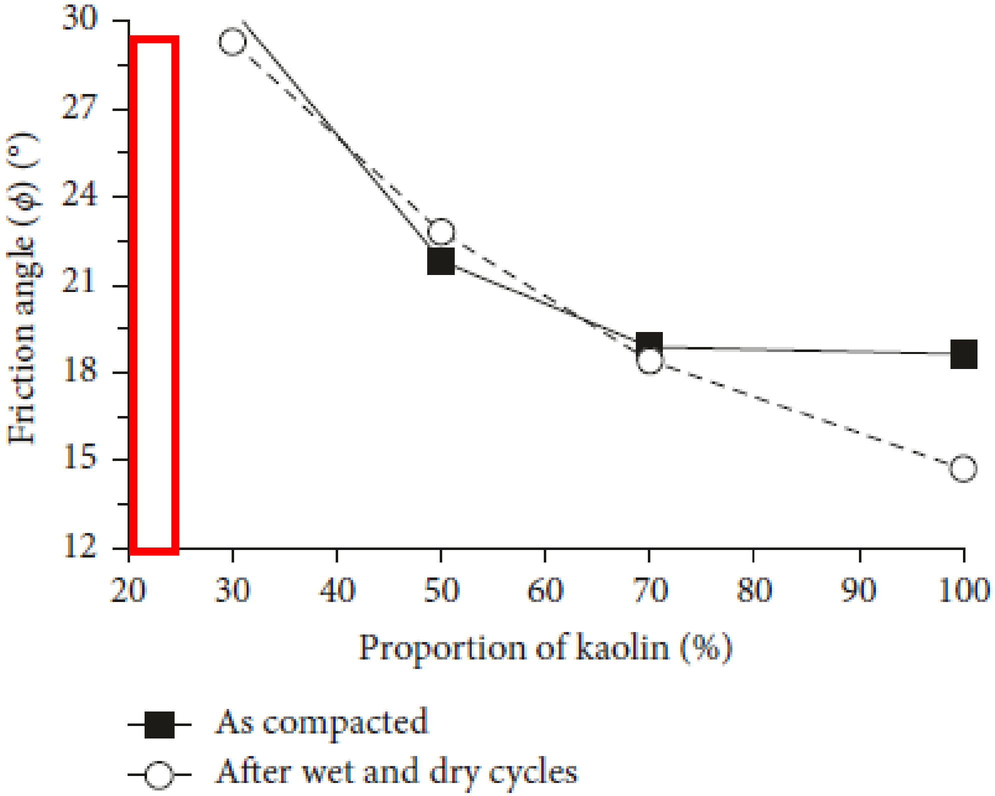
D60=0.041
D30=0.010
	Cu=

D10=	Cc=

(1) For the as-compacted samples, the frictional and cohesion shear strength appeared to be affected by the clay mineral content. The cohesion increases with increase in the kaolin/montmorillonite content up to a maximum of about 70% clay content. Afterwards, no appreciable change was observed as the cohesion only decreased moderately with further increase in kaolin/montmorillonite. The increase in cohesion was partly attributed to decrease in the void ratio with increase in the clay content.

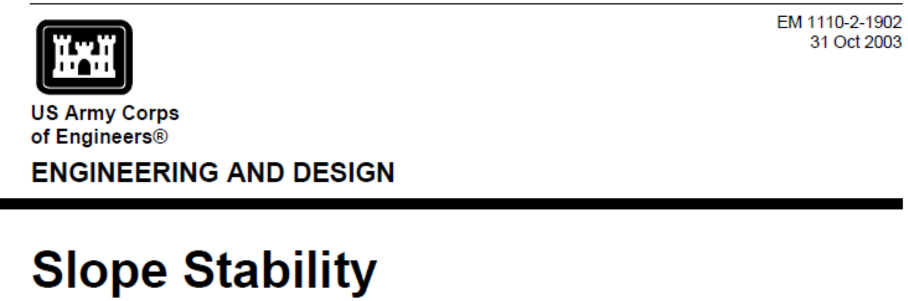
(3) Generally, when specimens were subjected to continuous wetting and drying, the cohesive strength of the soils were dramatically reduced in all clay mixtures. The reduction in cohesion in the montmorillonite-quartz mixtures was relatively smaller compared to that in the kaolin-quartz mixtures.





Implying ~100 psf (5 kPa) would be reasonable for cohesion…

…but a friction angle of ~28° if clays 100% kaolin…



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ENGINEERING AND DESIGN

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31 Oct 2003

Slope Stability

Tension Crack

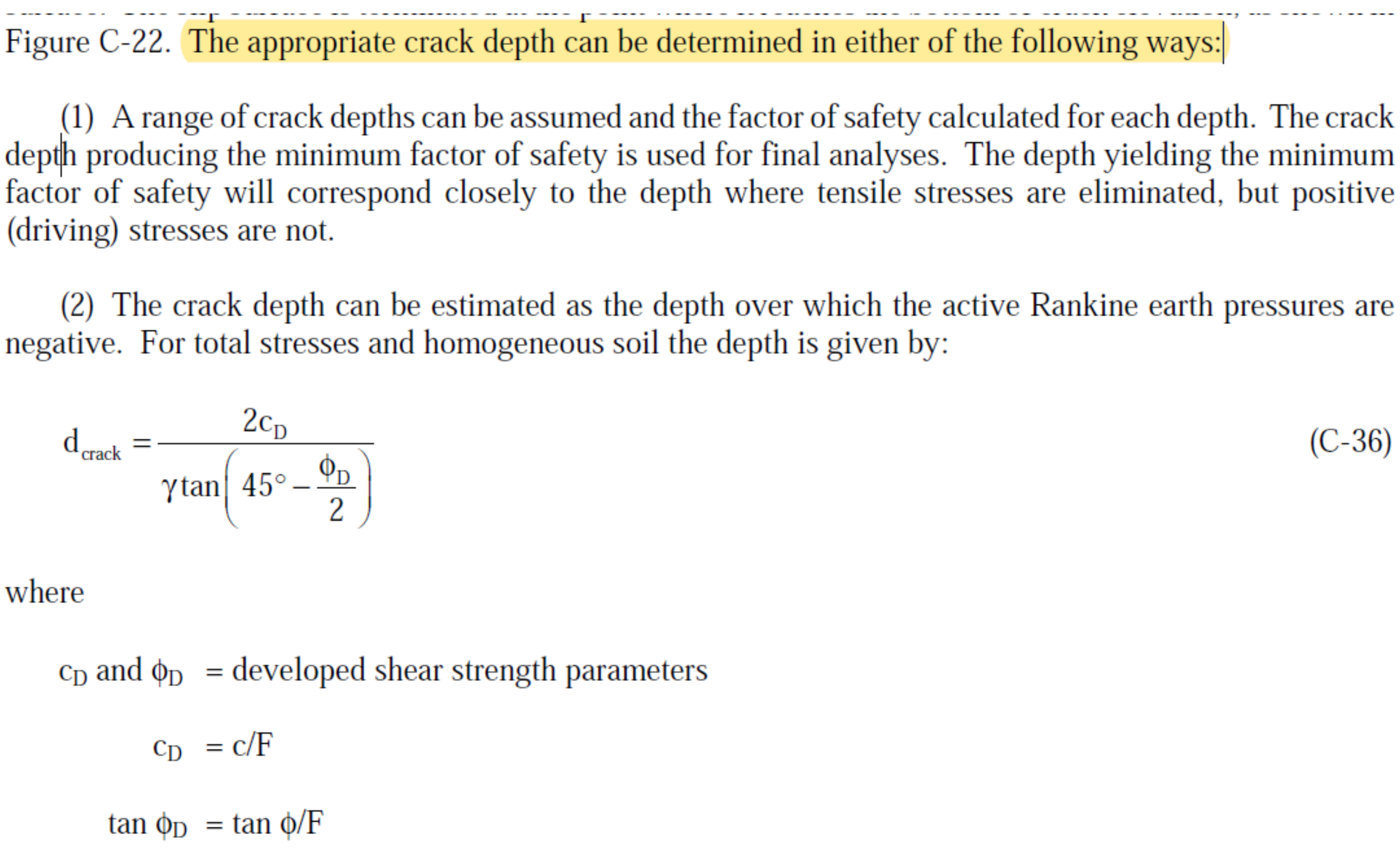


Figure C-22. The appropriate crack depth can be determined in either of the following ways:

(1) A range of crack depths can be assumed and the factor of safety calculated for each depth. The crack depth producing the minimum factor of safety is used for final analyses. The depth yielding the minimum factor of safety will correspond closely to the depth where tensile stresses are eliminated, but positive (driving) stresses are not.

(2) The crack depth can be estimated as the depth over which the active Rankine earth pressures are negative. For total stresses and homogeneous soil the depth is given by:

$$d_{crack} = \frac{2c_D}{\gamma \tan\left(45^\circ - \frac{\phi_D}{2}\right)} \qquad \text{(C-36)}$$

where

c_D and ϕ_D = developed shear strength parameters

$c_D = c/F$

$\tan \phi_D = \tan \phi / F$

Tension Crack

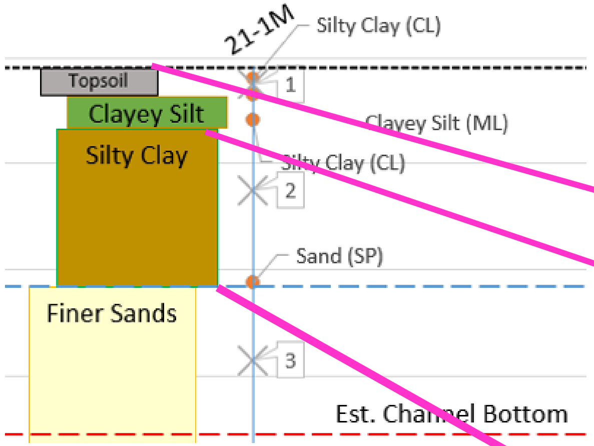
$$d_{crack} = \frac{2c_D}{\gamma \tan\left(45° - \frac{\phi_D}{2}\right)}$$

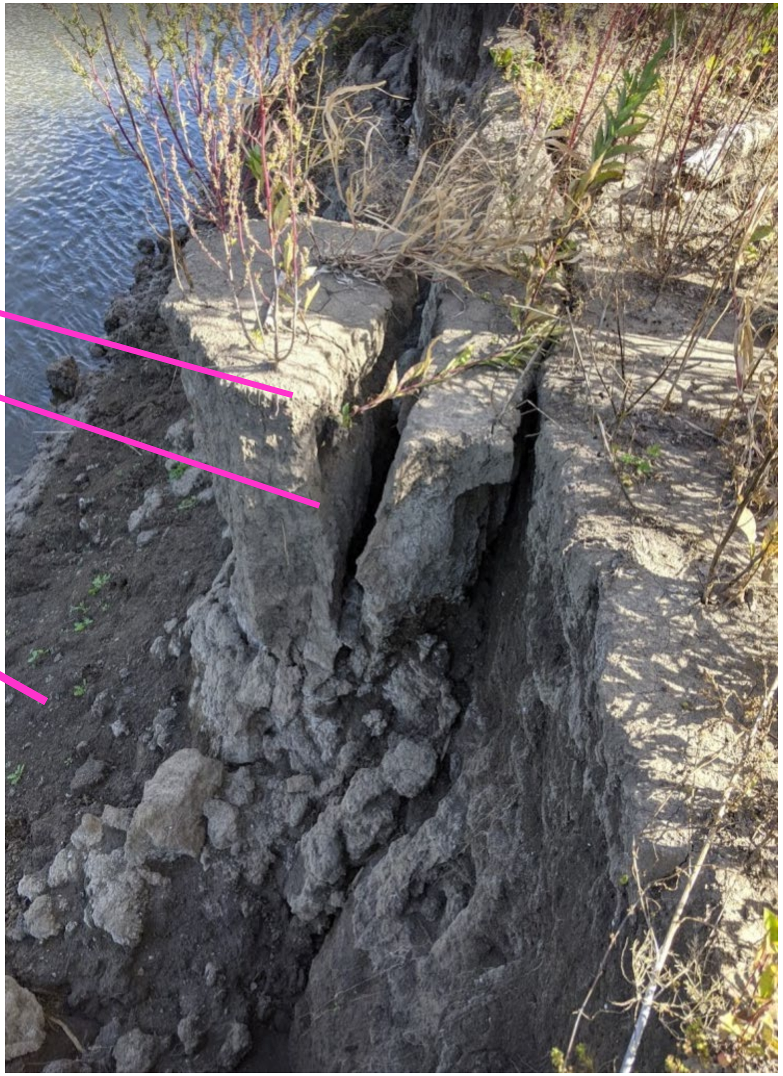
where

c_D and ϕ_D = developed shear strength parameters

c_D = c/F

$\tan \phi_D$ = $\tan \phi$/F





$$d_{crack\ SSS} = \frac{2 * 100\ psf}{115\ pcf\ * \tan\left(45° - \frac{20°}{2}\right)} = 2.48\ ft$$

$$d_{crack\ EOC} = \frac{2 * 200\ psf}{115\ pcf\ * \tan\left(45° - \frac{0°}{2}\right)} = 3.48\ ft$$

Seems reasonable for some cohesion given field evidence.

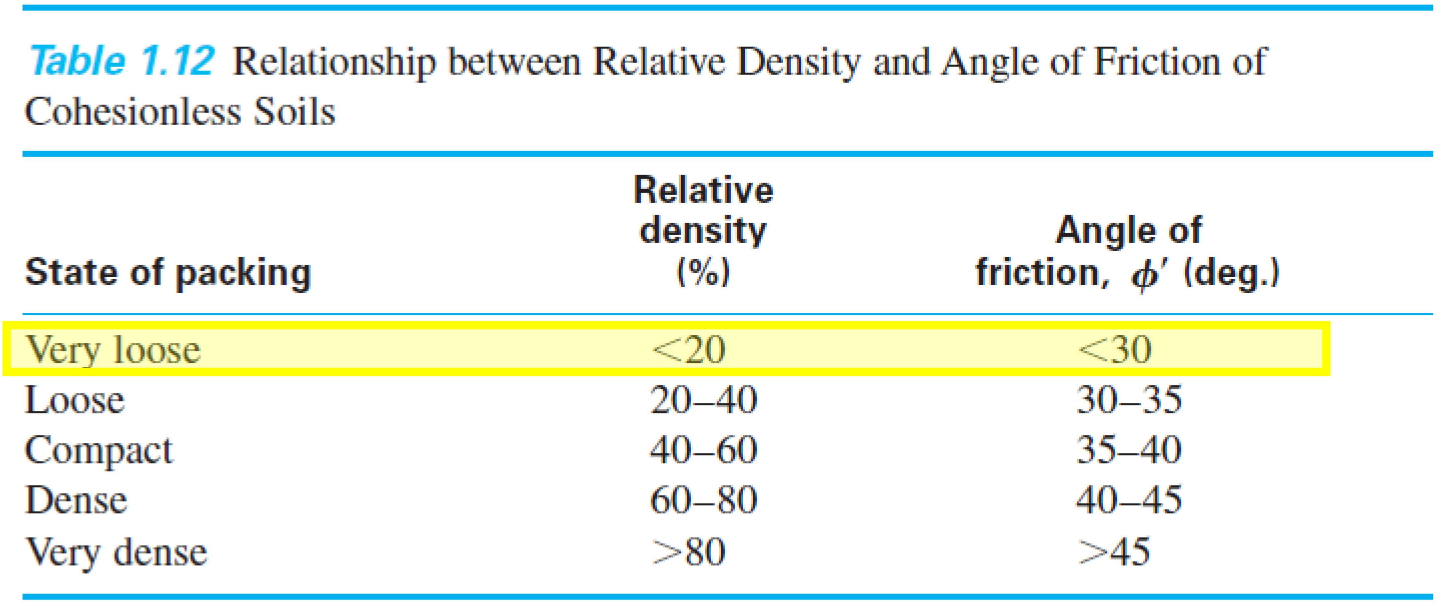


Table 1.12 Relationship between Relative Density and Angle of Friction of Cohesionless Soils

State of packing	**Relative density (%)**	**Angle of friction, ϕ' (deg.)**
Very loose	<20	<30
Loose	20–40	30–35
Compact	40–60	35–40
Dense	60–80	40–45
Very dense	>80	>45

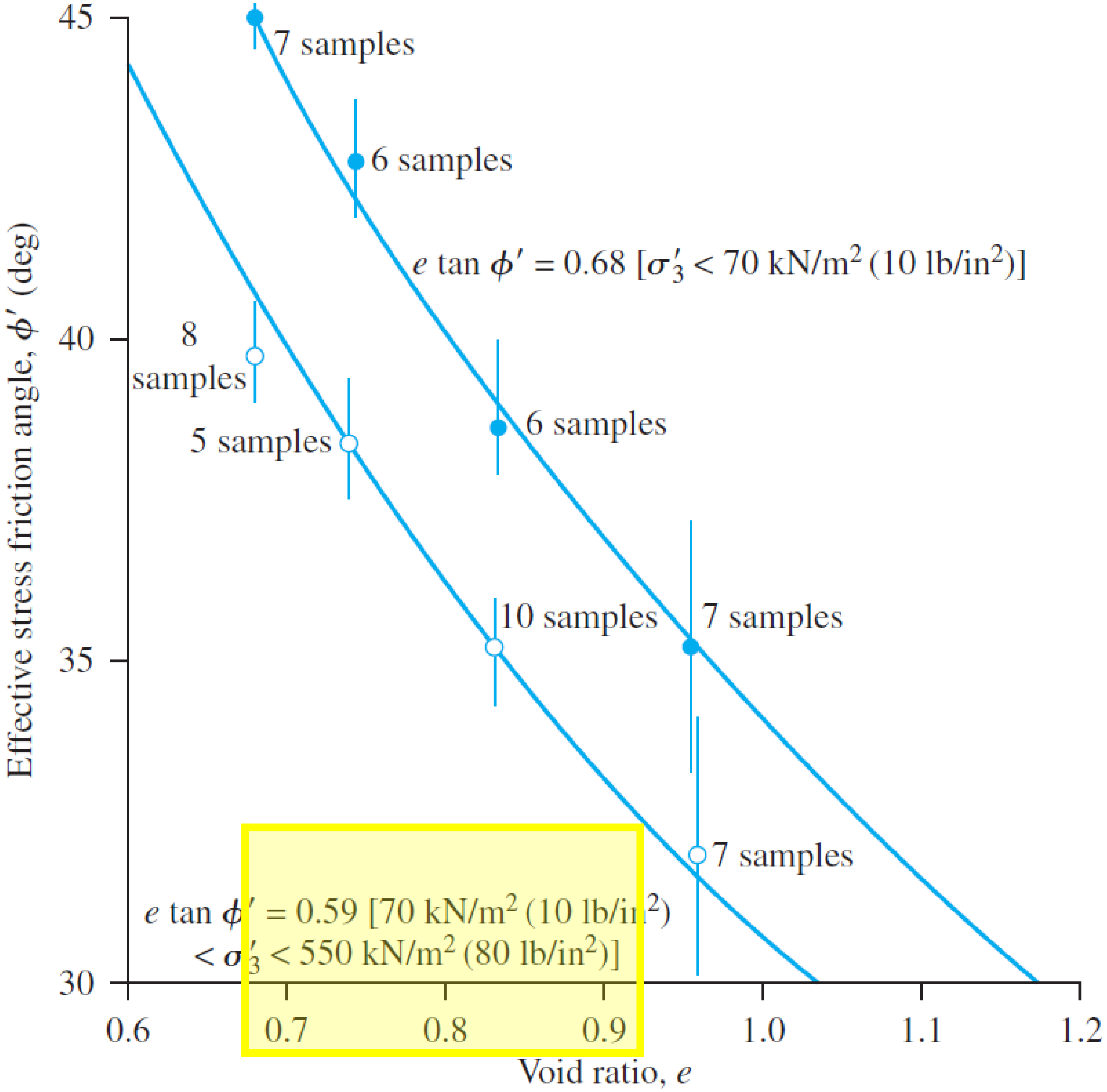
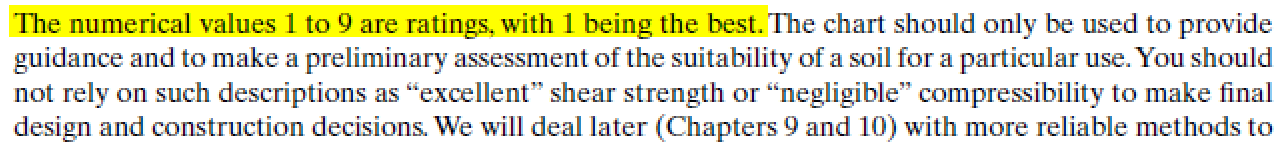
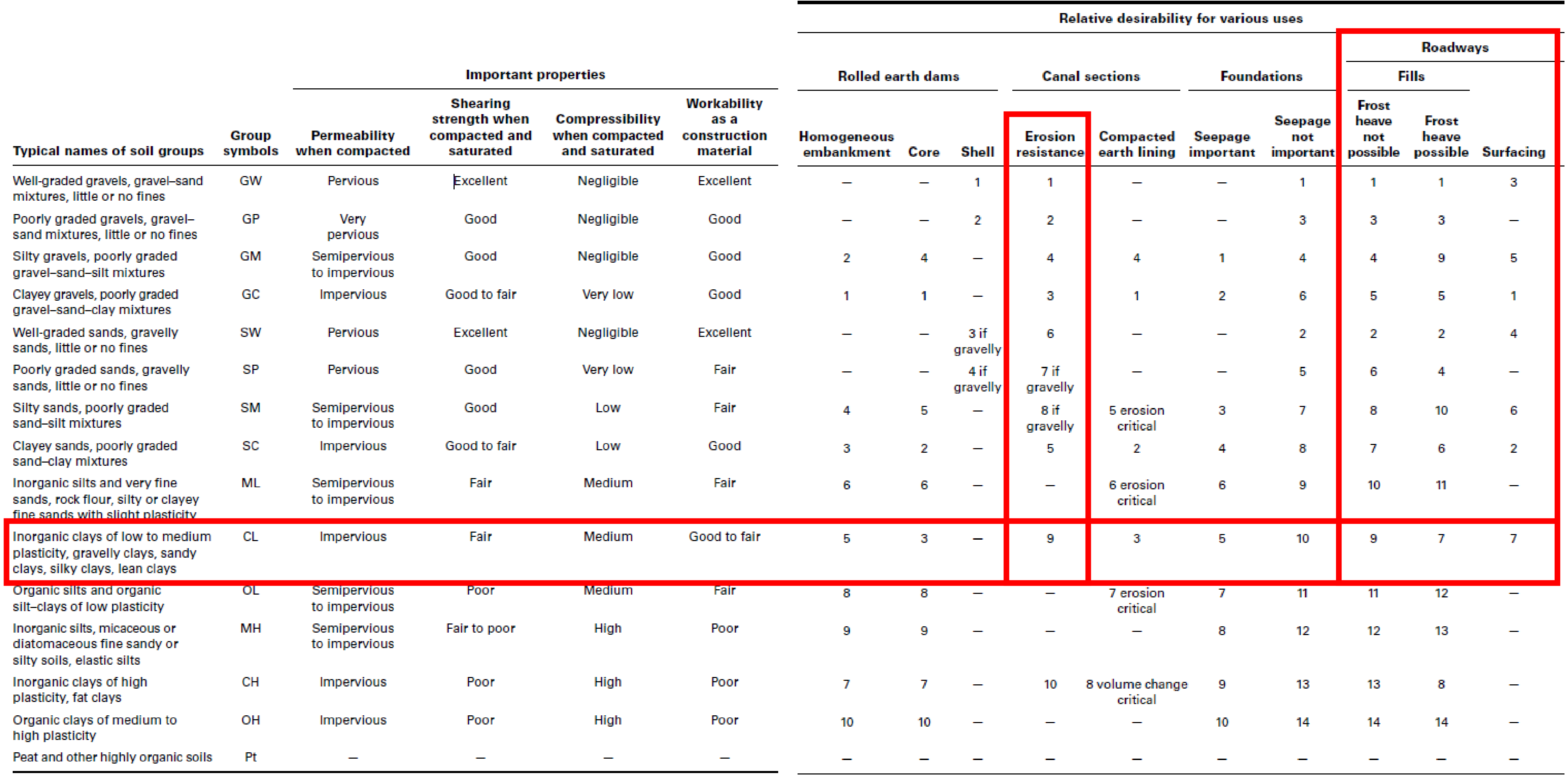


Figure 1.29 Variation of friction angle ϕ' with void ratio for Chattachoochee River sand (After Vesic, 1963) (From Vesic, A. B. Bearing Capacity of Deep Foundations in Sand. In Highway Research Record 39, Highway Research Board, National Research Council, Washington, D.C., 1963, Figure 11, p. 123. Reproduced with permission of the Transportation Research Board.)



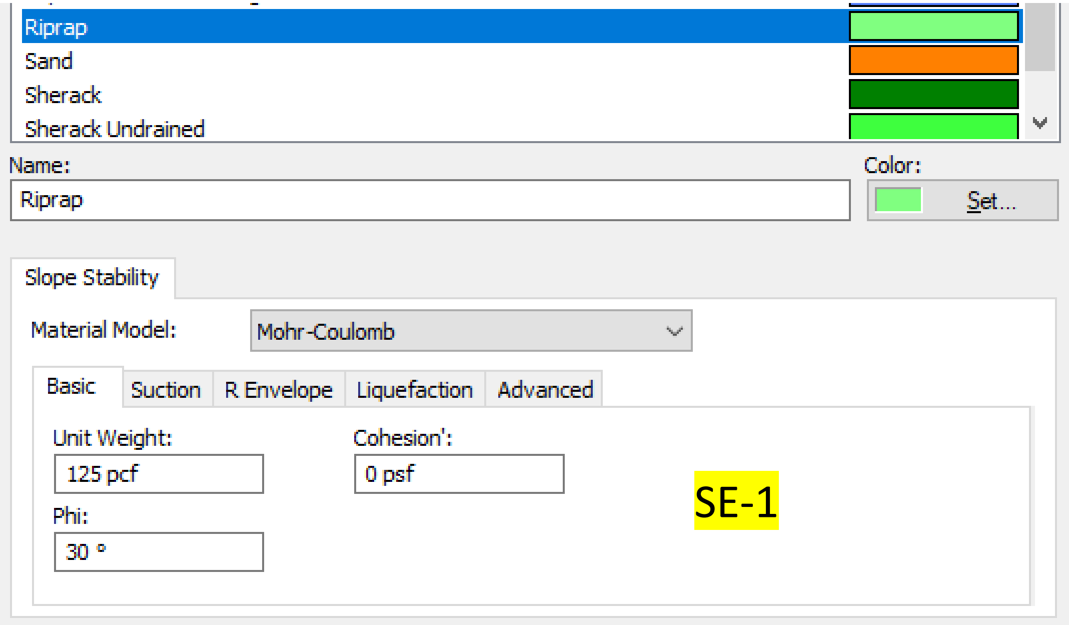
The numerical values 1 to 9 are ratings, with 1 being the best. The chart should only be used to provide guidance and to make a preliminary assessment of the suitability of a soil for a particular use. You should not rely on such descriptions as "excellent" shear strength or "negligible" compressibility to make final design and construction decisions. We will deal later (Chapters 9 and 10) with more reliable methods to

Budhu, pg. 77



		Important properties				Relative desirability for various uses									
						Rolled earth dams			Canal sections		Foundations		Roadways		
													Fills		
Typical names of soil groups	**Group symbols**	**Permeability when compacted**	**Shearing strength when compacted and saturated**	**Compressibility when compacted and saturated**	**Workability as a construction material**	**Homogeneous embankment**	**Core**	**Shell**	**Erosion resistance**	**Compacted earth lining**	**Seepage important**	**Seepage not important**	**Frost heave not possible**	**Frost heave possible**	**Surfacing**
Well-graded gravels, gravel–sand mixtures, little or no fines	GW	Pervious	Excellent	Negligible	Excellent	—	—	1	1	—	—	1	1	1	3
Poorly graded gravels, gravel–sand mixtures, little or no fines	GP	Very pervious	Good	Negligible	Good	—	—	2	2	—	—	3	3	3	—
Silty gravels, poorly graded gravel–sand–silt mixtures	GM	Semipervious to impervious	Good	Negligible	Good	2	4	—	4	4	1	4	4	9	5
Clayey gravels, poorly graded gravel–sand–clay mixtures	GC	Impervious	Good to fair	Very low	Good	1	1	—	3	1	2	6	5	5	1
Well-graded sands, gravelly sands, little or no fines	SW	Pervious	Excellent	Negligible	Excellent	—	—	3 if gravelly	6	—	—	2	2	2	4
Poorly graded sands, gravelly sands, little or no fines	SP	Pervious	Good	Very low	Fair	—	—	4 if gravelly	7 if gravelly	—	—	5	6	4	—
Silty sands, poorly graded sand–silt mixtures	SM	Semipervious to impervious	Good	Low	Fair	4	5	—	8 if gravelly	5 erosion critical	3	7	8	10	6
Clayey sands, poorly graded sand–clay mixtures	SC	Impervious	Good to fair	Low	Good	3	2	—	5	2	4	8	7	6	2
Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	ML	Semipervious to impervious	Fair	Medium	Fair	6	6	—	—	6 erosion critical	6	9	10	11	—
Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silky clays, lean clays	CL	Impervious	Fair	Medium	Good to fair	5	3	—	9	3	5	10	9	7	7
Organic silts and organic silt–clays of low plasticity	OL	Semipervious to impervious	Poor	Medium	Fair	8	8	—	—	7 erosion critical	7	11	11	12	—
Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	MH	Semipervious to impervious	Fair to poor	High	Poor	9	9	—	—	—	8	12	12	13	—
Inorganic clays of high plasticity, fat clays	CH	Impervious	Poor	High	Poor	7	7	—	10	8 volume change critical	9	13	13	8	—
Organic clays of medium to high plasticity	OH	Impervious	Poor	High	Poor	10	10	—	—	—	10	14	14	14	—
Peat and other highly organic soils	Pt	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Riprap Parameters



Riprap 🟩
Sand 🟧
Sherack 🟩
Sherack Undrained 🟩

Name: Riprap

Color: 🟩

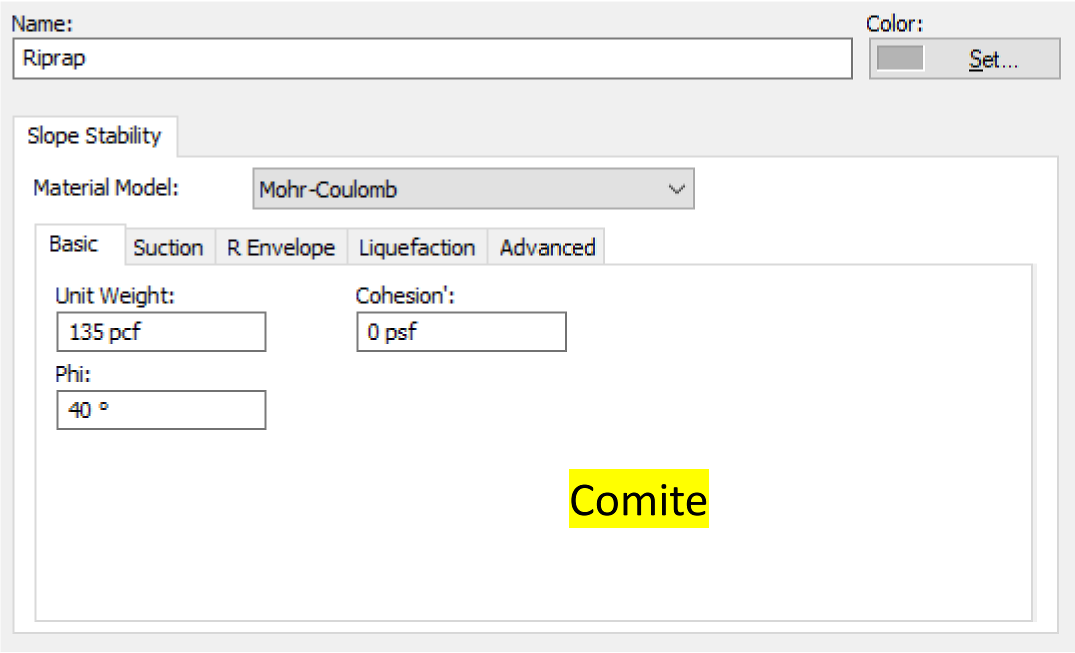
Material Model: Mohr-Coulomb

Unit Weight: 125 pcf

Cohesion': 0 psf

Phi: 30 °

SE-1



Name: Riprap

Color: ⬜

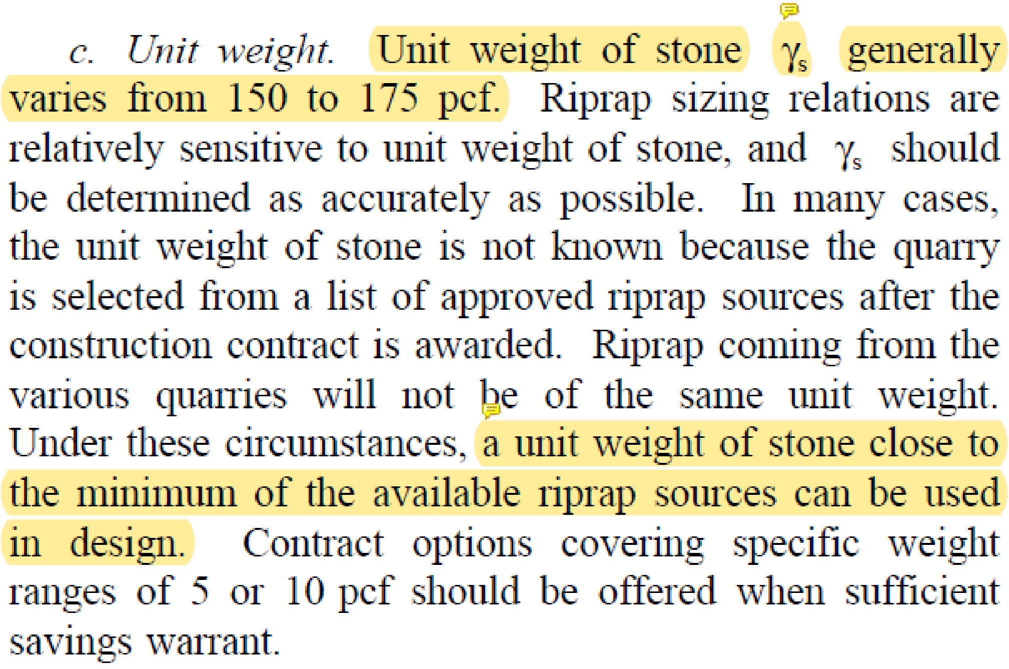
Material Model: Mohr-Coulomb

Unit Weight: 135 pcf

Cohesion': 0 psf

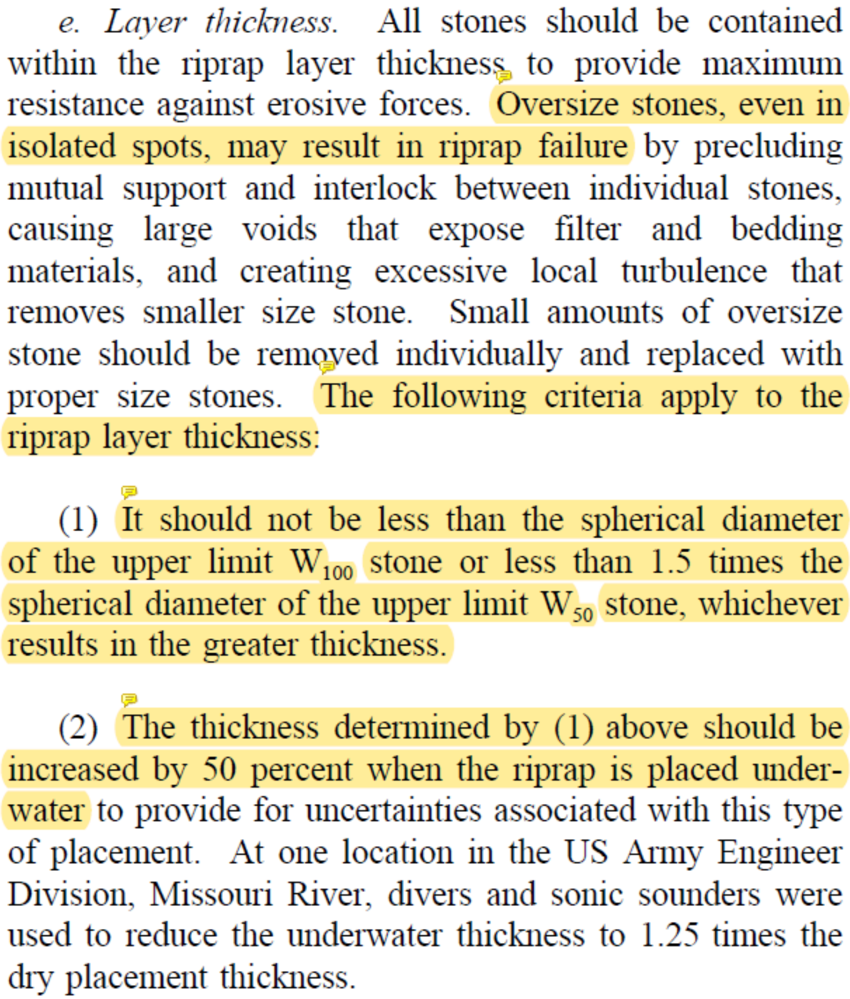
Phi: 40 °

Comite



c. *Unit weight.* Unit weight of stone γ_s generally varies from 150 to 175 pcf. Riprap sizing relations are relatively sensitive to unit weight of stone, and γ_s should be determined as accurately as possible. In many cases, the unit weight of stone is not known because the quarry is selected from a list of approved riprap sources after the construction contract is awarded. Riprap coming from the various quarries will not be of the same unit weight. Under these circumstances, a unit weight of stone close to the minimum of the available riprap sources can be used in design. Contract options covering specific weight ranges of 5 or 10 pcf should be offered when sufficient savings warrant.

Section Thickness? SEE REQUIREMENTS



e. Layer thickness. All stones should be contained within the riprap layer thickness to provide maximum resistance against erosive forces. Oversize stones, even in isolated spots, may result in riprap failure by precluding mutual support and interlock between individual stones, causing large voids that expose filter and bedding materials, and creating excessive local turbulence that removes smaller size stone. Small amounts of oversize stone should be removed individually and replaced with proper size stones. The following criteria apply to the riprap layer thickness:

(1) It should not be less than the spherical diameter of the upper limit W_{100} stone or less than 1.5 times the spherical diameter of the upper limit W_{50} stone, whichever results in the greater thickness.

(2) The thickness determined by (1) above should be increased by 50 percent when the riprap is placed underwater to provide for uncertainties associated with this type of placement. At one location in the US Army Engineer Division, Missouri River, divers and sonic sounders were used to reduce the underwater thickness to 1.25 times the dry placement thickness.

Weathered Rock

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Section III
Soil-Rock Contacts

12-12. General

Some of the most difficult excavation problems occur in rock that has been severely weathered or altered. While it is generally assumed that bedrock will be easy to locate and identify, the assumption may not always be correct. In some cases, weathering can form a residual soil that grades into unweathered bedrock, with several rock-like soil or soil-like rock transitions in between. These residual soils, saprolites, and weathered rocks require special consideration, since they may have characteristics of both rock and soil which affect rock excavations and foundation performance.

c. Metamorphic profiles. Since the structure or texture of metamorphic rocks can range from schistose to nearly massive gneissic, the weathering profiles can vary greatly, as illustrated in Figure 12-5. Foliations in the rocks and changes of the lithology enhance the variability that can be found in the weathering profiles in metamorphics. The results are differences in the depths of weathering profiles developed over each lithology, in some cases up to 50 meters of difference vertically in just a few feet horizontally (Deere and Patton 1971). Intrusive dikes commonly found in metamorphic terrains may either be more or less resistant to weathering than the surrounding rock, forming either ridges or very deep weathering profiles. Problems in this type of profile include slide instability along relict foliation planes,

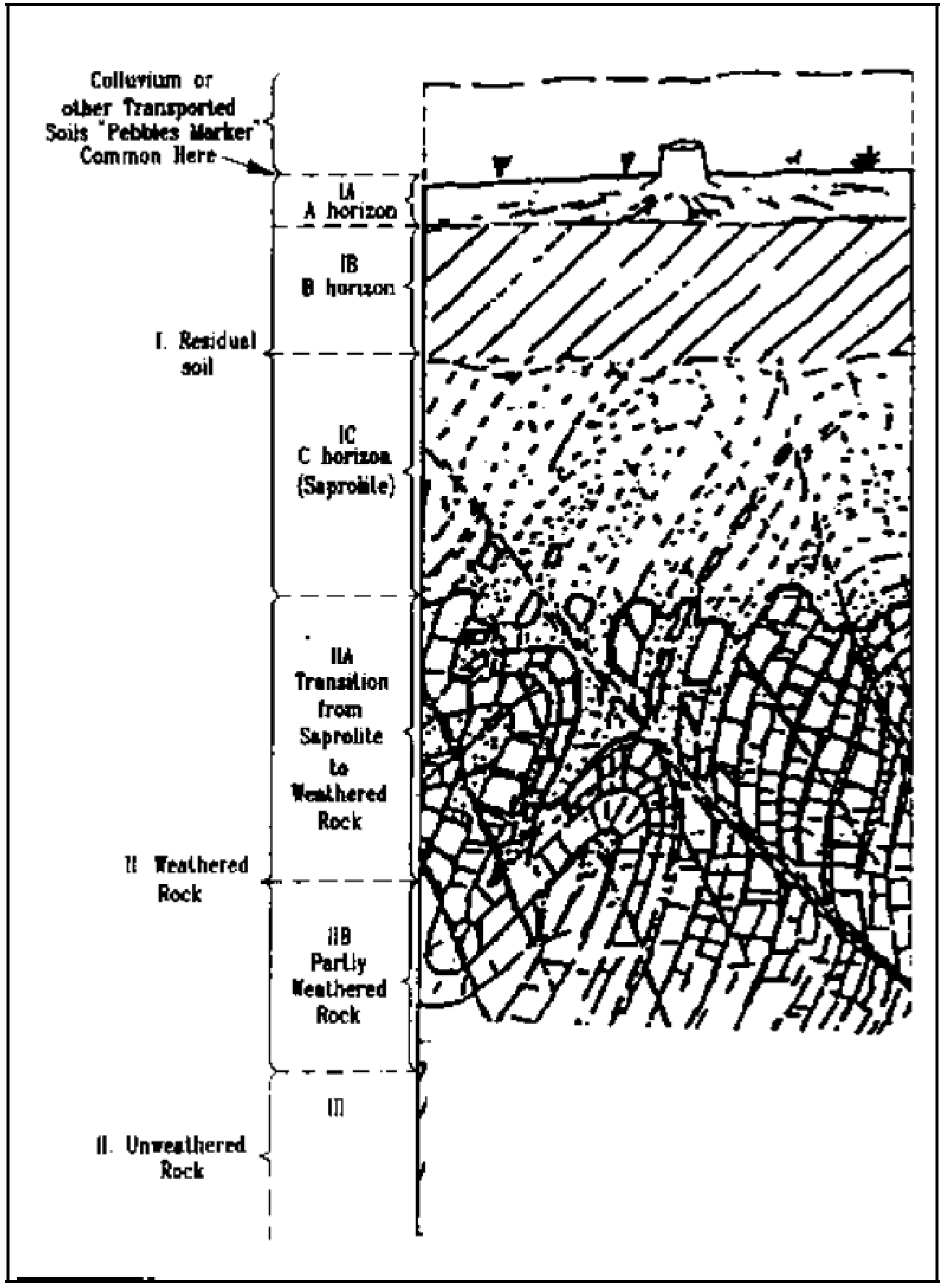
Colluvium or other Transported Soils "Pebbles Marker" Common Here
IA A horizon
IB B horizon
I. Residual soil
IC C horizon (Saprolite)
IIA Transition from Saprolite to Weathered Rock
II Weathered Rock
IIB Partly Weathered Rock
III
III. Unweathered Rock

Figure 12-5. Typical weathering profile for metamorphic rocks (from Deere and Patton 1971)

12-14. Design Considerations in Weathering Profiles

During subsurface investigations, saprolites most likely are classified as soils, since the samples recovered by subsurface drilling programs frequently end up as a disaggregated, crumbly material with no apparent structure. The sampling technique frequently destroys the interparticle bonding and gives the designer a poor idea of the actual conditions. Care should be taken during sampling to determine if saprolites and relict structures exist if they will be exposed in rock excavations.

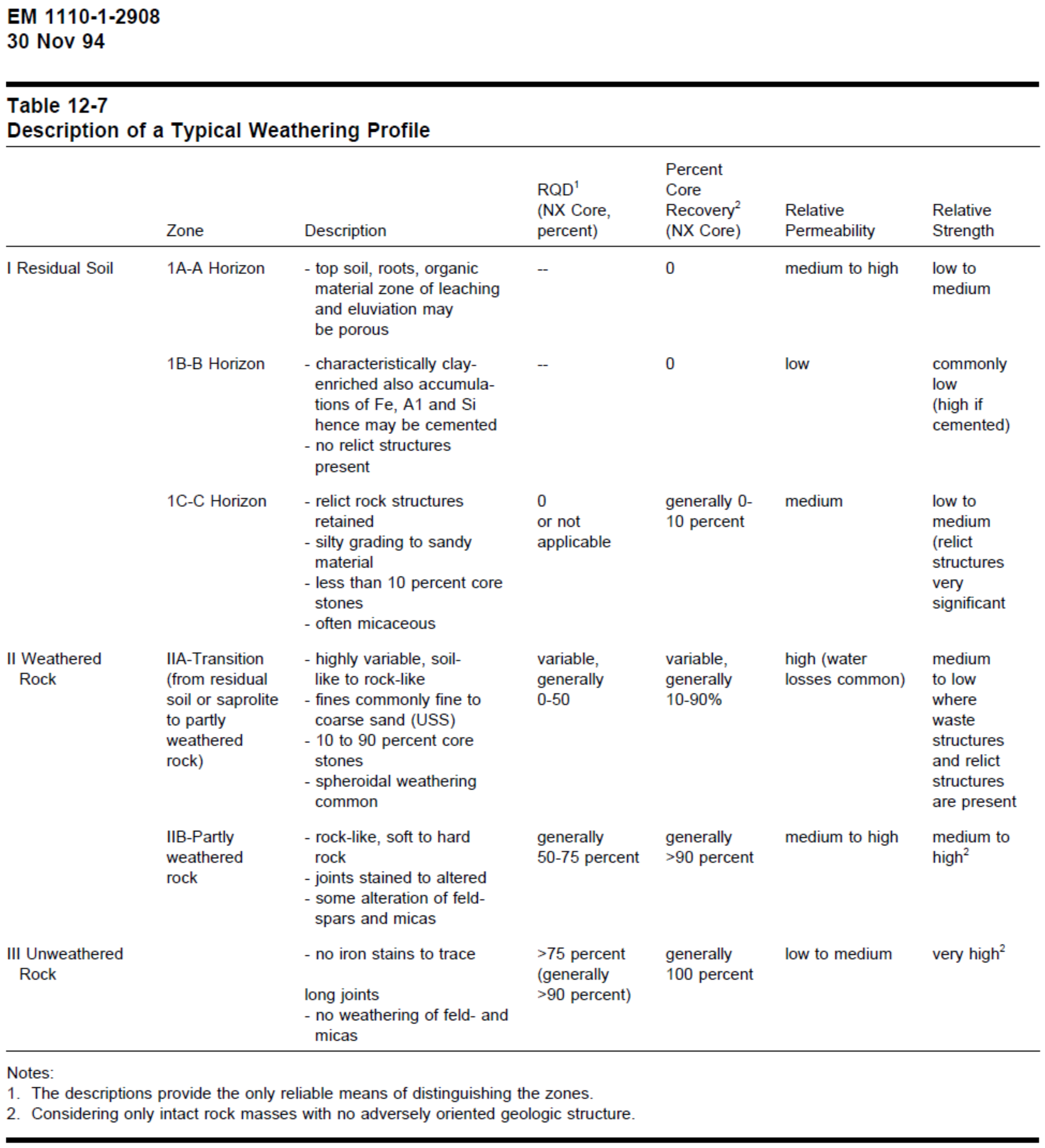

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Table 12-7
Description of a Typical Weathering Profile

	Zone	Description	RQD[1] (NX Core, percent)	Percent Core Recovery[2] (NX Core)	Relative Permeability	Relative Strength
I Residual Soil	1A-A Horizon	- top soil, roots, organic material zone of leaching and eluviation may be porous	--	0	medium to high	low to medium
	1B-B Horizon	- characteristically clay-enriched also accumulations of Fe, A1 and Si hence may be cemented - no relict structures present	--	0	low	commonly low (high if cemented)
	1C-C Horizon	- relict rock structures retained - silty grading to sandy material - less than 10 percent core stones - often micaceous	0 or not applicable	generally 0-10 percent	medium	low to medium (relict structures very significant
II Weathered Rock	IIA-Transition (from residual soil or saprolite to partly weathered rock)	- highly variable, soil-like to rock-like - fines commonly fine to coarse sand (USS) - 10 to 90 percent core stones - spheroidal weathering common	variable, generally 0-50	variable, generally 10-90%	high (water losses common)	medium to low where waste structures and relict structures are present
	IIB-Partly weathered rock	- rock-like, soft to hard rock - joints stained to altered - some alteration of feld-spars and micas	generally 50-75 percent	generally >90 percent	medium to high	medium to high[2]
III Unweathered Rock		- no iron stains to trace long joints - no weathering of feld- and micas	>75 percent (generally >90 percent)	generally 100 percent	low to medium	very high[2]

Notes:
1. The descriptions provide the only reliable means of distinguishing the zones.
2. Considering only intact rock masses with no adversely oriented geologic structure.

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https://doi.org/10.1155/2019/8217029

Research Article

Shear Strength of Compacted Clays as Affected by Mineral Content and Wet-Dry Cycles

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The behaviors of high-plasticity clays depend largely on the clay mineral content. Recently, it has been observed that sudden slope failures of most clay slopes occur in regions pronounced with repeated rainfall and sunny climate. The reason for this is still unclear. Examining the effect of clay minerals and drastic weather changes on shear strength will be useful in predicting the performance of structures built in such soils and to take precautionary measures to improve the properties before failure. Therefore, a series of quick direct shearing tests were conducted on 11 artificial clay mixtures. The cohesion and frictional strength properties were determined and linked to the proportion of clay minerals and the number of wetting and drying cycles. The results show a significant reduction in shear strength after exposure to wetting and drying. Generally, montmorillonite-dominated mixtures were less susceptible to the changes in cohesion strength than kaolin-dominated mixtures, and the reduction in frictional strength was relatively insignificant.

1. Introduction

It is well acknowledged that the shear strength of compacted soils influences the stability of embankment slopes, the bearing capacity of foundations, and the performance of earth-retaining structures. Recently, it has been observed that the conventional method of using peak strength for the design of clay slopes overestimates the shear strength [1–3]. Therefore, the issue of determining the appropriate shear strength and the major influencing factors is a major concern for engineers during design and construction [4]. A typical example is the Carsington embankment which failed at a strength level considerably less than the peak strength [5].

It is now well established that the mechanical properties of clay depend largely on the type, the content of clay minerals, and the interactions between the clay mineral particles. The proportion of clay minerals, even in small quantities, can have significant effect on the engineering behavior of the soil mass [6]. A review of literature also shows that clay slopes that fail in the field experience seasonal rainfall and sunny climate conditions. The continuous exposure to wetting-drying cycles can reduce the overall mechanical strength [7–10]. This phenomenon is typically known to cause deformation and failure of engineering structures. In view of all that has been studied so far, one may suppose that the proportion of expansive clay minerals coupled with exposure to cyclical dry and wet environments are the two key factors that control the behavior of expansive clays. Nonetheless, the evidence of the relationship between these two key factors and shear strength reduction in clay soils is inconclusive. Wright et al. [11] attempted to demonstrate that cyclic wetting and drying can loosen the soil structure and reduce the strength of compacted clays towards the fully softened strength. Their work, however, focused on natural soils from Texas and therefore the extent to which their conclusions and assumptions can be applied is limited to soils with similar properties. To date, a great deal of research into clays has focused on the swelling and shrinkage characteristics [12–16]; however, the contribution of clay mineral content to the essential mechanism of strength reduction has not been well understood.

This paper describes an experimental investigation of the shear strength behavior of different compacted artificial soil mixes with different clay mineral contents. By choosing to use artificial soil mixes, the spatial variability that occurs in natural high plastic clay soils is decreased to the barest minimum, and the influence of the dominant clay minerals can be adequately studied.

2. Materials and Methods

2.1. Soils. In this study, 11 different remolded samples were prepared by combining double mixtures of commercially available powdered kaolinite, montmorillonite, and quartz in proportions of 30%, 50%, 70%, and 100% based on dry weight. To ensure that clay soils of varying strength characteristics were obtained for this study, kaolinite which is the strongest clay mineral and montmorillonite which is the weakest were chosen. Henceforth, the letters K, M, and Q in the sample description represent kaolin, montmorillonite, and quartz, respectively, whilst the proceeding numbers denote the percentage of those minerals in the mixture. The physical and plasticity properties of the soils used were investigated in accordance with the procedures specified by the Chinese standard GB/T 50123-1999 (Ministry of Construction P. R China, 1999). The montmorillonite had a liquid limit of 328, a plastic limit of 33, a specific gravity of 2.69, and 90% clay-sized particles (particles smaller than 0.005 mm). The pure kaolin on the other hand was characterized by a specific gravity of 2.60, a liquid limit of 55, and a plastic limit of 27. About 90% of the kaolin contained clay-sized particles. The quartz had a specific gravity of 2.65, and approximately, 70% of the quartz fell within the silt range (0.005 mm and 0.075 mm). Figure 1 shows the particle size distribution curves for various minerals obtained using a BT9300H laser particle size analyzer. Also, the X-ray diffraction test was conducted on the kaolin and montmorillonite samples that were purchased to identify their clay mineral compositions. The samples were dried and placed in a Rigaku DMAX/RB instrument with Cu Kα radiation. The major crystalline phases were investigated at an angular range of 5–90° (2θ) with an increment of 0.02° per step. The diffraction pattern and peaks were compared with standard patterns prepared by the Committee of Powder Diffraction Data Service using Jade software. The result is presented in Figure 2.

2.2. Preparation of Samples. Compaction test was performed in accordance with the Chinese standard GB/T 50123 [17] for the proctor compaction test. 2.3 kg of each soil mixture with the designated mineral composition by weight was measured and mixed in the dry state until a fairly uniform distribution was obtained. A 102 mm diameter mold was used to compact the samples by dropping a 5.5 lbf (24.4 N) rammer from a height of 305 mm into three layers with 25 blows each. For each soil mixture, a minimum of 5 samples at different moisture contents were prepared. Following the determination of the maximum dry density and optimum moisture content of each soil sample, it was necessary to replicate the soil conditions for the direct shearing test. Therefore, all the soil mixtures in their appropriate mineral proportions were statically compacted into steel rings with a diameter of 61.8 mm and a height of 20 mm at optimum conditions. A hydraulic jack was used to compact the samples. The inside of the rings was lubricated to reduce friction between the samples and the steel rings.

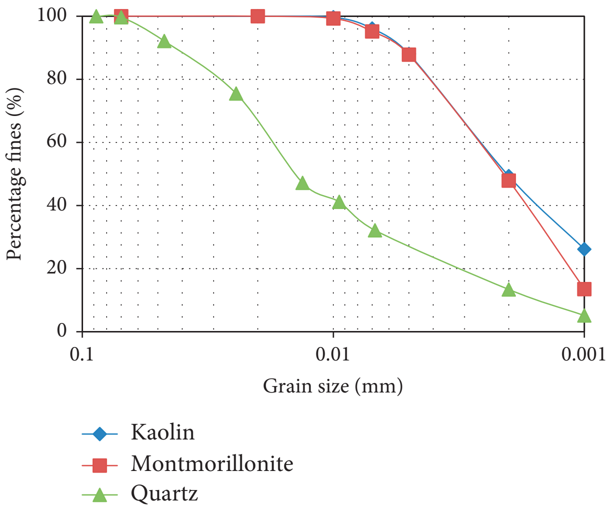


Figure 1: Grain size distribution of kaolin, montmorillonite, and quartz.

2.3. Wetting and Drying Cycles. The statically compacted remolded samples in the steel rings were subjected to continuous wetting and drying to simulate the effect of rainfall and drought on compacted clay soils. Each sample was sandwiched between a filter paper and a porous stone to allow for double drainage. A steel ring together with porous stones and an elastic rubber membrane were used to secure the sample from disintegrating.

All specimens were subjected to 15 cycles of wetting and drying. This was enough to ensure maximum expansion of the clay soils and no further noticeable particle breakdown. The first cycle consisted of a wetting phase followed by a drying phase and another wetting phase. For each wetting cycle, the samples were inundated in water for a period of 24 hours whilst for the drying phase, each sample was kept in the oven at a temperature of 40 ± 5°C until the moisture content dropped to about 50% less than the compacted moisture content. This was checked by taking the samples out of the oven periodically and measuring the weight.

2.3.1. Direct Shear Test. The test was conducted in accordance to the procedures outlined in the Chinese standard GB/T 50123 [17] for determining the shear strength of the soil using a shear box. Two series of unconsolidated quick direct shear tests were performed on the soil mixtures. In the first series (as-compacted samples), the specimen was compacted and subjected to the direct shear test immediately

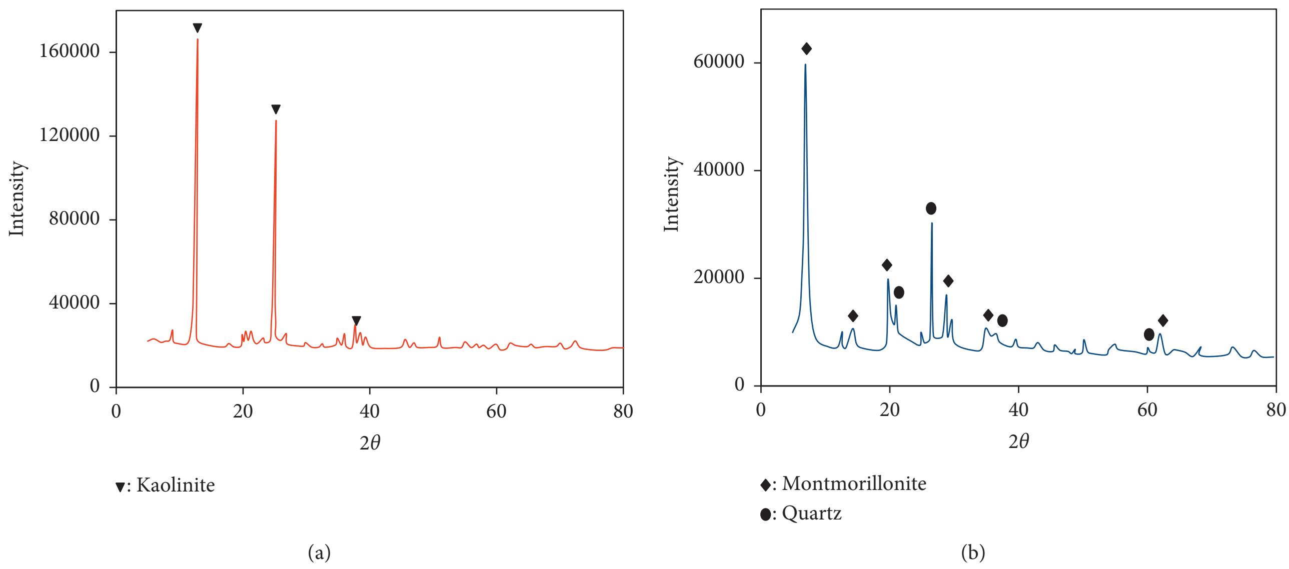


Figure 2: XRD analysis of (a) kaolin and (b) montmorillonite.

afterwards. In the second series, the specimen was compacted and then exposed to wetting and drying cycles before it was sheared. The shear strength parameters investigated were cohesion and internal angle of friction. Four direct shear tests were conducted on each soil mixture using vertical stresses of 50 kPa, 100 kPa, 150 kPa, and 200 kPa. A strain rate of 0.08 mm/min was applied in all the tests.

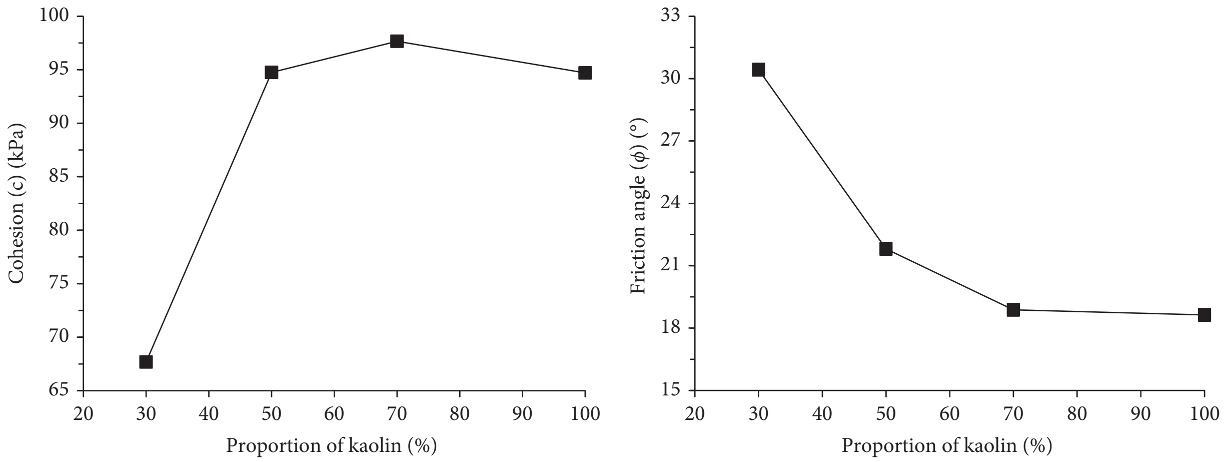
3. Results and Discussion

3.1. Shear Strength Parameters of As-Compacted Samples. To evaluate the cohesion and frictional strength behavior under peak conditions, the Mohr–Coulomb failure criterion was used to analyze each measured dataset. The plot of peak shear stress for different proportions of the kaolin-quartz mixture is depicted in Figures 3(a) and 3(b). The data for pure end sample of kaolin were added for reference. It was observed that increasing the proportion of kaolin led to an increase in cohesion and a decrease in the internal friction angle. The cohesion increased from 67.7 kPa for K30Q70 to 97.7 kPa for K70Q30 whiles the angle of internal friction decreased from 30.4° to 18.9°, respectively. Further increase in the kaolin content from K70Q30 to K100 resulted in a continuous decrease in the friction angle as shown in Figure 3(b) and a slight decrease in cohesion, as shown in Figure 3(a).

From Figure 3(a), the initial increase in cohesion may be attributed to decrease in the void ratio with increase in the kaolin content. The kaolin particles to some extent behaved as a filling material in the pore spaces of the relatively larger and dense quartz (up to 70%). However, beyond 70% kaolin content (when the void ratio reached a minimum), the quartz particles became more dispersed and more water was needed to reach maximum cohesion. It can be concluded that this decreased the electromagnetic attractions between the kaolin clay particles and caused the cohesion to decrease slightly. The trend is similar to the results presented by Mullins and Panayiotopoulos [18]. The plausible explanation for the results in Figure 3(b) is that as the kaolin content increased, the clay particles controlled the overall behavior of the mixture causing the quartz particles to slip and slide, leading to a reduction in the frictional strength. The trend is qualitatively similar to those presented by Lupini et al. [19].

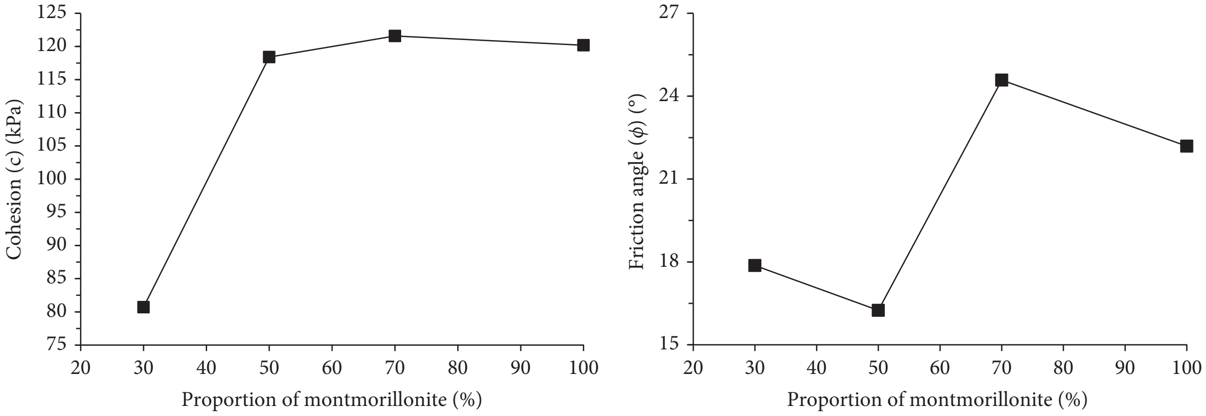
Figure 4 shows shear strength data for montmorillonite-quartz mixtures. The cohesion behavior was more dominant but similar to the trend observed in the kaolin-quartz mixtures. From Figure 4(a), it can be observed that increasing the montmorillonite content from M30Q70 to M70Q30 led to an increase in the cohesion shear strength. Interestingly, the pure end data of the M100 sample also exhibited a slight decrease in cohesion. Figure 4(b) shows how the friction angle changes with increasing montmorillonite content. The relationship observed in Figure 4(b) shows a disjointed pattern. The pattern shows a moderate drop in friction up to 50%. From 50% to 70%, the friction angle increased steeply with increasing montmorillonite content. From M70Q30 to M100, another decrease in the friction angle was observed similar to the initial trend.

Using the montmorillonite X-ray diffraction analysis presented in Figure 2, an attempt was made to explain the result in Figure 4. Figure 2(b) shows that the montmorillonite mineral contains about 10–15% quartz. It was deduced that as the proportion of montmorillonite was increased from 30% to 50%, the friction angle reduced because of increasing clay content and decreasing quartz content. However, just after 50%, the extra contribution of quartz from the montmorillonite specimen led to the discrepancy in the trend. As such, the sudden increase in frictional strength may be as a result of the relatively high proportion of quartz in the mixture. Coincidentally, increasing quartz particles increased the frictional angle. Beyond 70% montmorillonite content, it can be assumed that the clay particles were dominant and caused the frictional strength to decrease again.



(a) (b)

Figure 3: Variation of shear strength properties with clay proportion in the kaolin-quartz mixture: (a) cohesion and (b) frictional angle.



(a) (b)

Figure 4: Variation of shear strength properties with clay proportion in the montmorillonite-quartz mixture: (a) cohesion and (b) frictional angle.

The data for montmorillonite-kaolin mixtures (30%, 50%, and 70%) are plotted in Figure 5. It can be seen in Figure 5(a) that cohesion decreased from 88.9 kPa to 74.9 kPa when the content of montmorillonite was increased from 30% to 70%. This observation confirms the trend of results shown in Figures 3 and 4. As the mixture of montmorillonite and kaolin can basically be considered to be pure clay, it seems to be the point that when the content of kaolin and montmorillonite content were increased from 70% to 100% in the kaolin-quartz mixture and montmorillonite-quartz mixtures, respectively, the behavior of these mixtures gradually approached that of a pure clay soil. So the influence of the quartz in Figures 3 and 4 was suppressed in the mixtures at this point. When the mixtures approached pure clay soils, increasing the clay content beyond a certain critical moisture content caused the cohesion to decrease. The variation of the friction angle with increasing proportion of montmorillonite as presented in Figure 5(b) shows an increase in frictional strength with increasing montmorillonite content. The X-ray diffraction results for pure kaolin (see Figure 2(a)) show that the kaolin used was about 98% pure and therefore any behavior observed is mostly due to kaolin clay particles. However, the montmorillonite had a few quartz particles as earlier on explained. So with increasing proportion of montmorillonite in this mixture, the cohesion decreased due to the increased presence of quartz particles. The frictional strength on the other hand increased because the increased quartz particles from the montmorillonite specimen possess high frictional strength.

3.2. Effects of Optimum Moisture Content on the Shear Strength of As-Compacted Samples. To examine why the difference in cohesion and friction angle was observed in the various mixtures in Figures 3–5, the cohesion and friction angles were analyzed in relation to the moisture content at which samples were compacted for kaolin-quartz mixtures, montmorillonite-quartz mixtures, and montmorillonite-kaolin mixtures, as shown in Table 1. It was observed that initially as the water content increased from about 17.4% to 28.8%, all samples which were compacted in that range

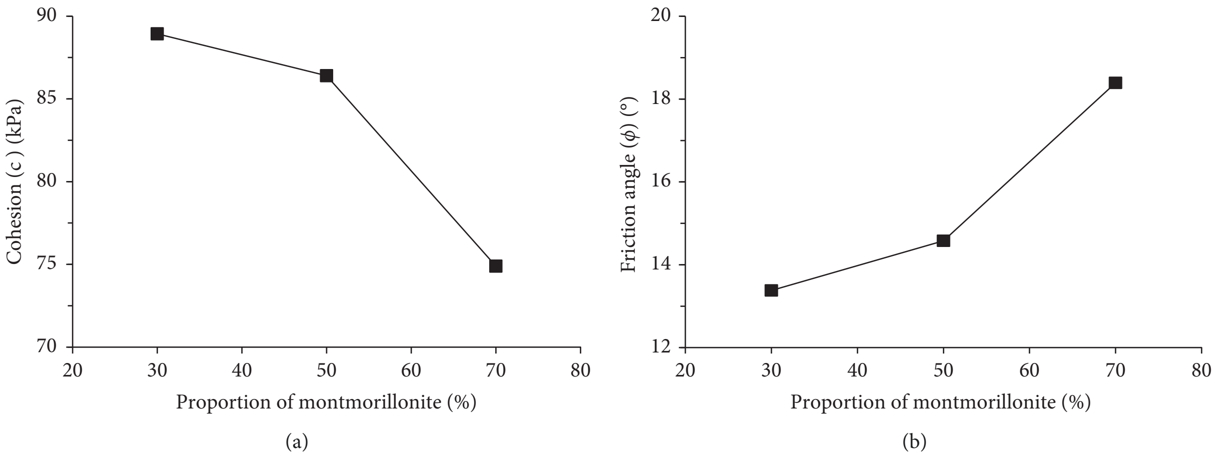


Figure 5: Variation of shear strength with clay proportion in the montmorillonite-kaolin mixture: (a) cohesion and (b) frictional angle.

Table 1: Shear strength results with water content for as-compacted soils.

Samples	Cohesion (c), kPa	Frictional angle (φ), degree	Water content (%)
K30Q70	67.68	30.43	17.4
K50Q50	94.75	21.81	21.3
K70Q30	97.66	18.88	26.1
K100	94.70	18.63	32.6
M30Q70	80.71	17.87	22.1
M50Q50	118.40	16.25	24.1
M70Q30	121.57	24.58	28.8
M100	120.18	22.19	38.3
M30K70	88.93	13.38	34.5
M50K50	86.40	14.58	35.8
M70K30	74.89	18.39	40.3

exhibited a trend of increasing cohesion with increasing water content. However, beyond that range, any other specimen that was prepared in all the three mixture groups exhibited a decreasing cohesion pattern with increasing water content. Therefore, the decrease in cohesion between 75% and 100% montmorillonite content in the montmorillonite-quartz mixture and kaolin in the kaolin-quartz mixture as well as the continuous decrease in cohesion observed in the montmorillonite-kaolin mixture with increase in the montmorillonite content, respectively, can be partly attributed to the high water content at which they were compacted. In general, it can be explained that as the water content was increased beyond the critical maximum value, the distance of separation between the clay minerals increased and the electrostatic attractions (van der Waals forces) decreased. The influence of water content can also be explained by the orientation of clay particles compacted at wet and dry side of optimum [20]. Al-Shayea [21] studied the influence of the clay and moisture content on remolded unsaturated soils using the Mohr–Coulomb shear criterion. His results showed that cohesion increases to a maximum and then declines for all clay contents similar to the shape of a compaction curve. He explained that this behavior is attributed to cementation and adhesion due to compaction, electrostatic and electromagnetic attractions, and capillary suction. He further observed that all these sources of cohesion increase the cohesion intercept with increasing clay content and increasing water content. However, the effect of increasing water content was only to certain maximum limits, beyond which it begins to decrease.

3.3. Shear Strength Parameters of the Specimen Subjected to Wetting and Drying. Seasonal climatic variation in clay soils induces shrinkage and swelling leading to changes in soil behavior and posing difficulties in engineering field application [22]. Figure 6 presents the plots of cohesion and friction angles versus the proportion of different clay minerals to show the effect of cyclic wetting and drying on the shear strength characteristics of compacted soils after being subjected to 15 cycles of wetting and drying.

3.3.1. Influence of Wet and Dry Cycles on Cohesion. Generally it can be seen in Figure 6 that when specimens were subjected to continuous wetting and drying, the cohesive strength of the soils was dramatically reduced in all clay mixtures. In the kaolin-quartz mixture, as shown in Figure 6(a), the K30Q70 exhibits complete drop in cohesion after 15 cycles of wetting and drying. The lowest percentage reduction in cohesion was recorded in K50Q50 with a value of 89%. Similar reduction in cohesive strength was observed in montmorillonite-quartz as depicted in Figure 6(c) and

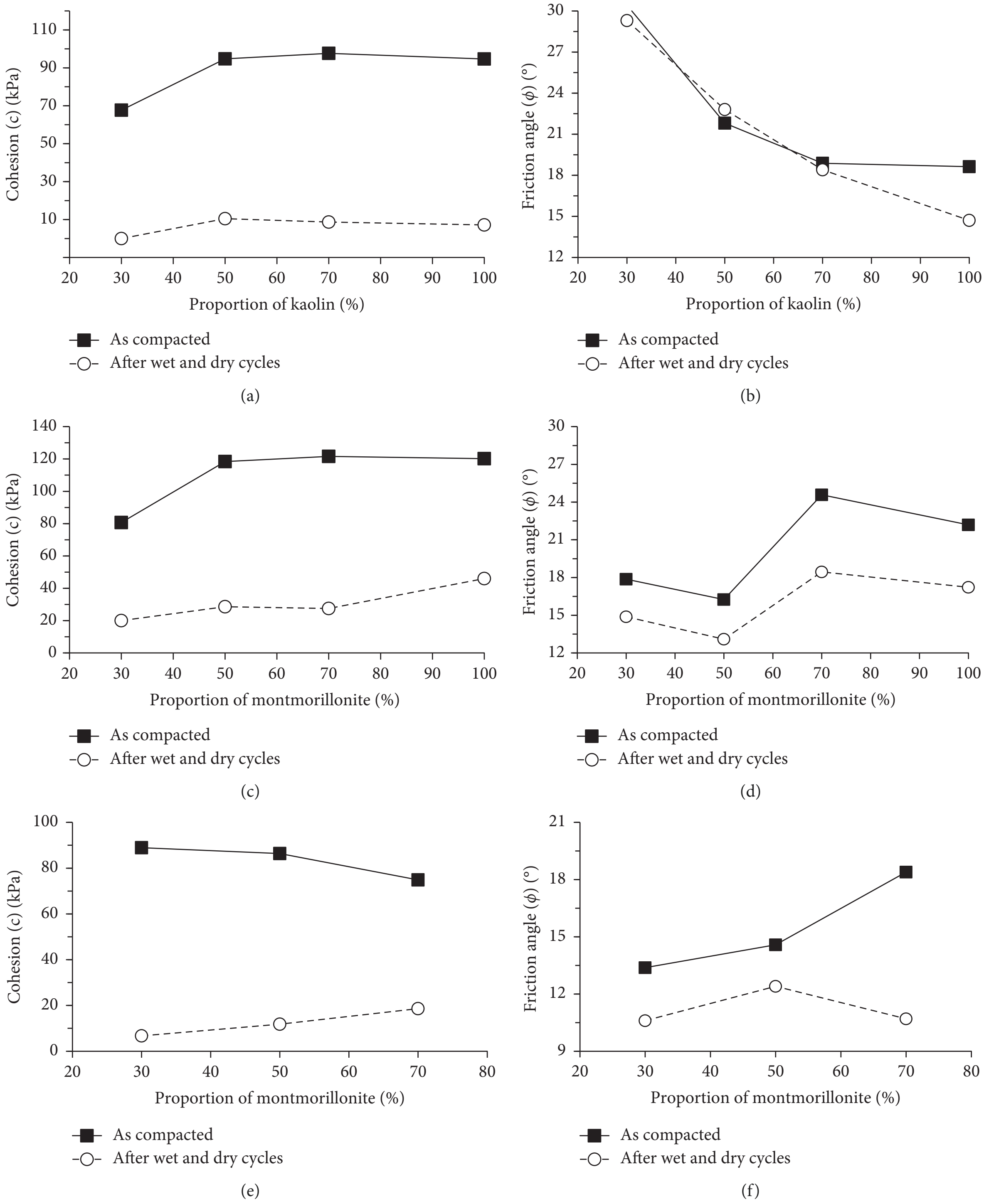


Figure 6: Comparison of shear strength characteristics between the as-compacted specimen and specimen subjected to wetting and drying: (a, b) kaolin-quartz mixtures; (c, d) montmorillonite-quartz; (e, f) montmorillonite-kaolin mixture.

montmorillonite-kaolin mixtures, as shown in Figure 6(e). Generally, the reduction in cohesion in both montmorillonite-quartz mixtures and kaolin-quartz mixtures was very high. The pure montmorillonite specimen recorded a lower value of 62% reduction. Also, the montmorillonite-kaolin samples recorded significant reduction in cohesion with a minimum of 75% in M70K30.

3.3.2. Influence of Wet and Dry Cycles on Friction. Figure 6 also shows the effect of wetting and drying on the friction angle of the compacted clay specimens. It can be seen that the difference in the friction angle between the as-compacted specimen and the wet and dry specimen is not very significant after 15 cycles of wetting and drying. It is noticeable that the K30Q70, K70Q30, and K100 specimens exhibited slight reductions in frictional strength. However, K50Q50 showed a deviation from this trend as there is about 5% increase in friction. In the montmorillonite-quartz group from Figure 6(d), it can be observed that frequent wetting and drying caused relatively greater decrease in the friction angle. The plot for montmorillonite-kaolin mixtures presented in Figure 6(f) also shows results similar to the montmorillonite-quartz mixtures. Generally, it can be noticed that increased kaolin and montmorillonite content in both kaolin-dominated soils and montmorillonite-dominated soils led to a relatively smaller decrease in the friction angle after 15 cycles. Rogers and Wright [23] after carrying out repeated wetting and drying on packed remolded clays also noticed that there was no significant change in the friction angles that was observed.

4. Conclusions

Based on laboratory testing of 11 artificial clay soil mixtures consisting of kaolinite, montmorillonite, and quartz, the shear strength characteristics of compacted clays before and after subjecting to cyclic wetting and drying conditions were analyzed. The impact of dominating clay mineral and cyclic wetting and drying on the cohesion and frictional strength behavior were described, and the following conclusions can be drawn:

1. For the as-compacted samples, the frictional and cohesion shear strength appeared to be affected by the clay mineral content. The cohesion increases with increase in the kaolin/montmorillonite content up to a maximum of about 70% clay content. Afterwards, no appreciable change was observed as the cohesion only decreased moderately with further increase in kaolin/montmorillonite. The increase in cohesion was partly attributed to decrease in the void ratio with increase in the clay content.
2. At the same clay mineral content, montmorillonite-dominated mixtures achieved a high cohesion shear than kaolin-dominated mixtures in the as-compacted samples. The quantity and type of clay minerals are thus important when determining the shear strength.
3. Generally, when specimens were subjected to continuous wetting and drying, the cohesive strength of the soils were dramatically reduced in all clay mixtures. The reduction in cohesion in the montmorillonite-quartz mixtures was relatively smaller compared to that in the kaolin-quartz mixtures.

By eliminating external factors involved in natural soil formation, this study has demonstrated that the content of clay minerals is a major factor for shear strength reduction and may be the cause of sudden failures in clay slopes.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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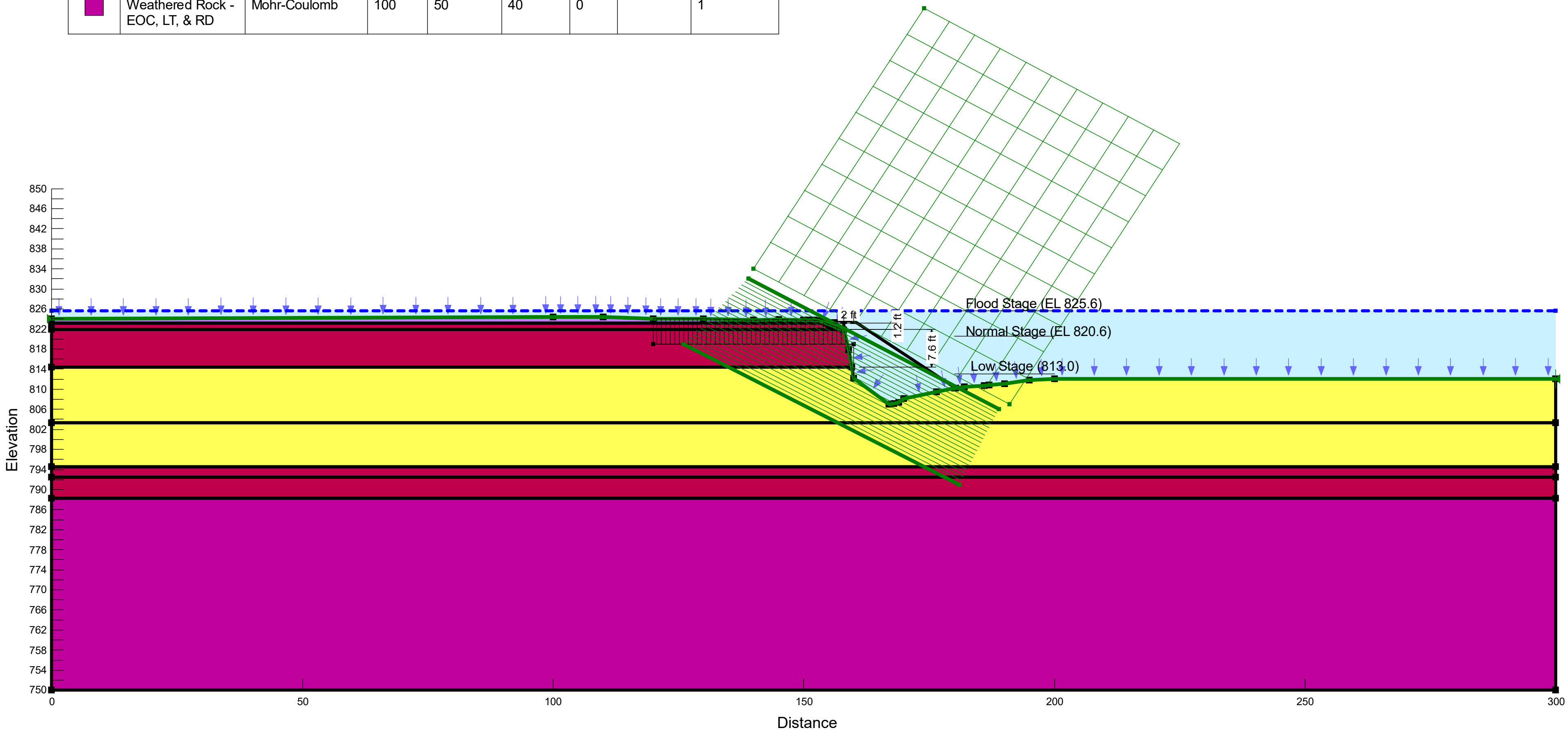
Attachment 6: Design and Analysis

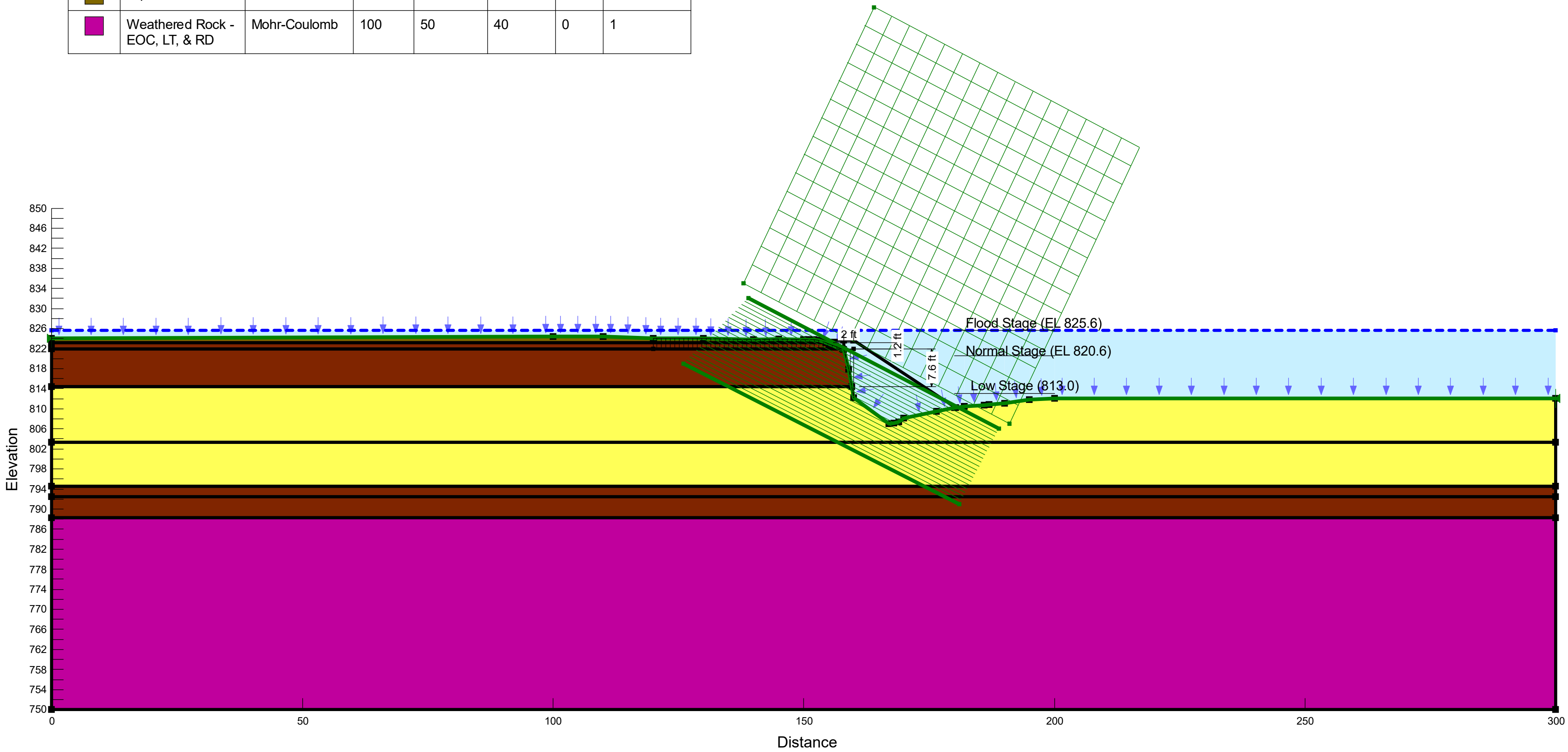
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 1 - Existing Conditions
Name: Flood Stage - EOC - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

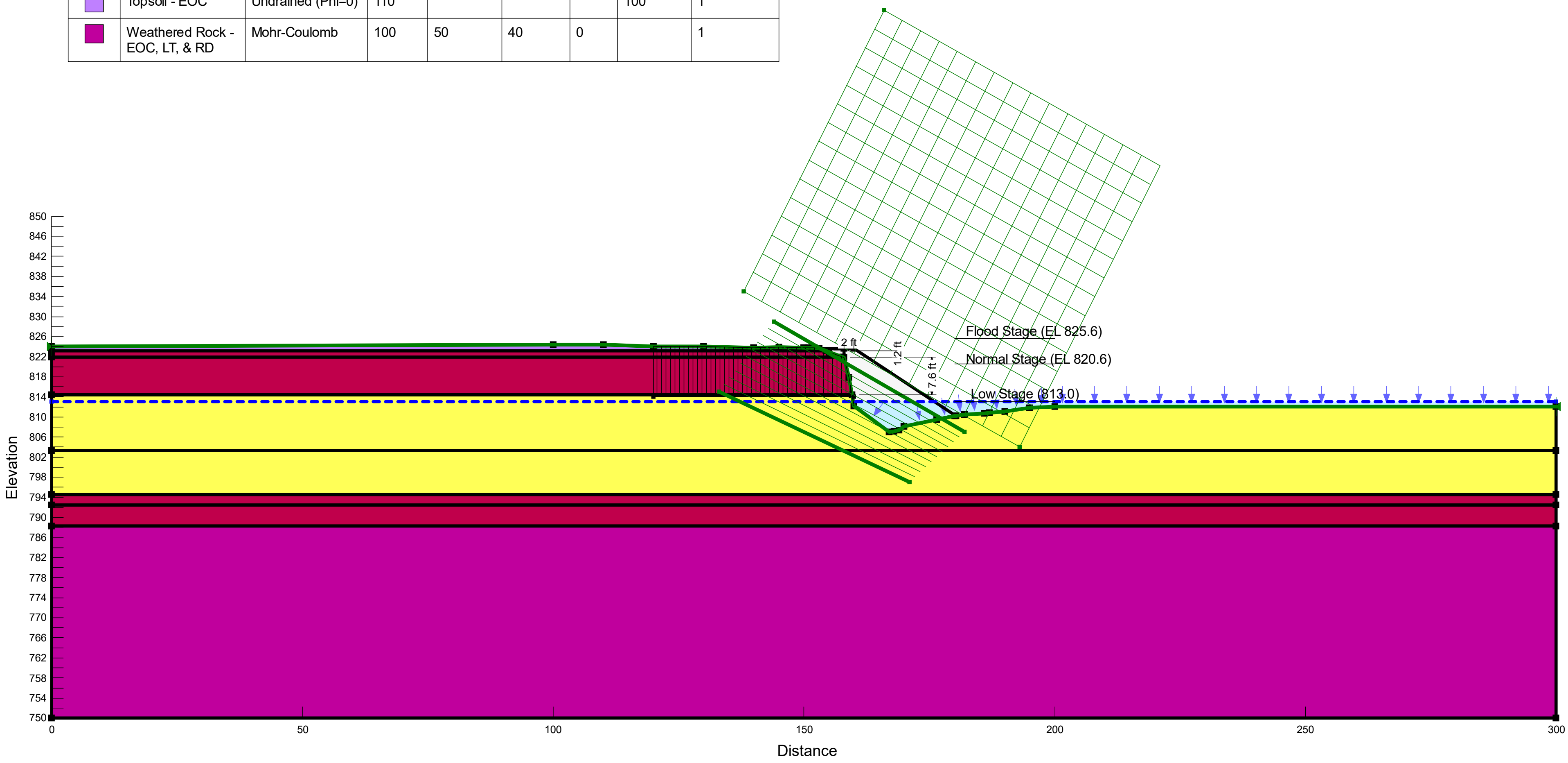
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 1 - Existing Conditions
Name: Flood Stage - LT - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

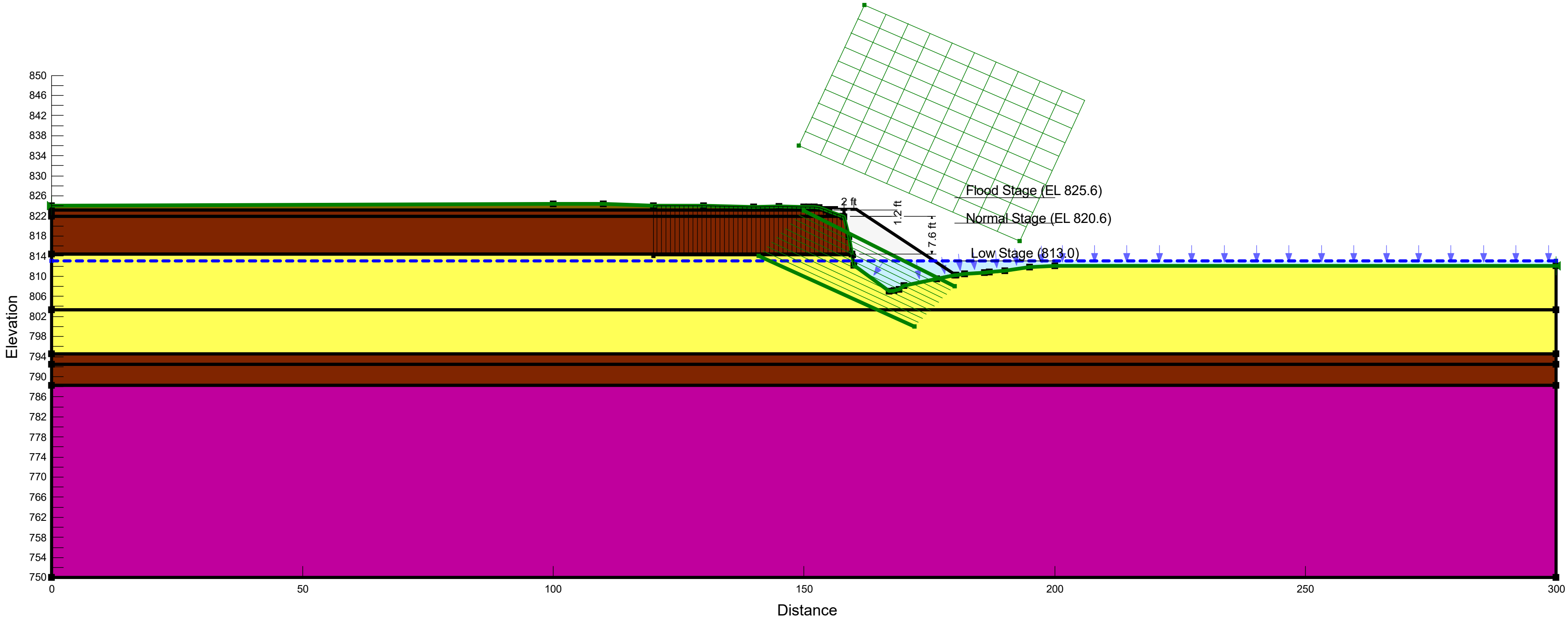
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 1 - Existing Conditions
Name: Low Stage - EOC - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

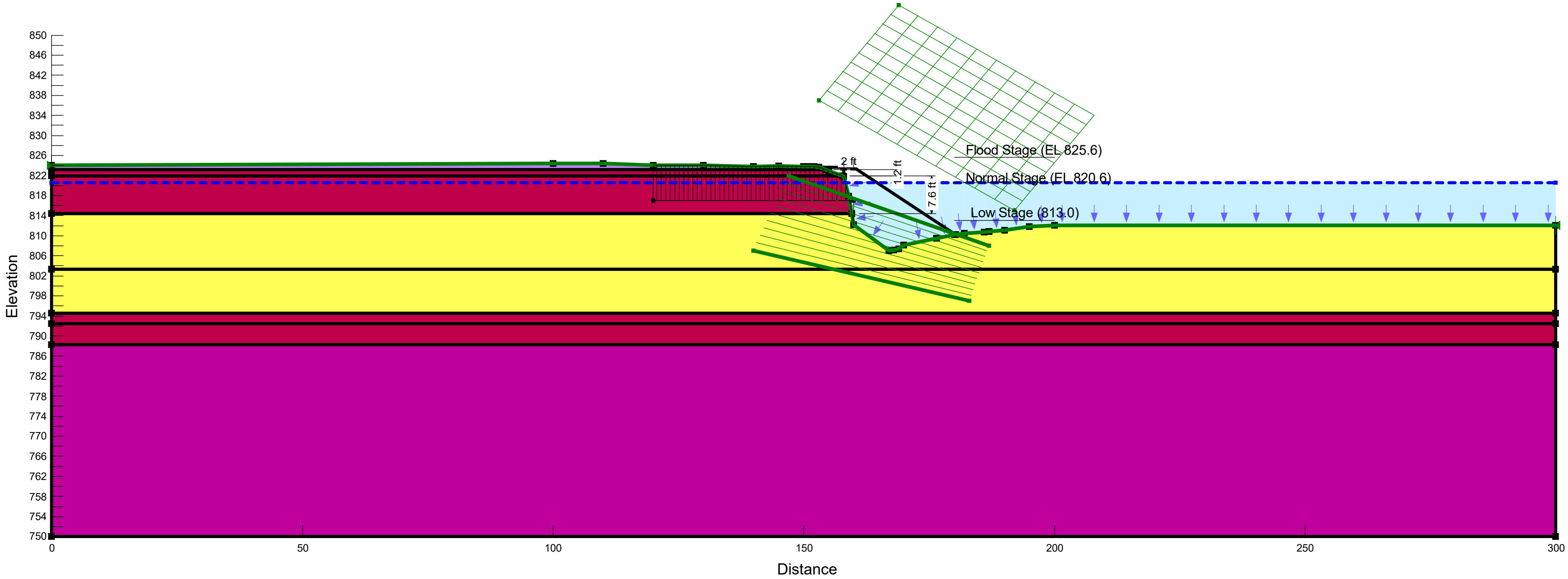
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 1 - Existing Conditions
Name: Low Stage - LT - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

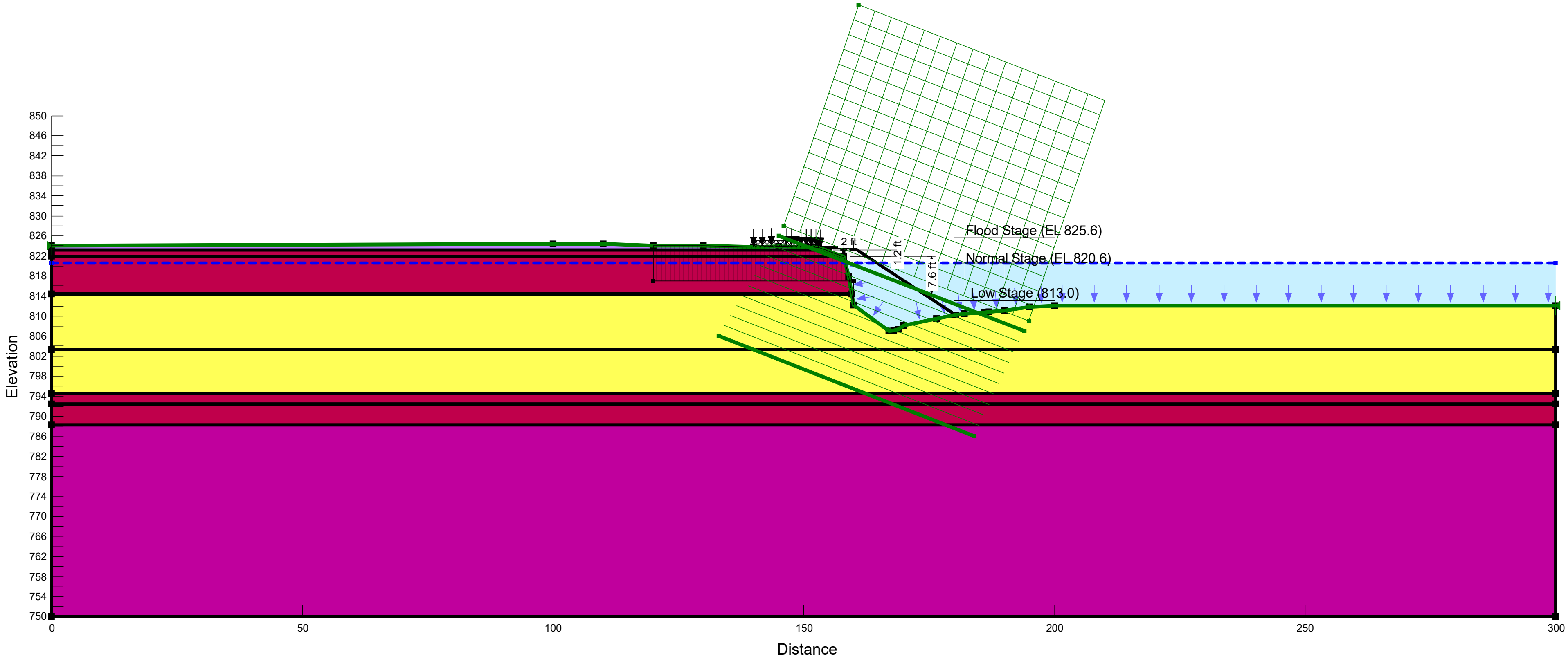
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 1 - Existing Conditions
Name: Normal Stage - EOC - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

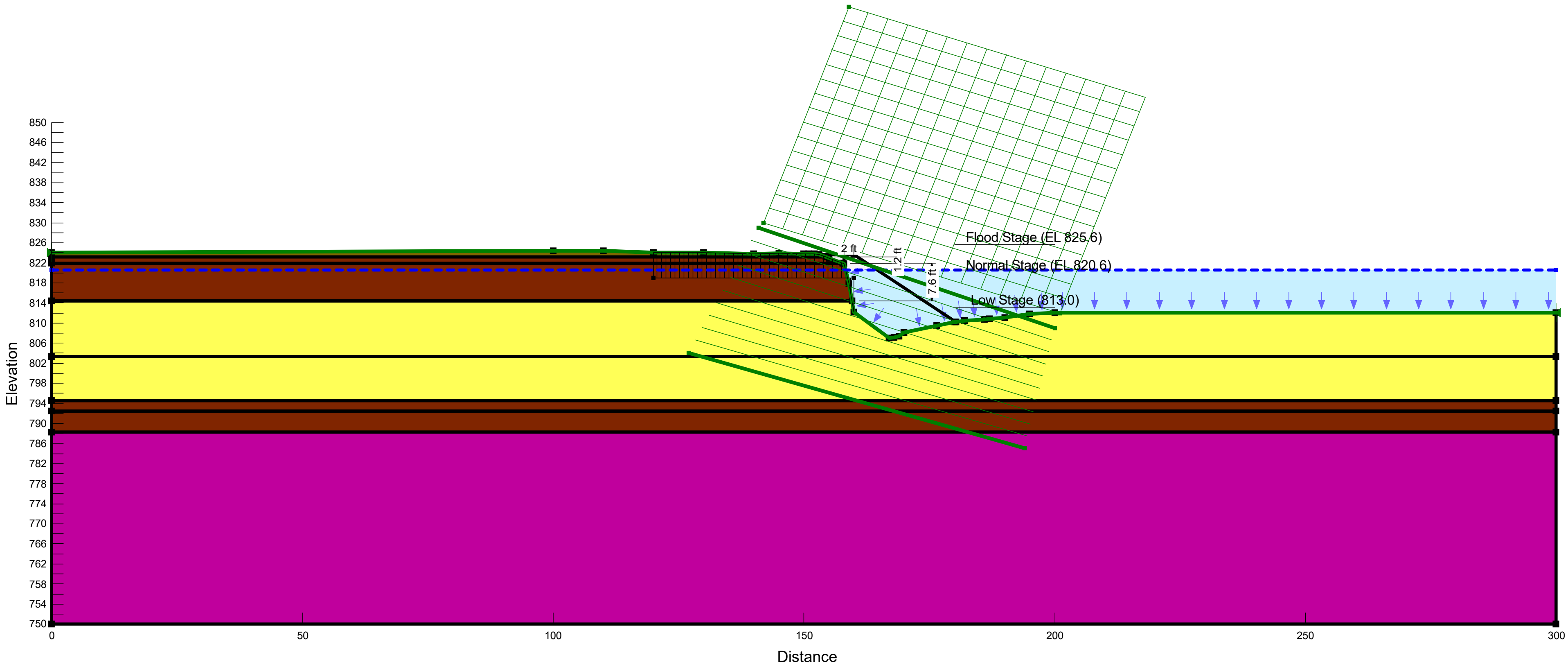
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 1 - Existing Conditions
Name: Normal Stage - EOC - Surcharge - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

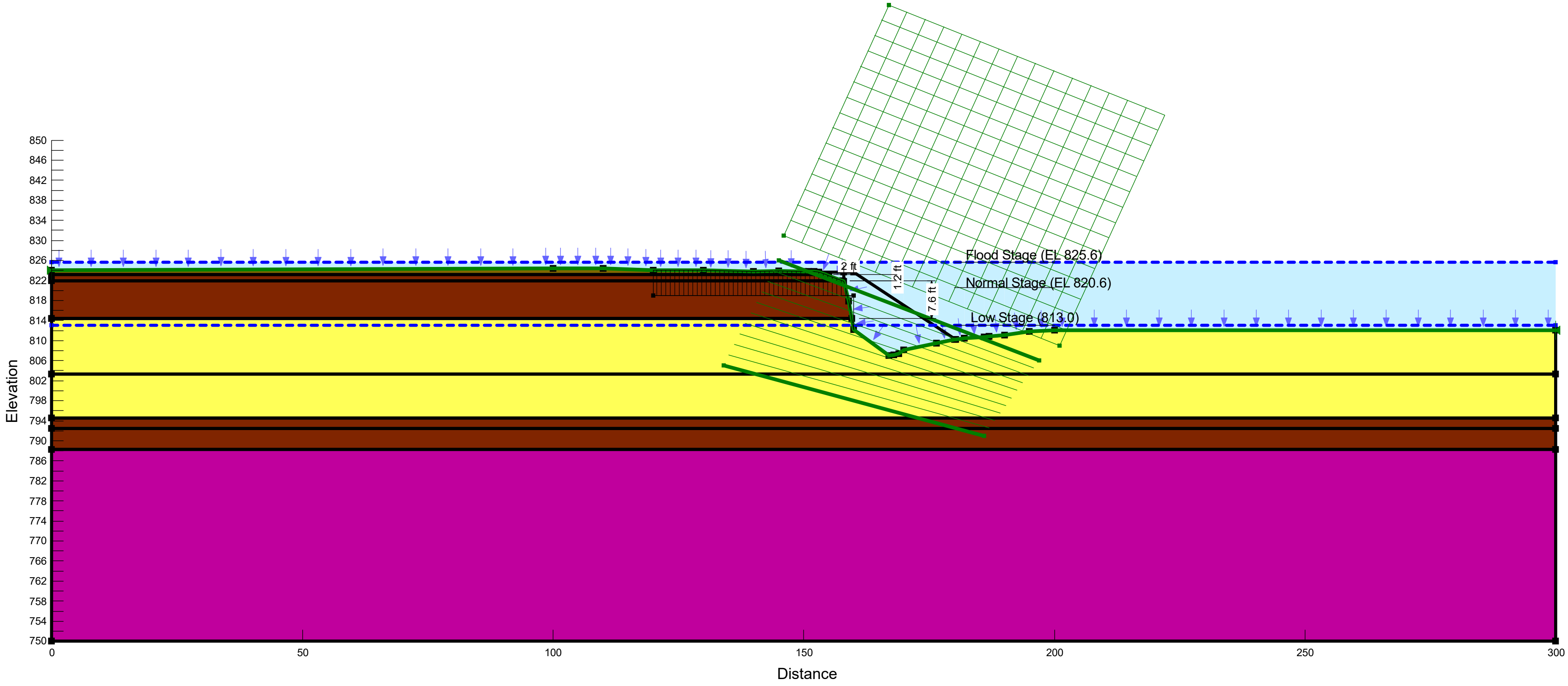
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 1 - Existing Conditions
Name: Normal Stage - LT - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

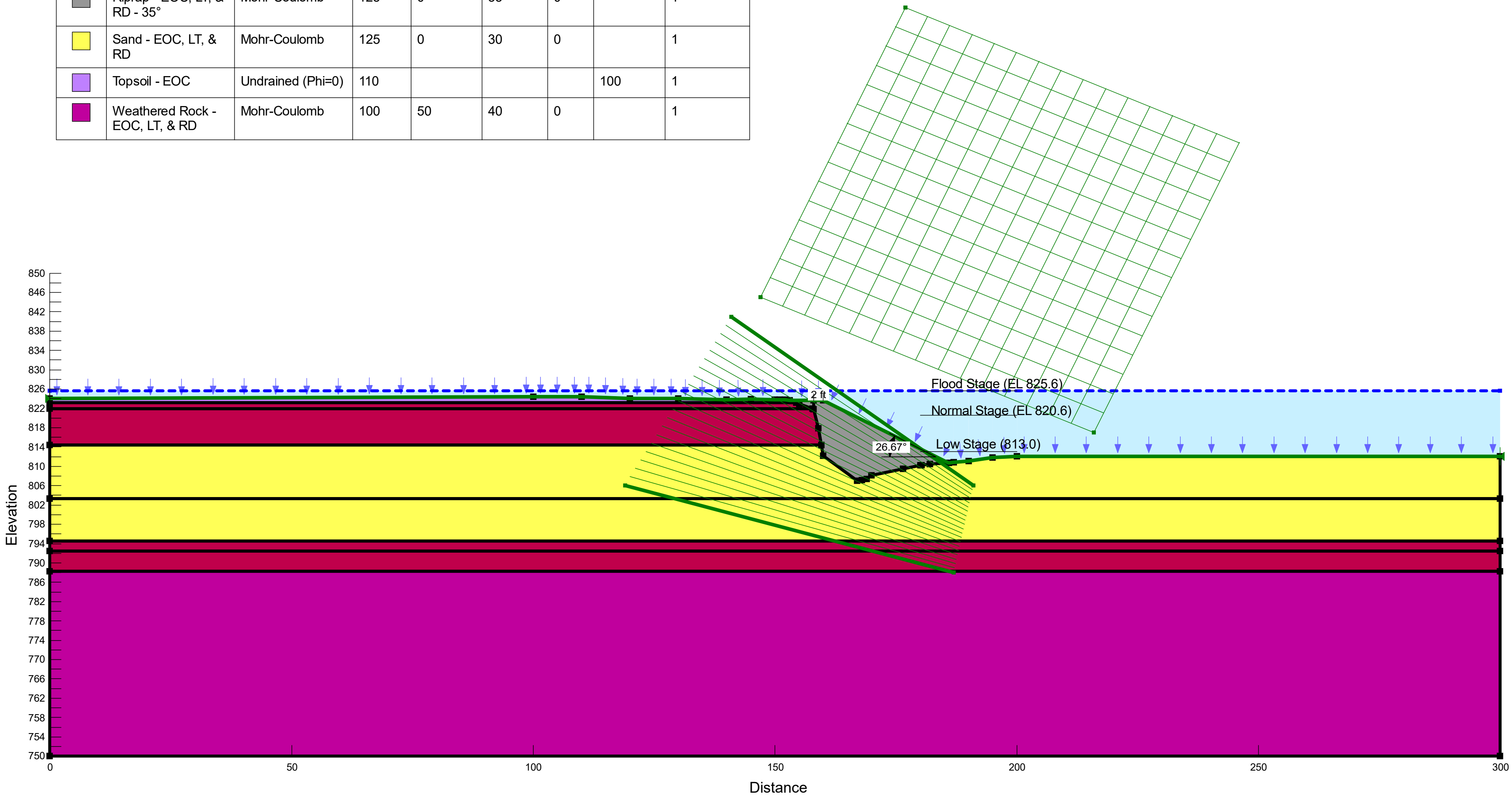
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2



Name: 1 - Existing Conditions
Name: Varied PZ Line - RD - F to N - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

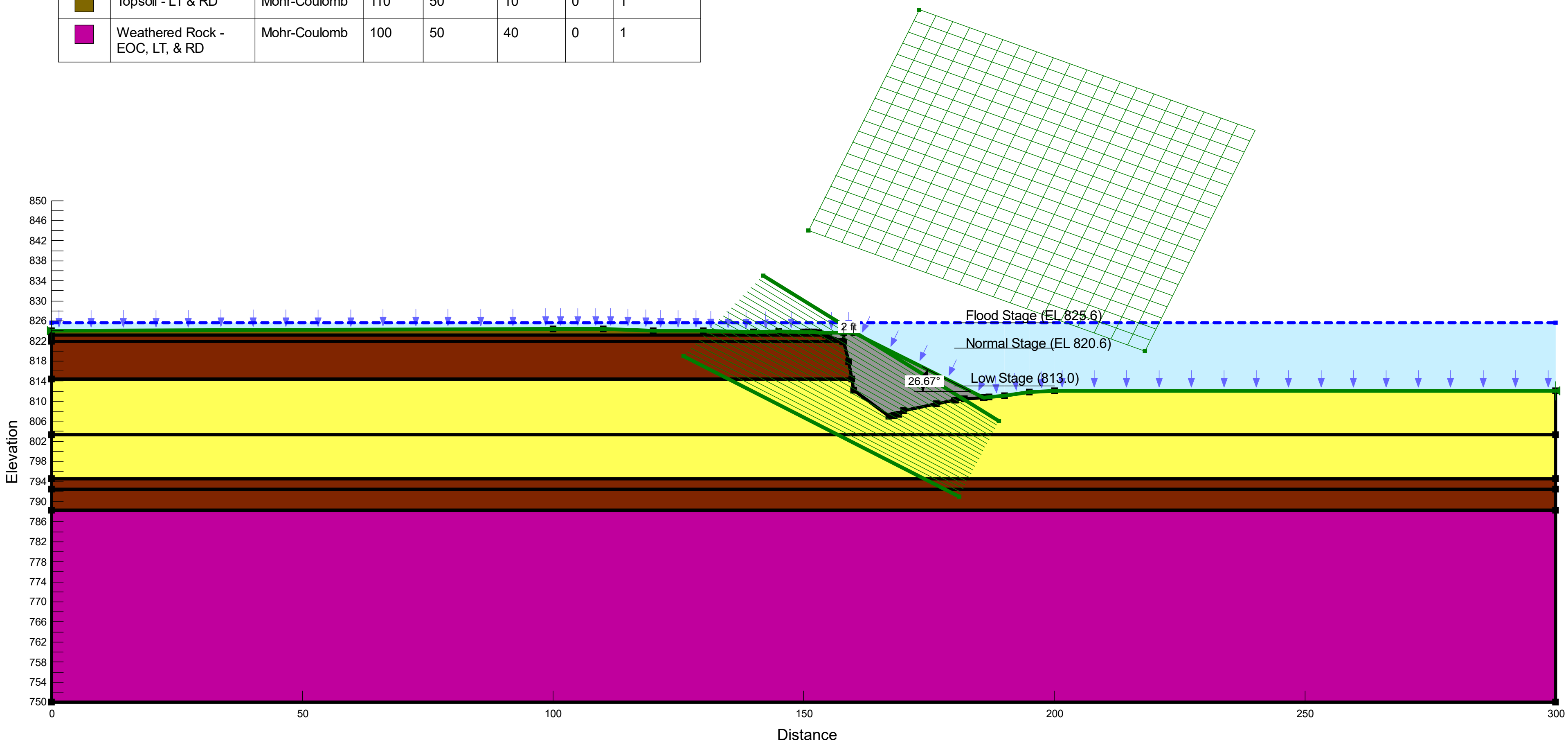
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Flood Stage - EOC - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

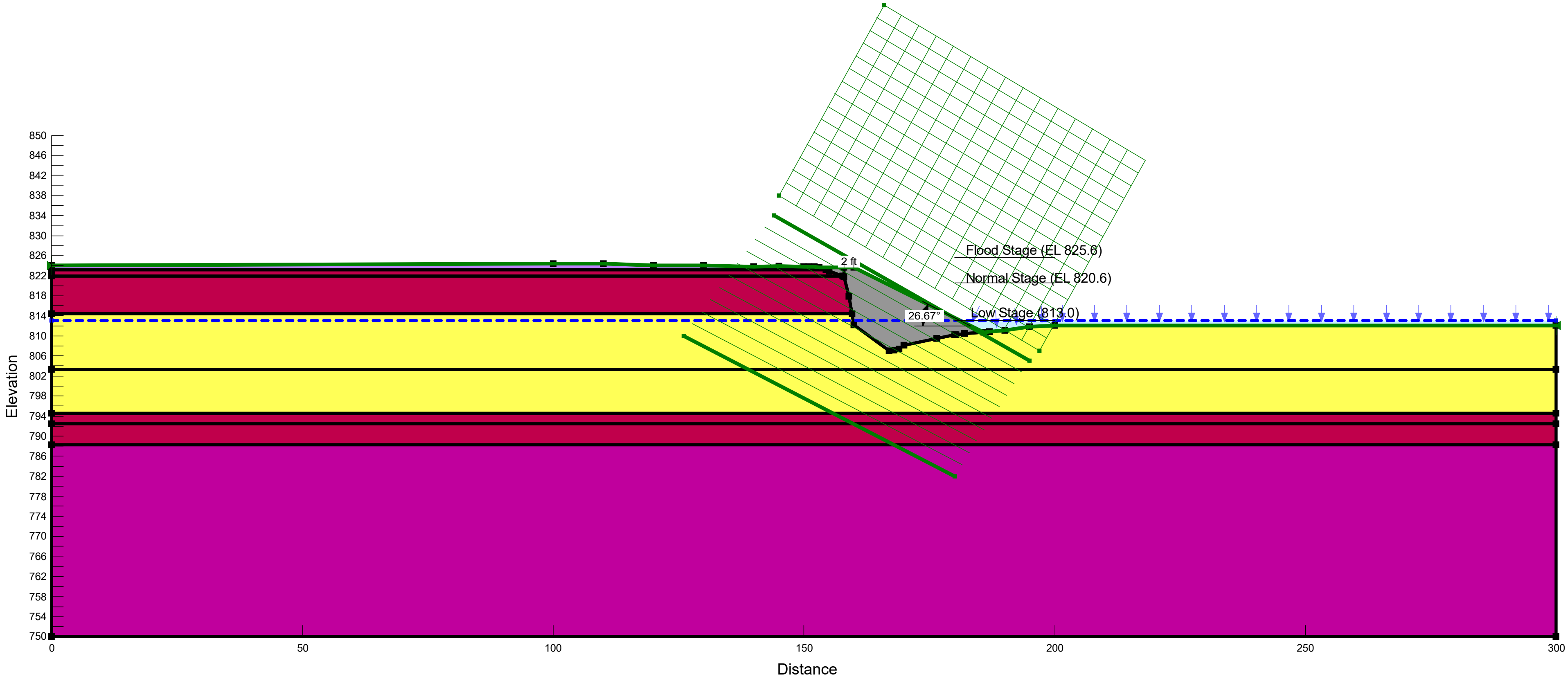
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Flood Stage - LT - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

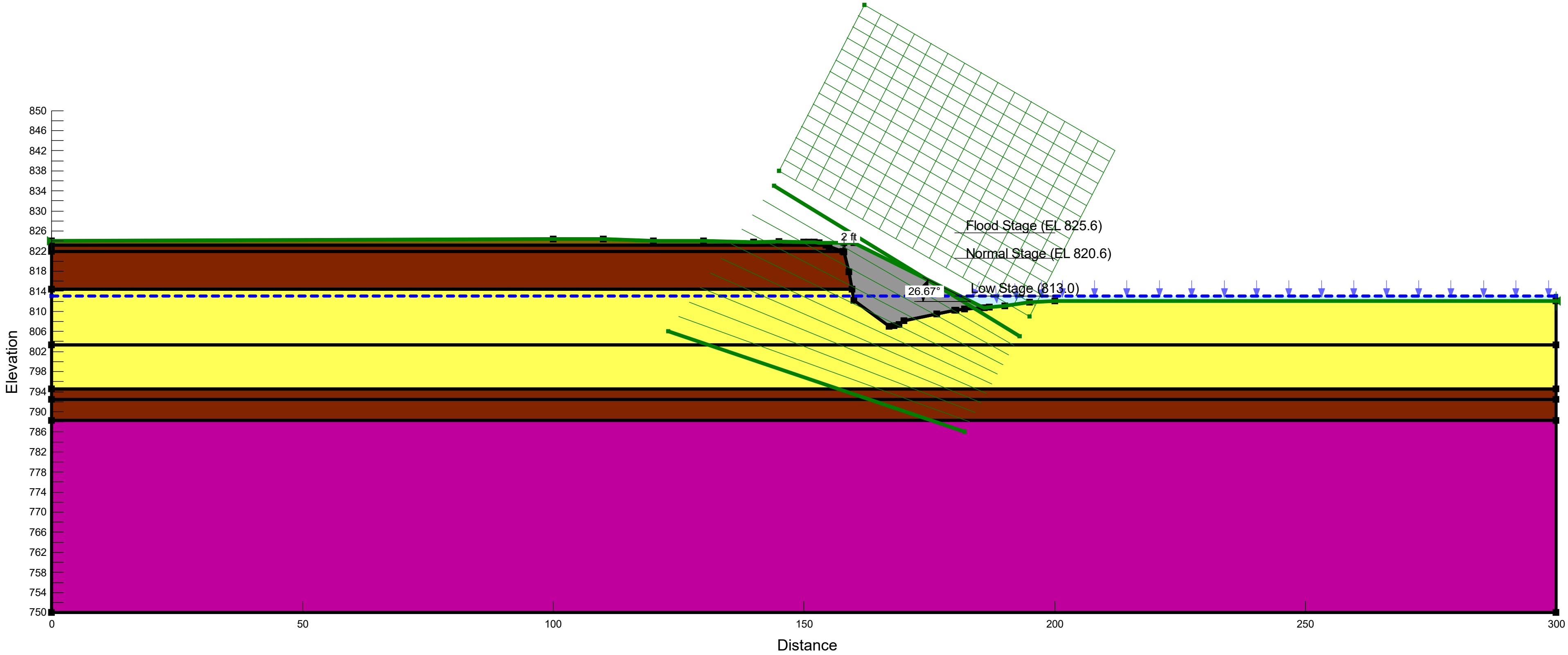
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Low Stage - EOC - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

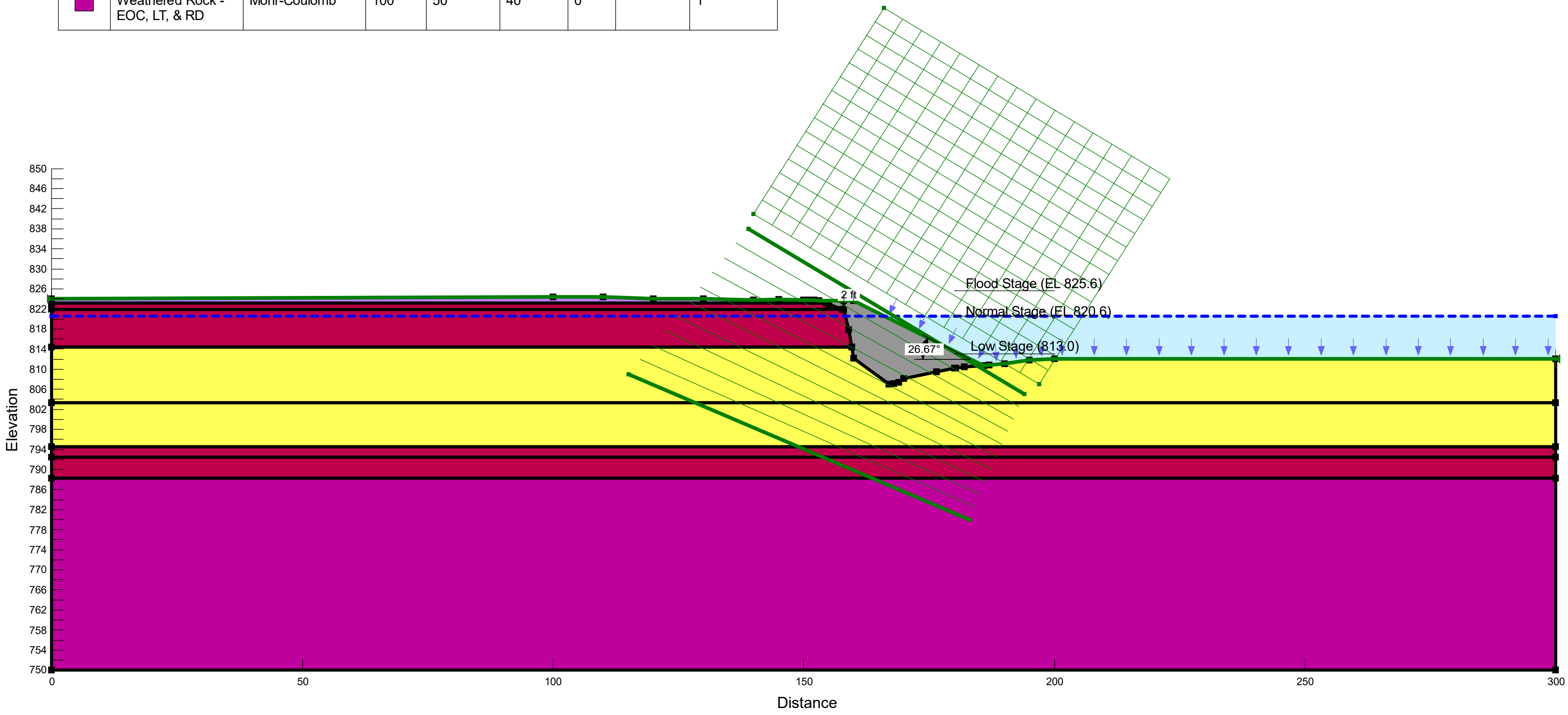
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Low Stage - LT - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

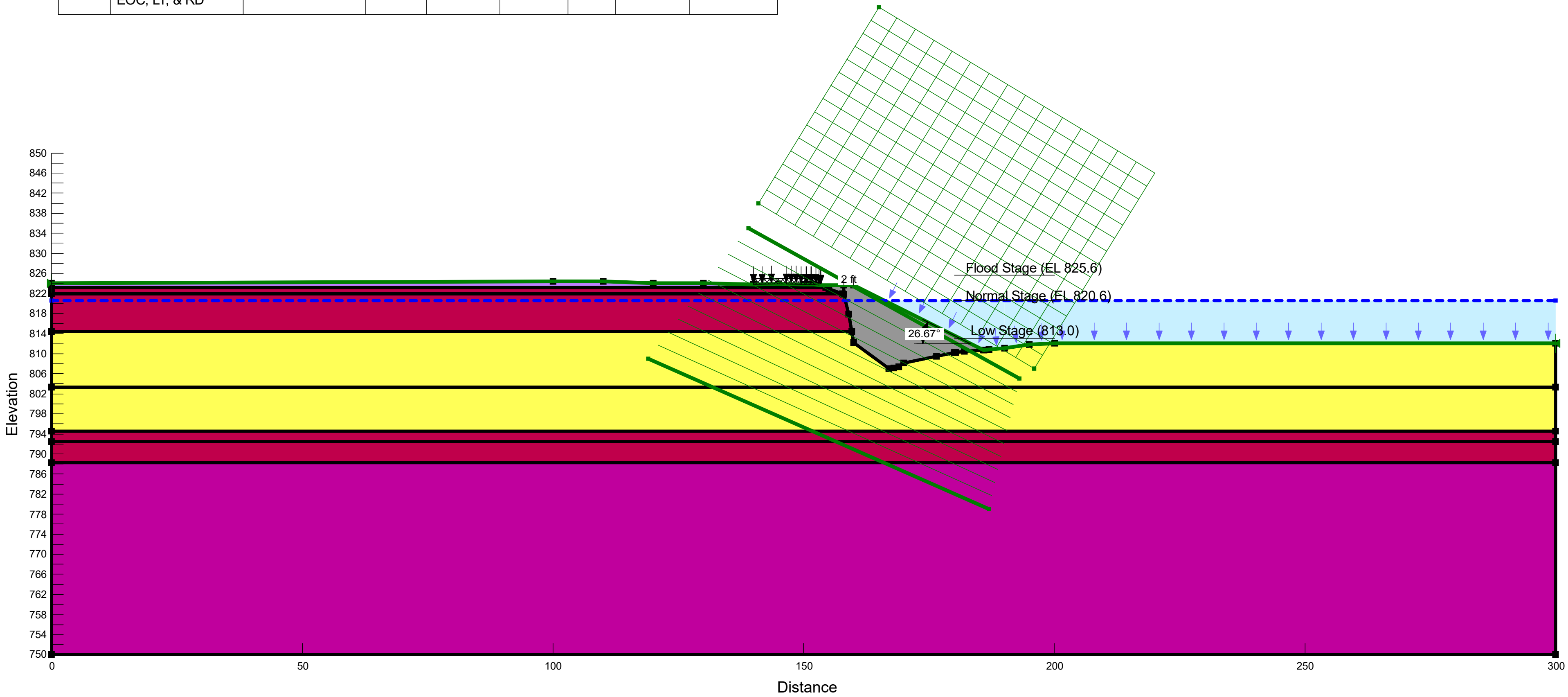
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Normal Stage - EOC - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

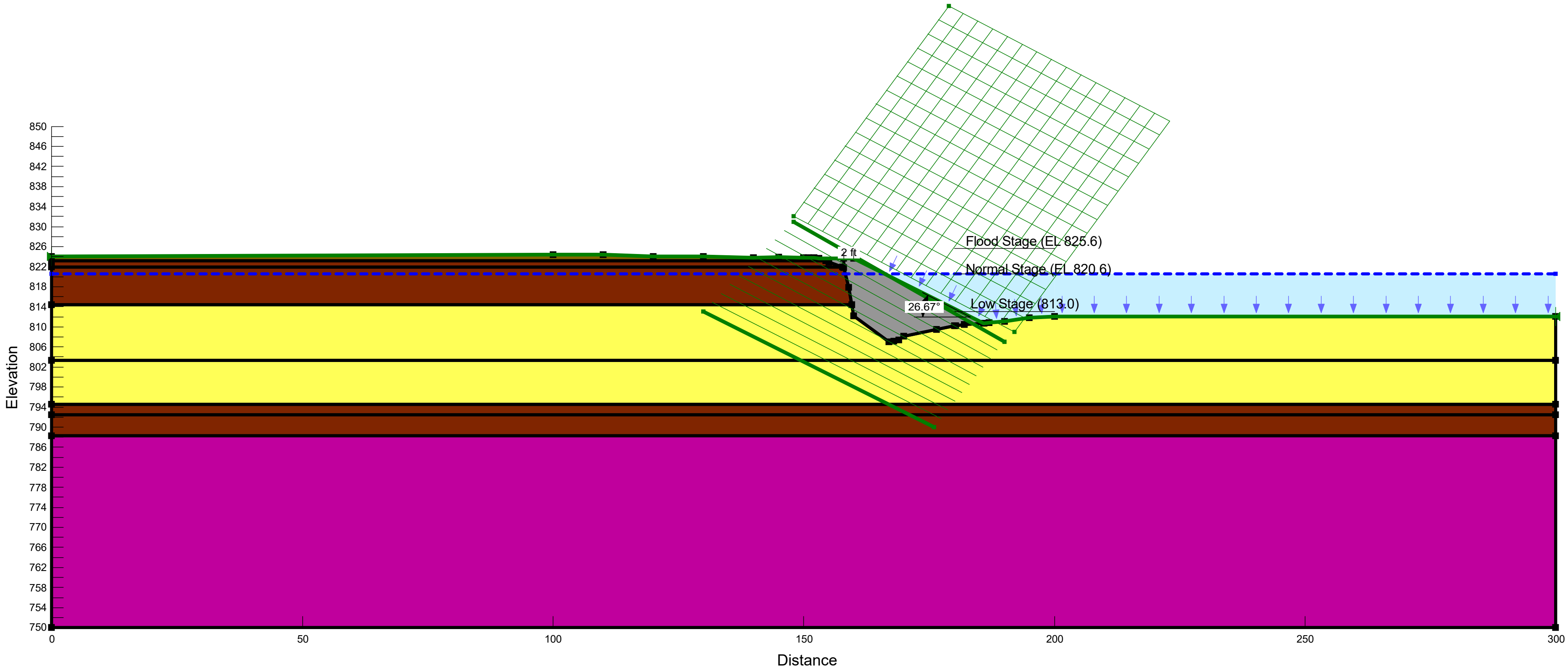
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Normal Stage - EOC - Surcharge - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

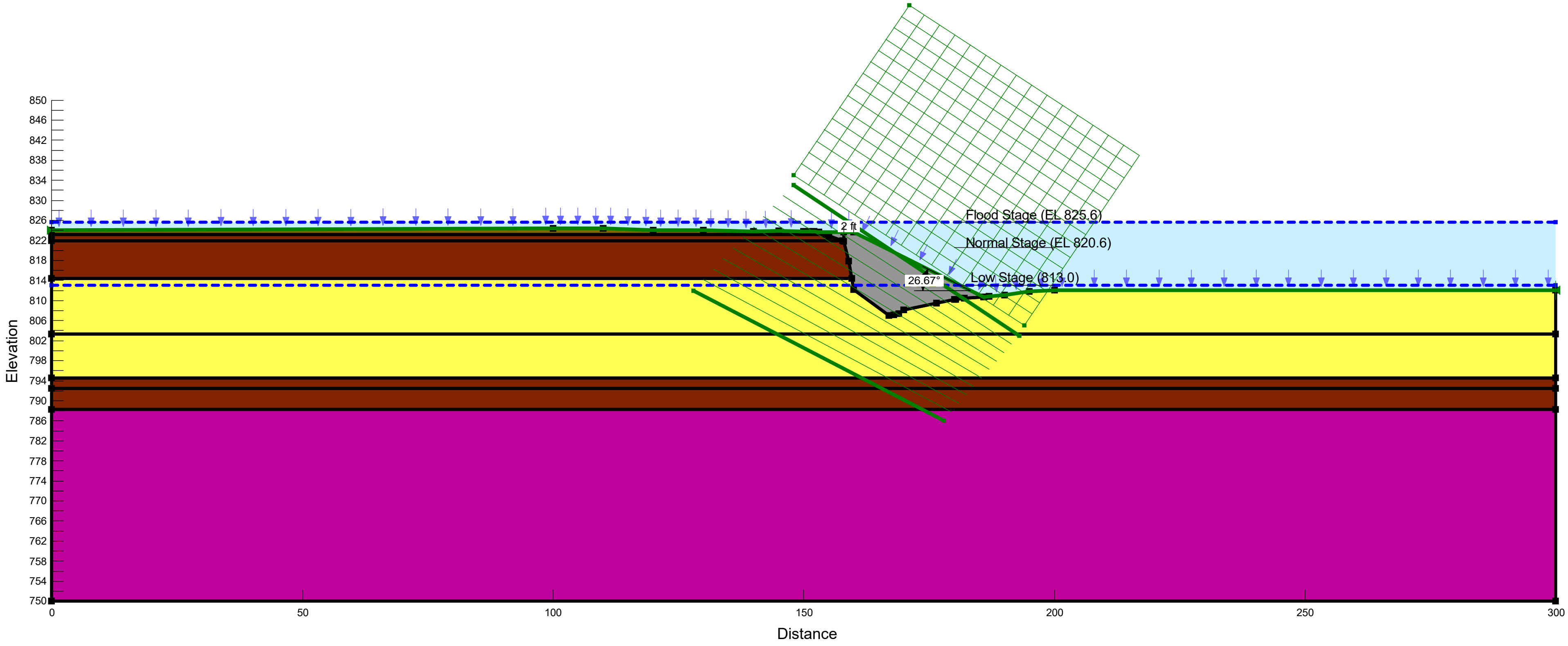
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
▨	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Normal Stage - LT - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

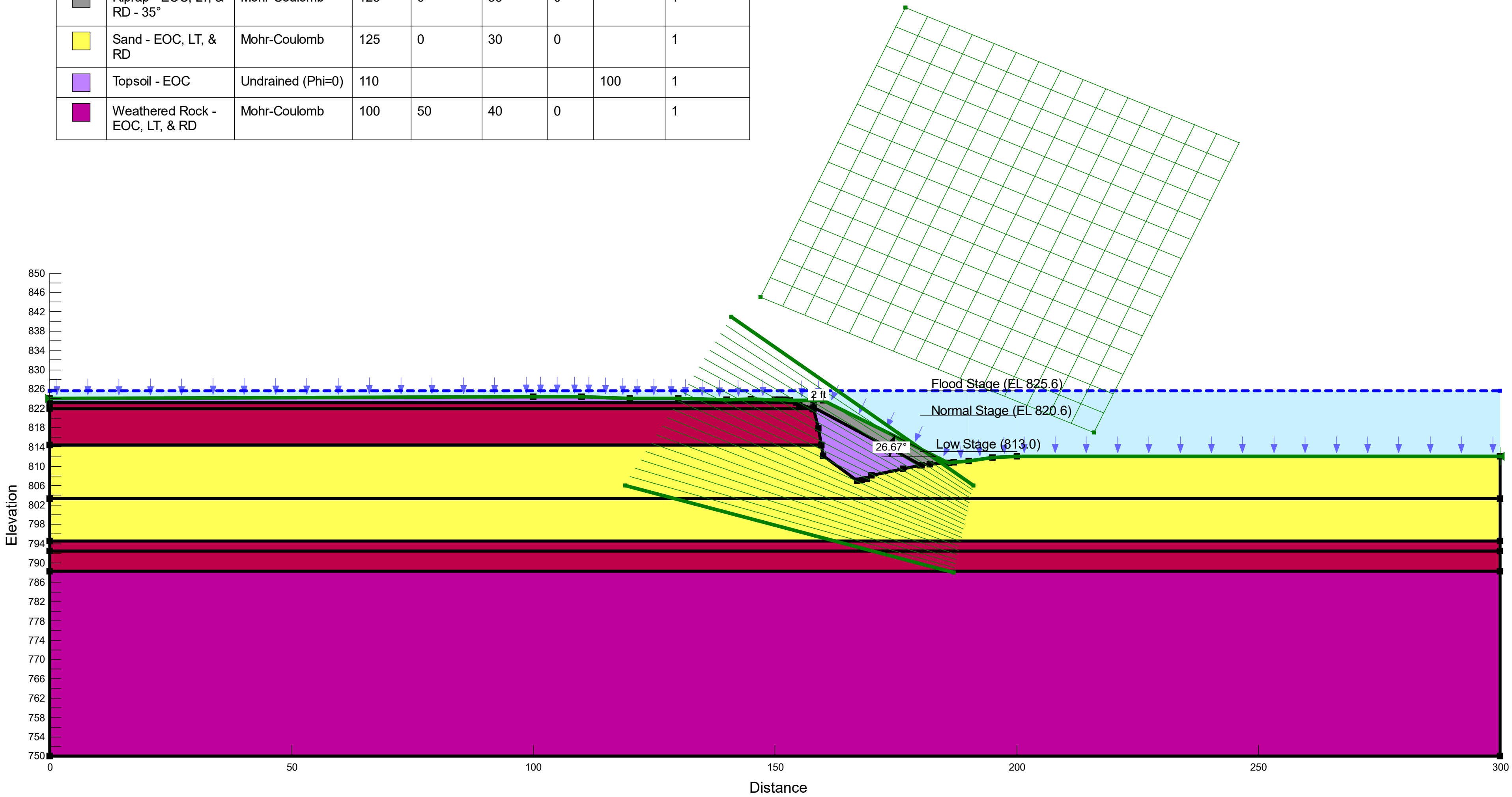
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	0	35	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2



Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Varied PZ Line - RD - F to L - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

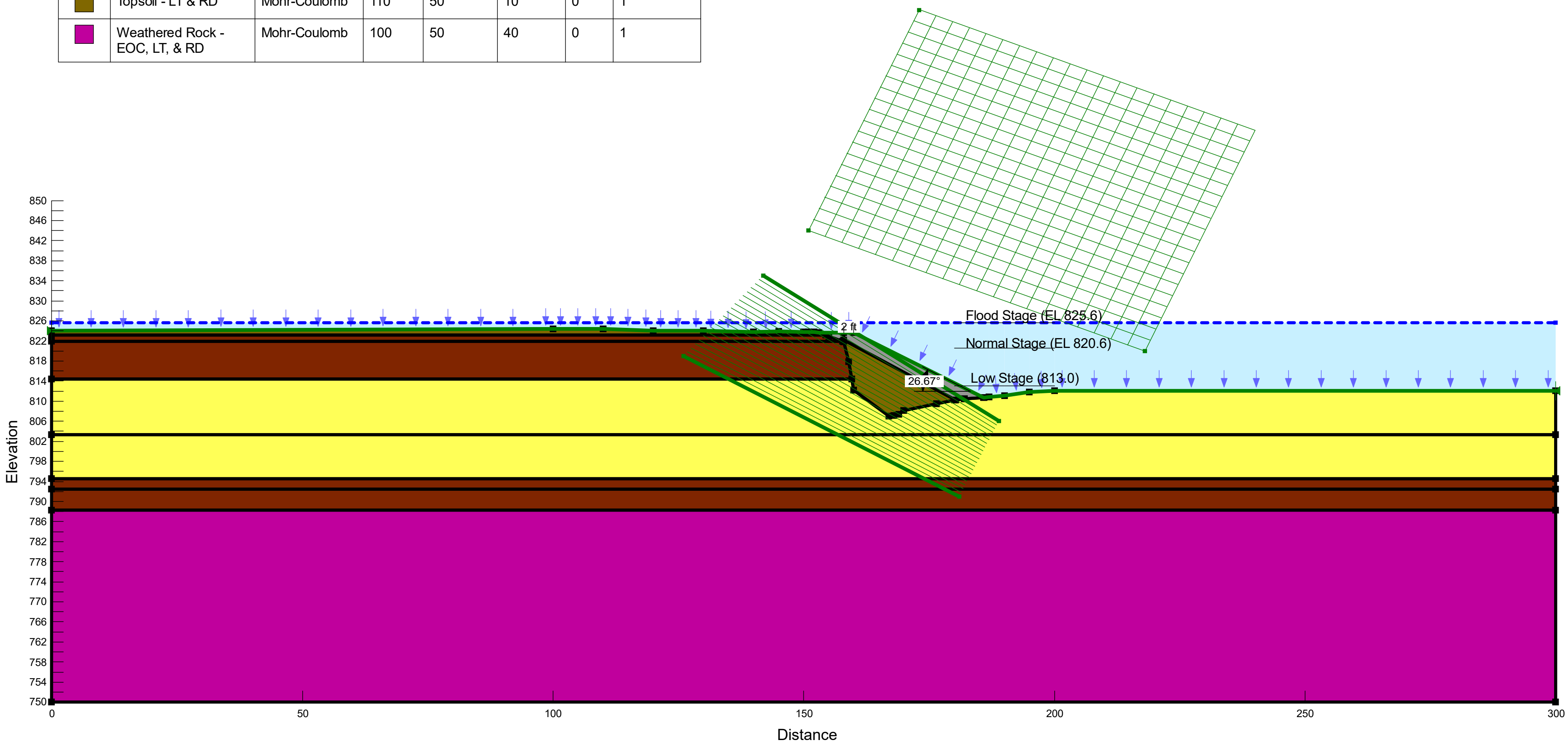
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Flood Stage - EOC - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

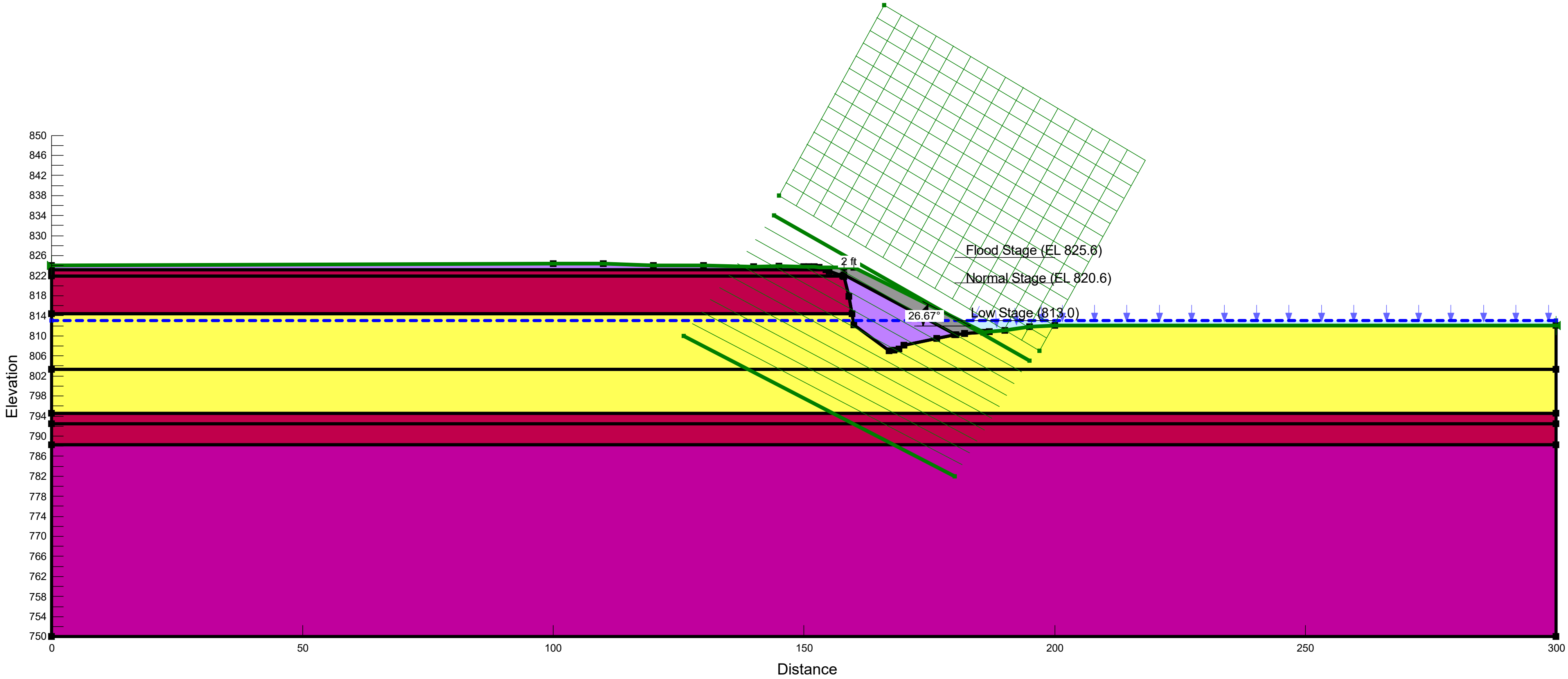
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Flood Stage - LT - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

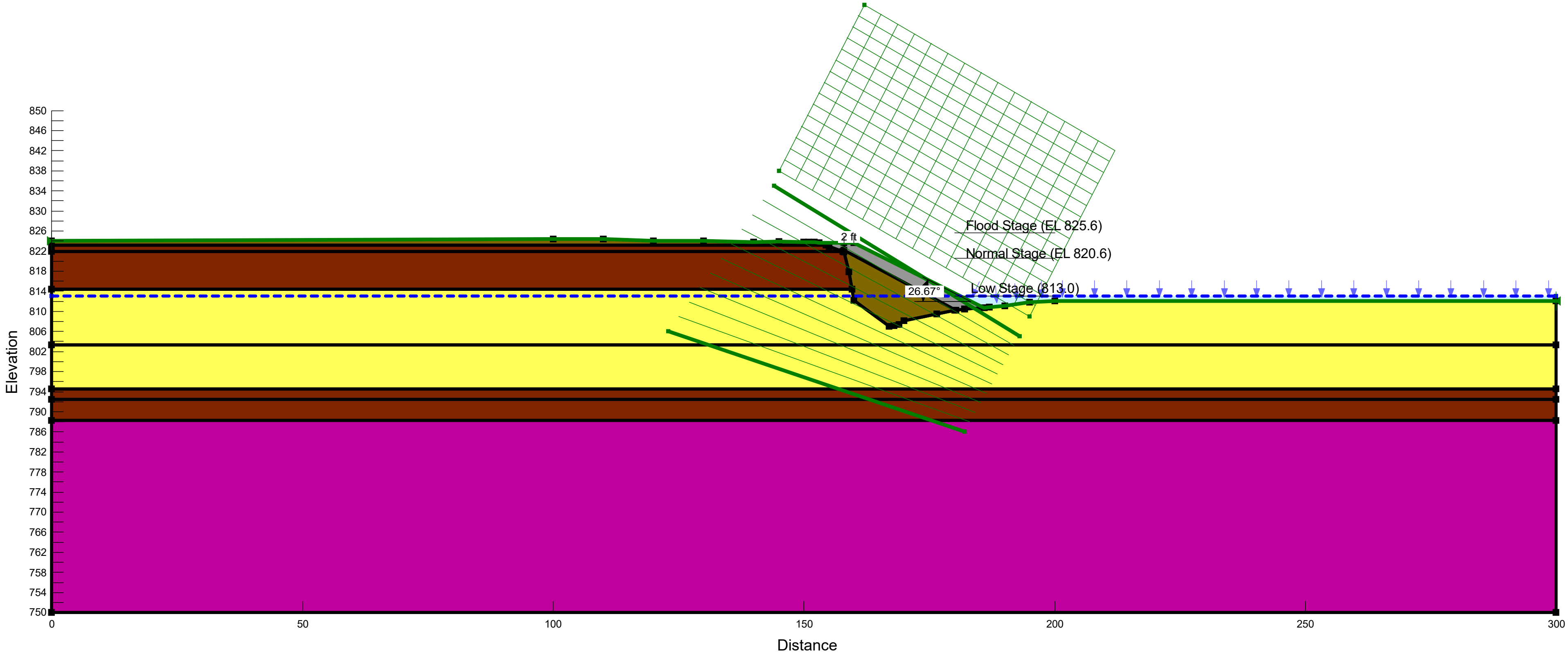
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Low Stage - EOC - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

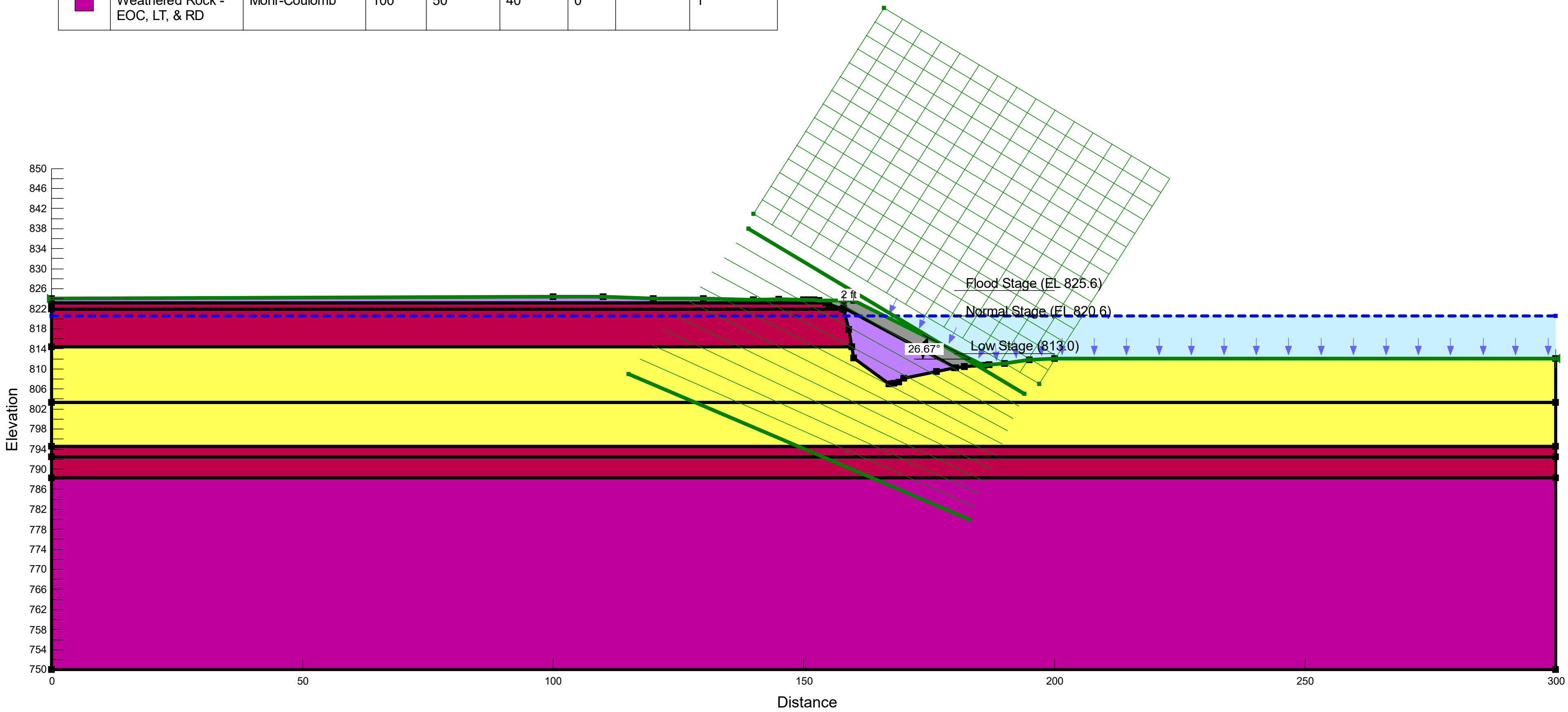
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Low Stage - LT - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

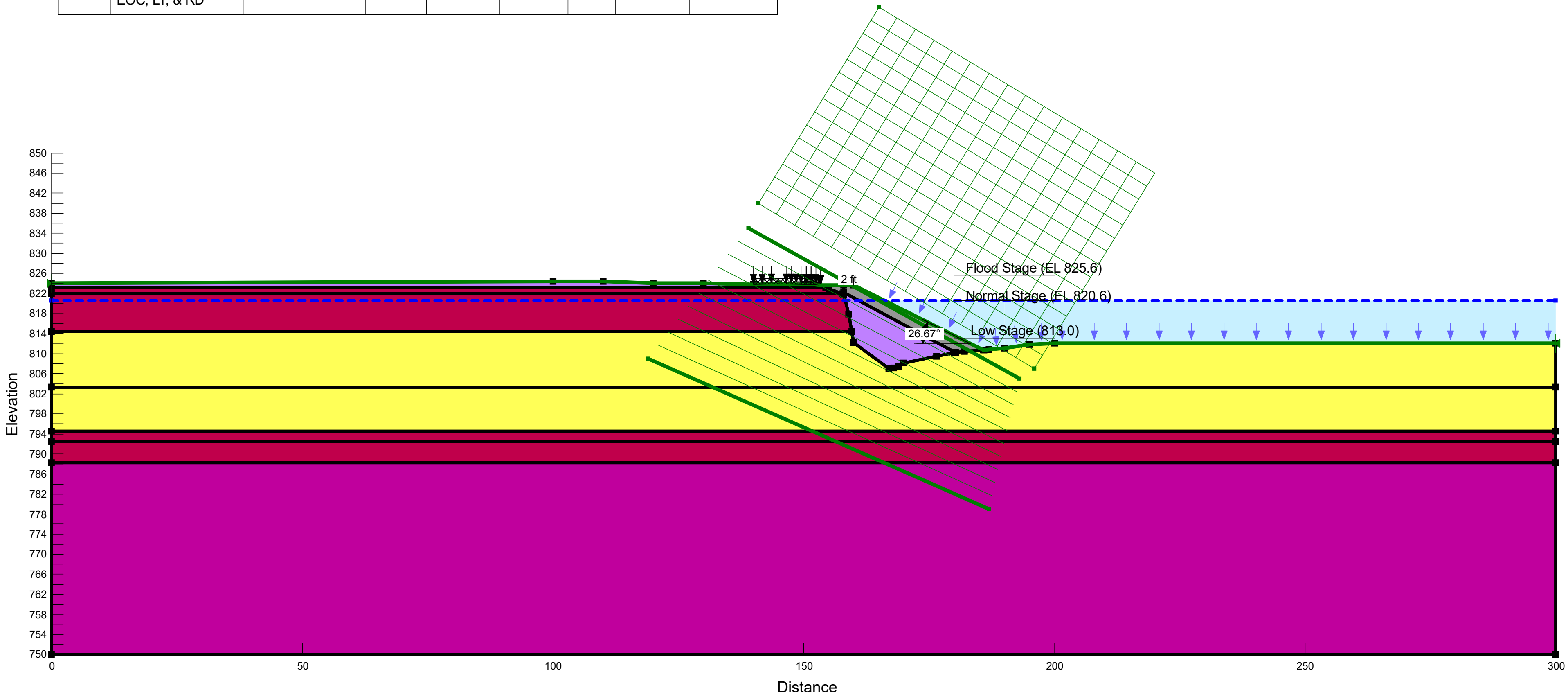
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
▒	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Normal Stage - EOC - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

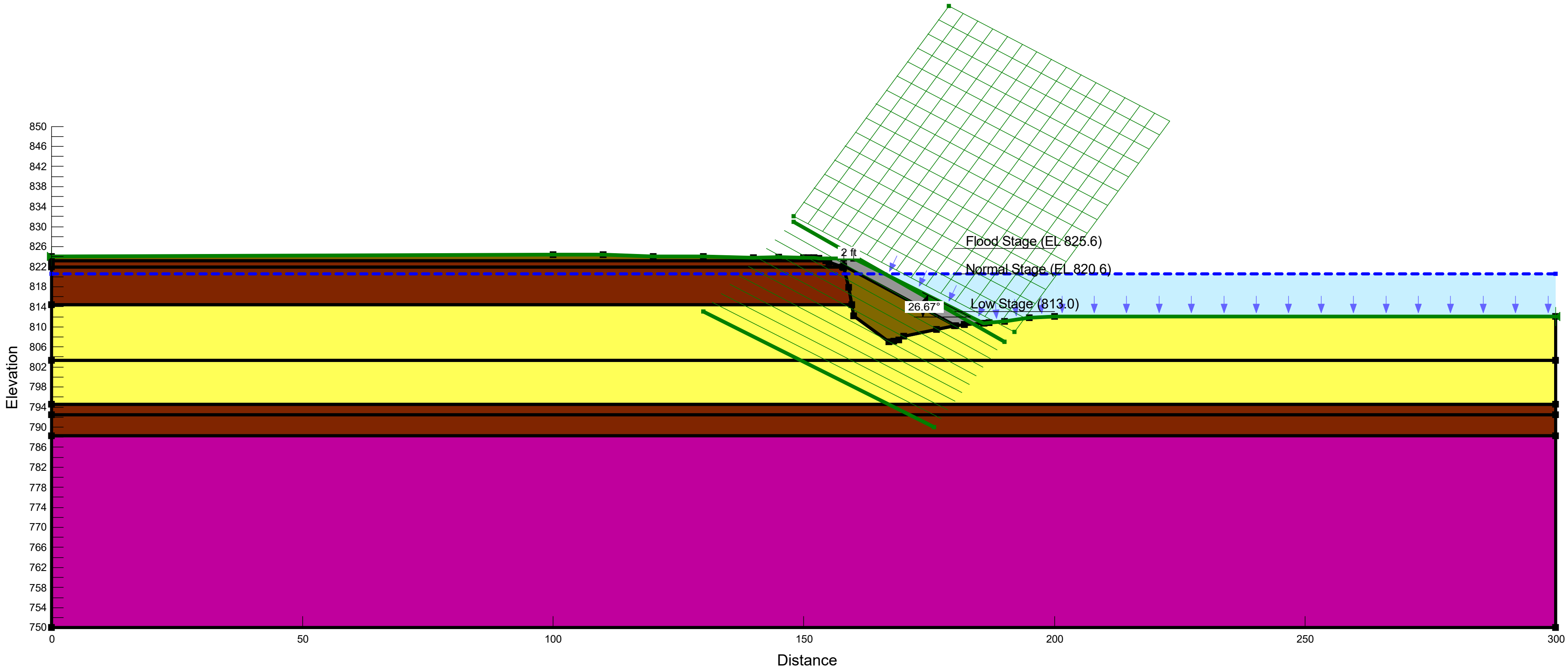
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
■	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Normal Stage - EOC - Surcharge - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

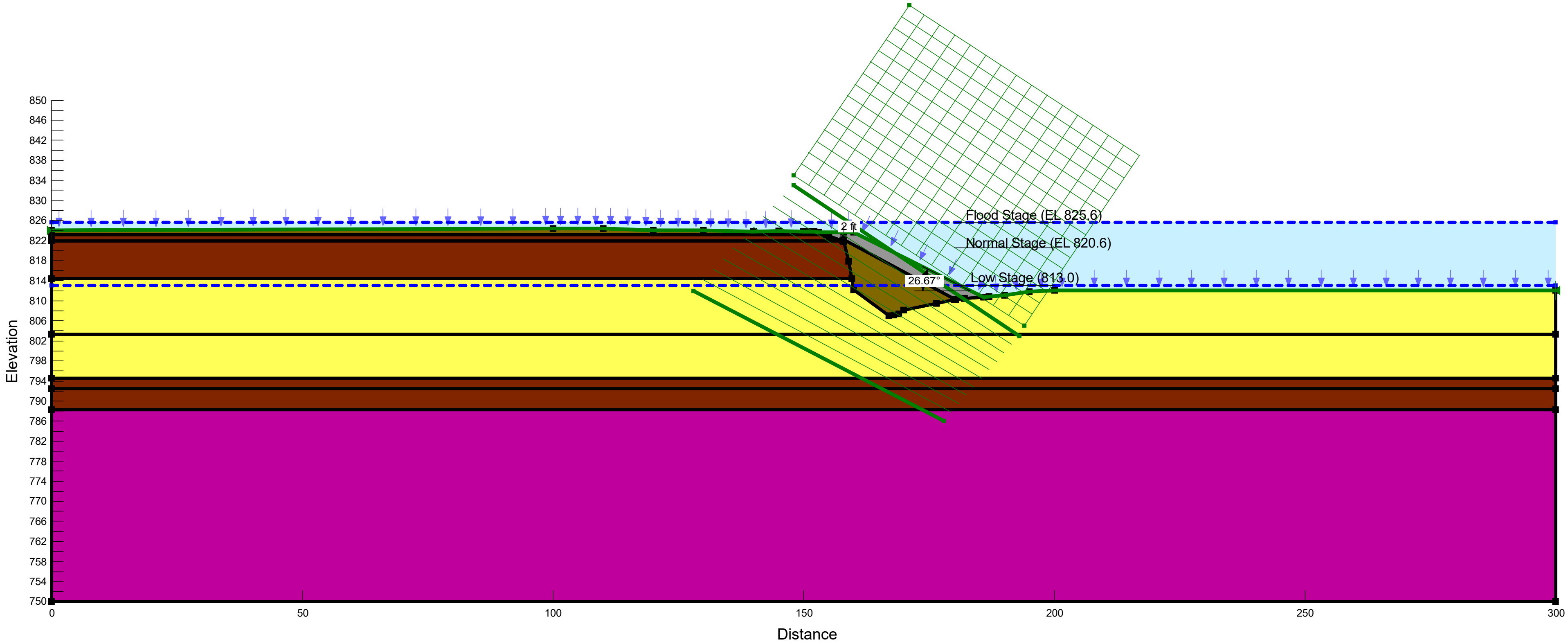
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
▨	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Normal Stage - LT - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

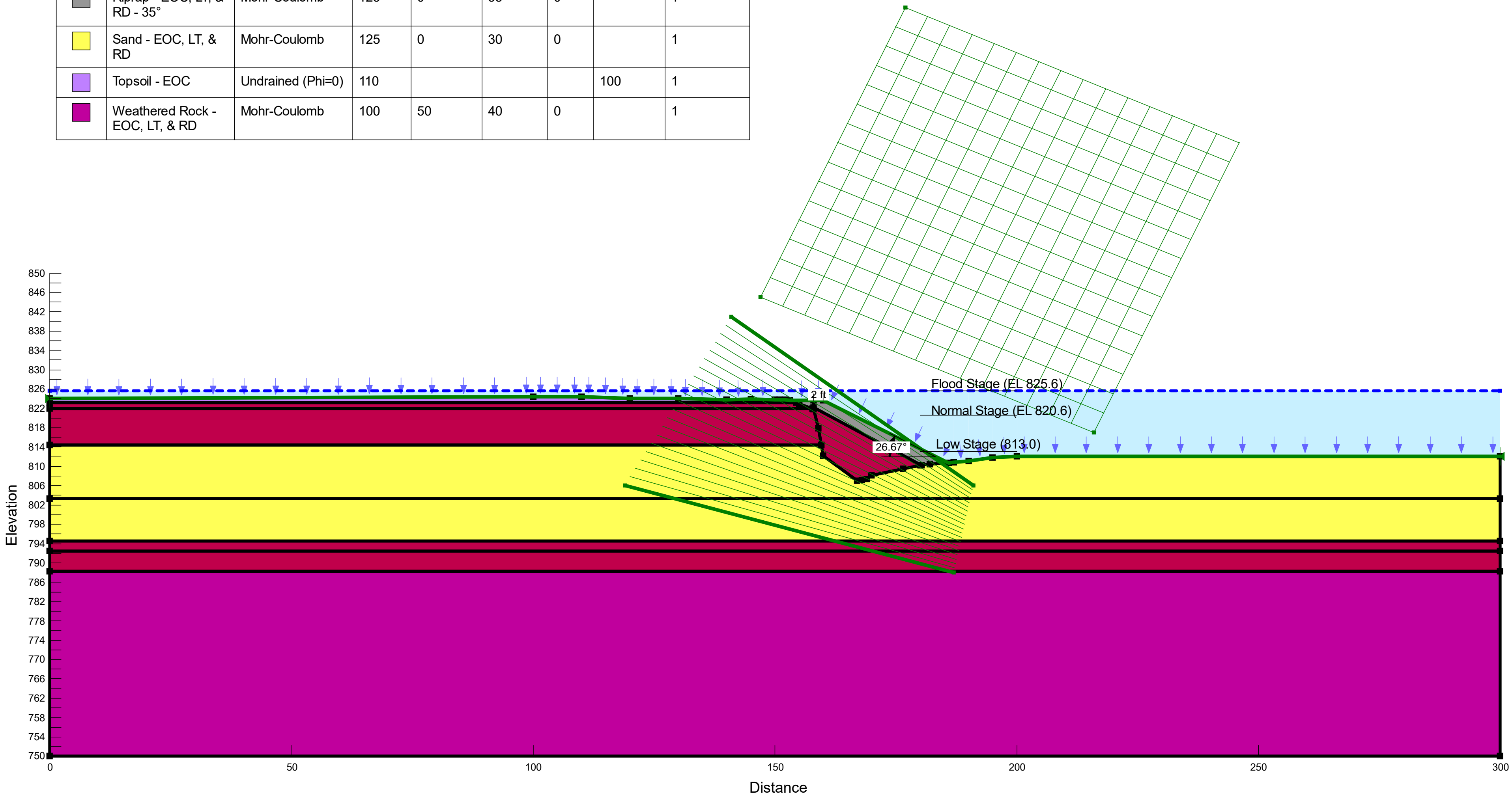
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	0	35	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2



Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Varied PZ Line - RD - F to L - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

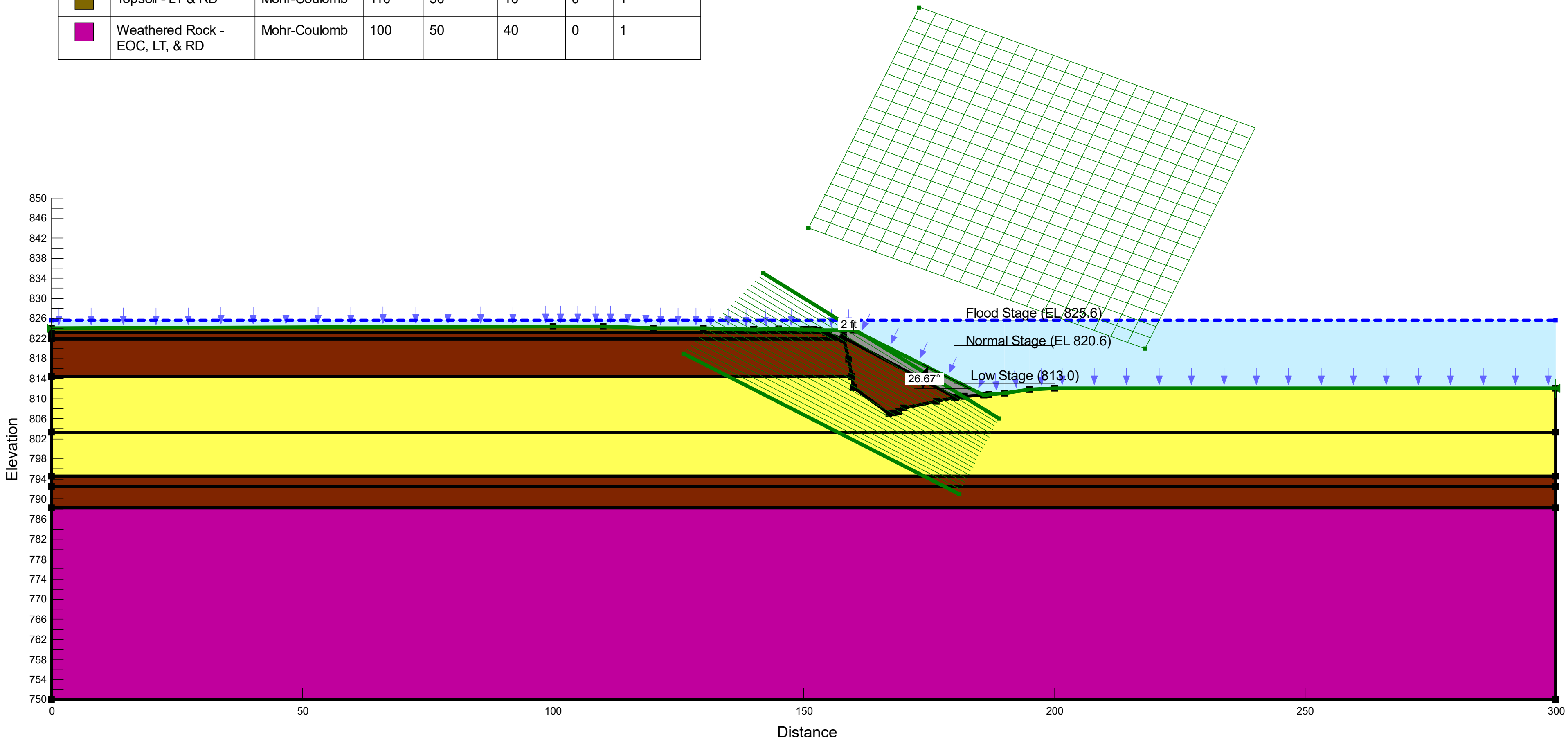
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Flood Stage - EOC - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

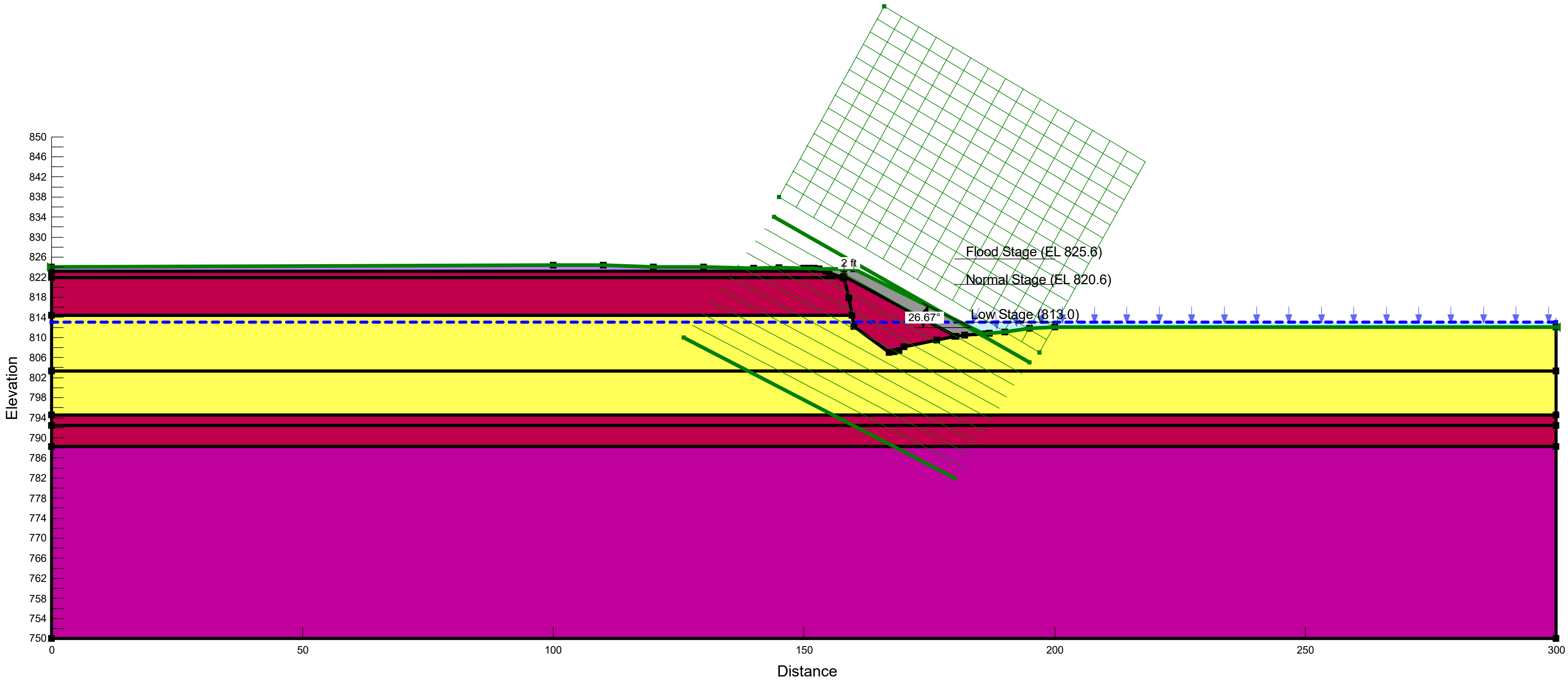
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Flood Stage - LT - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

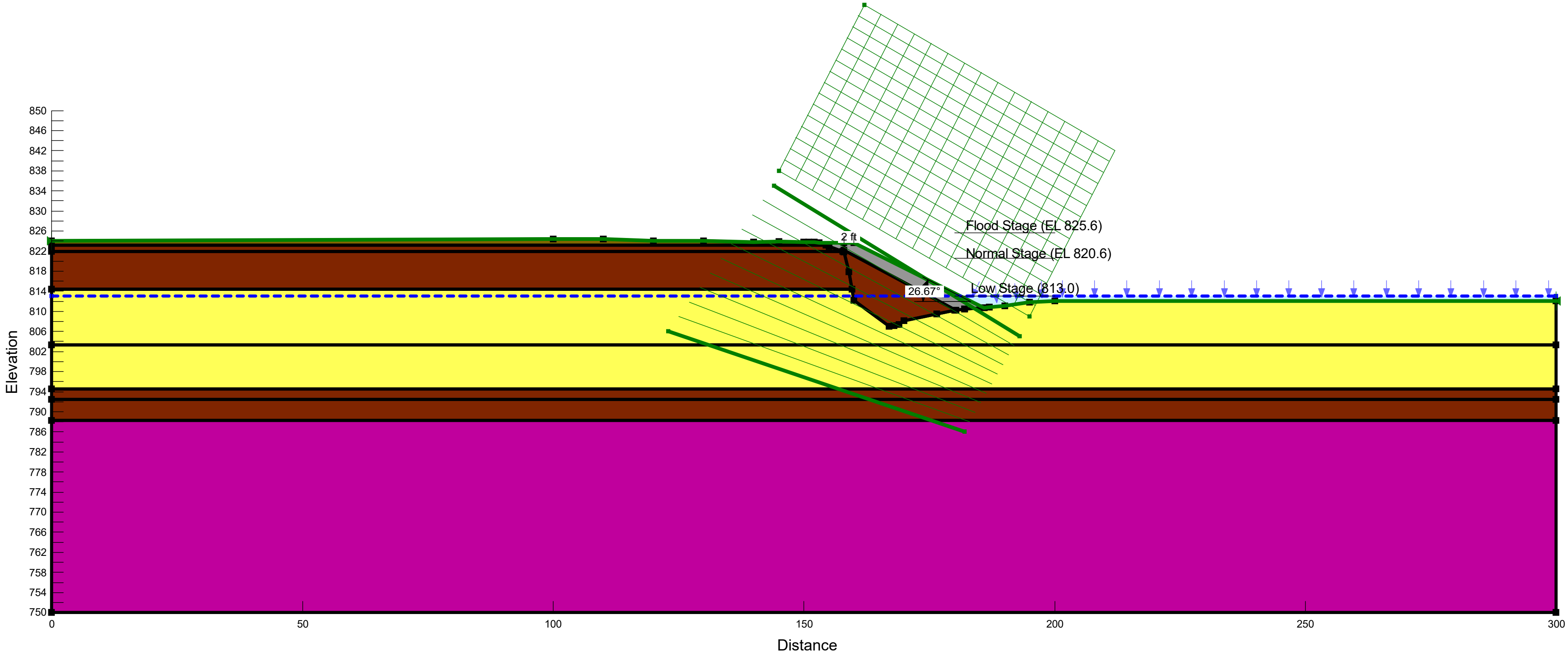
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
◼	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Low Stage - EOC - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

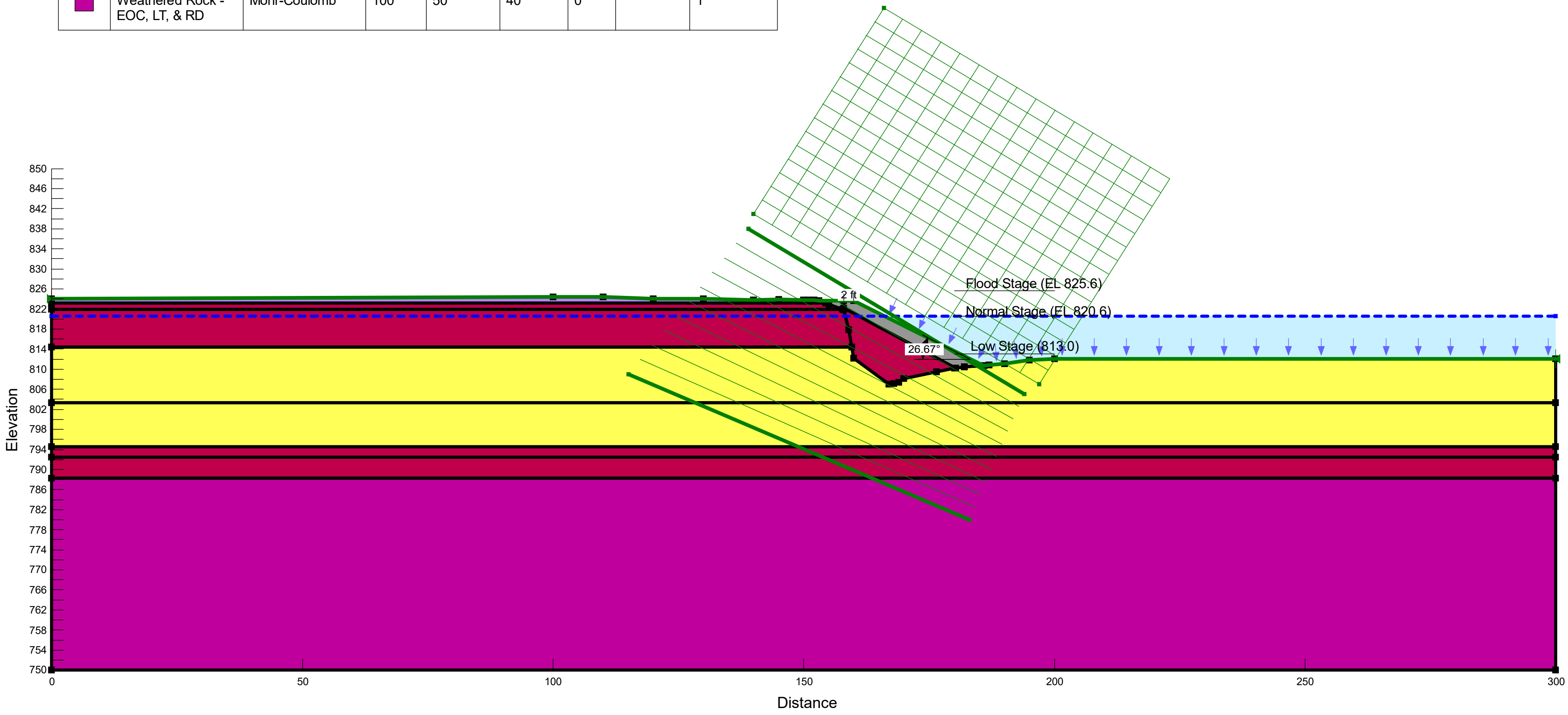
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
▨	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Low Stage - LT - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

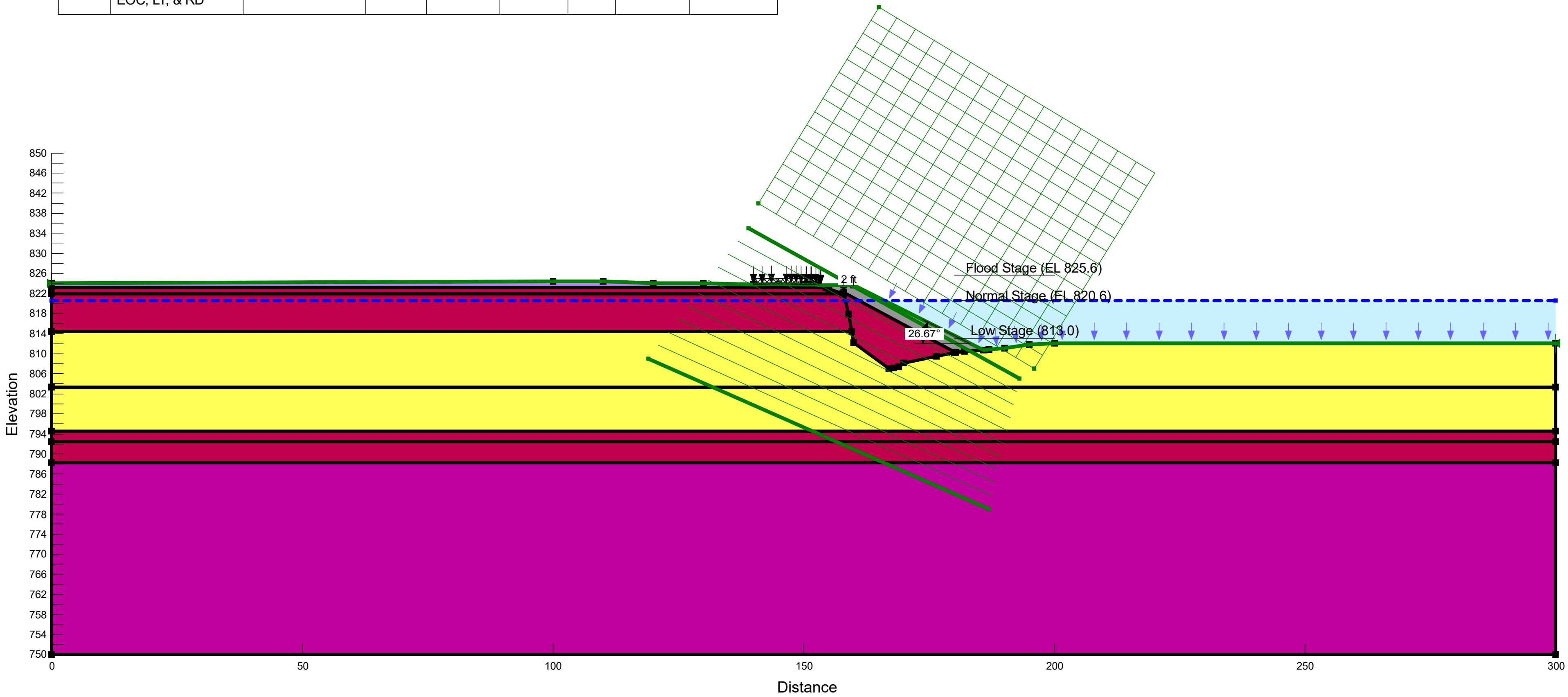
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Normal Stage - EOC - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

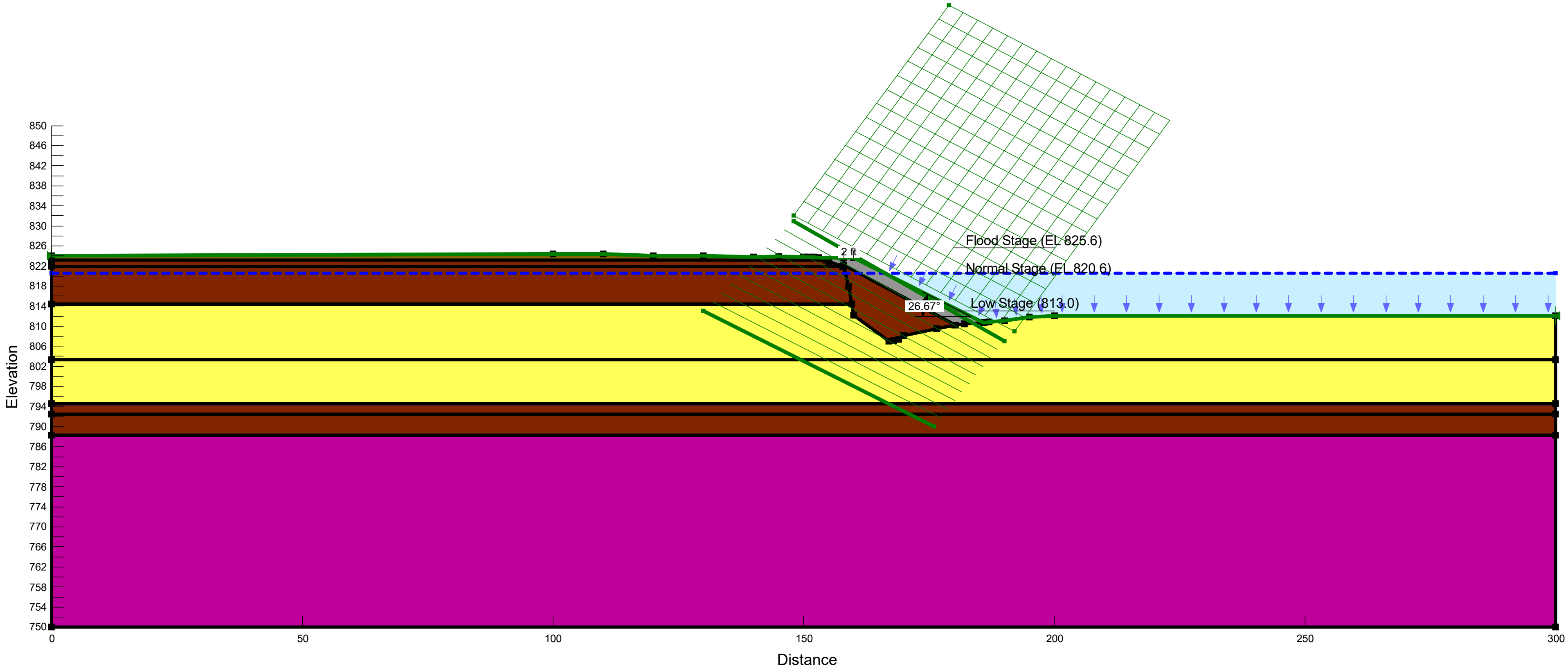
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Normal Stage - EOC - Surcharge - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

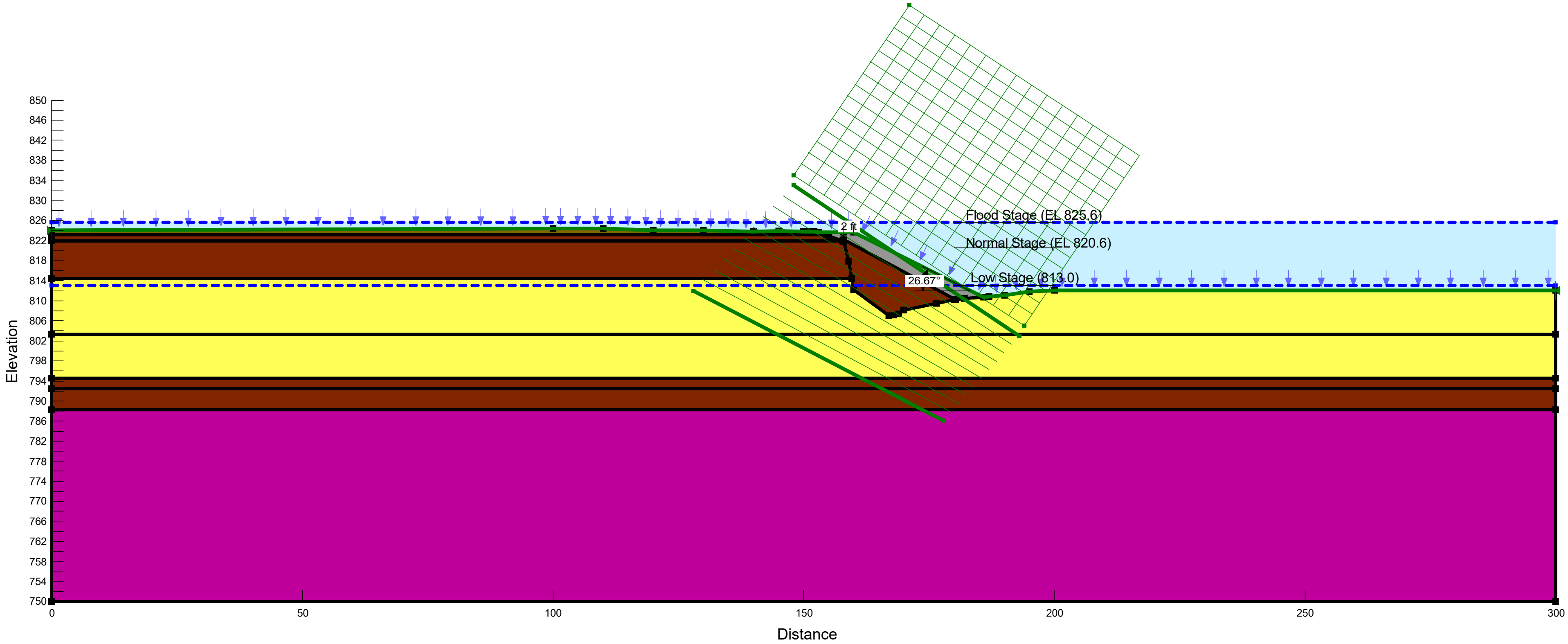
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Normal Stage - LT - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

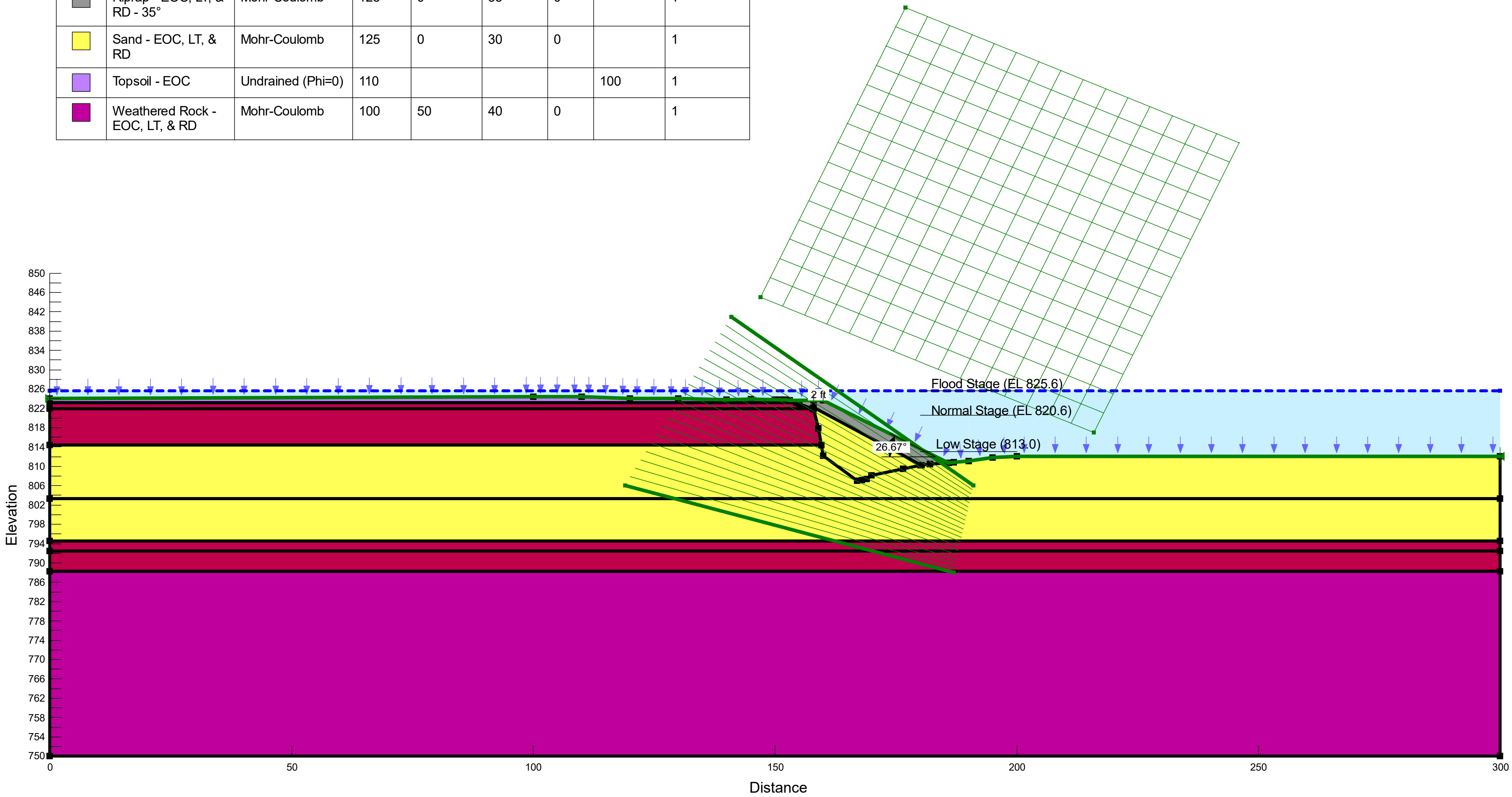
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	0	35	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2



Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Varied PZ Line - RD - F to L - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

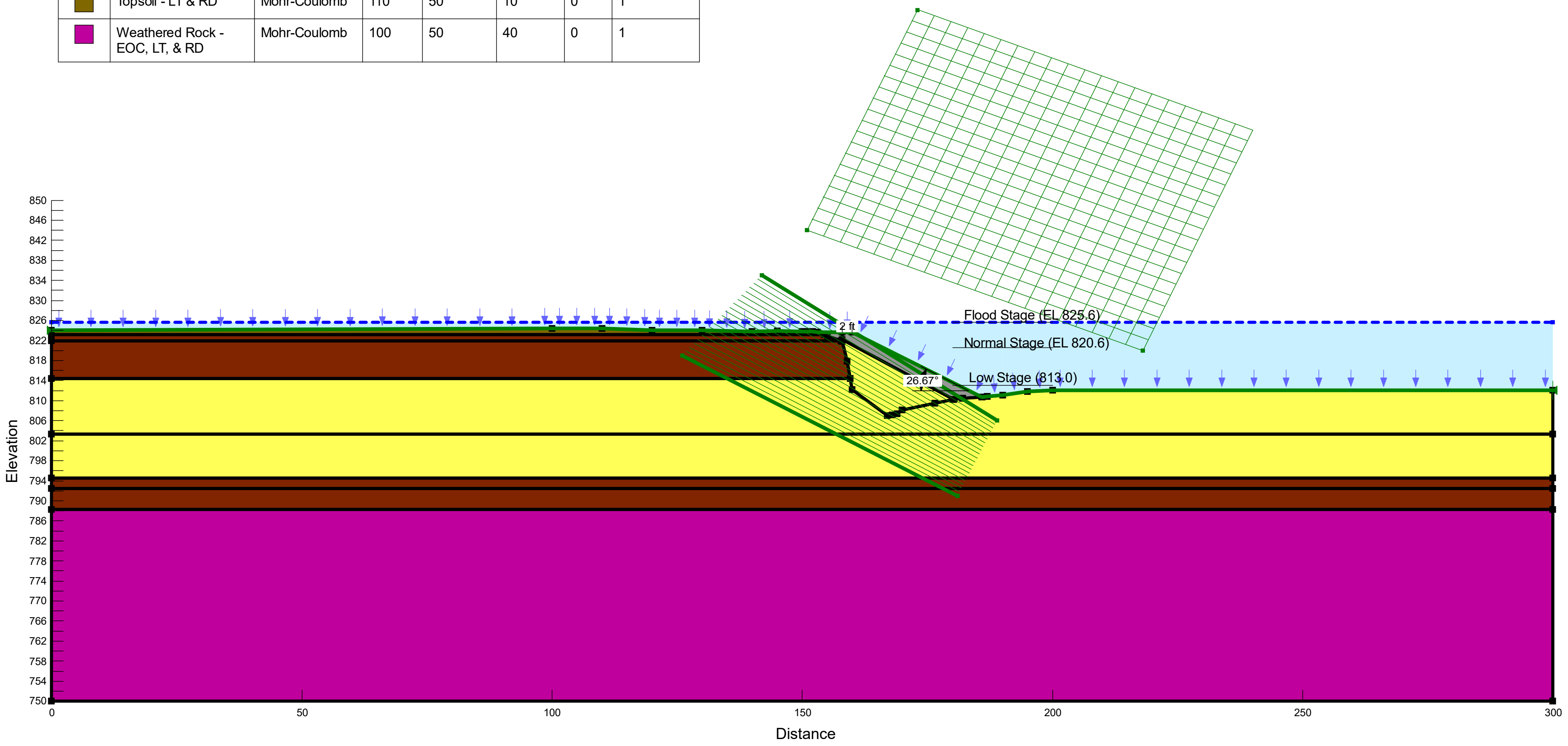
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Flood Stage - EOC - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

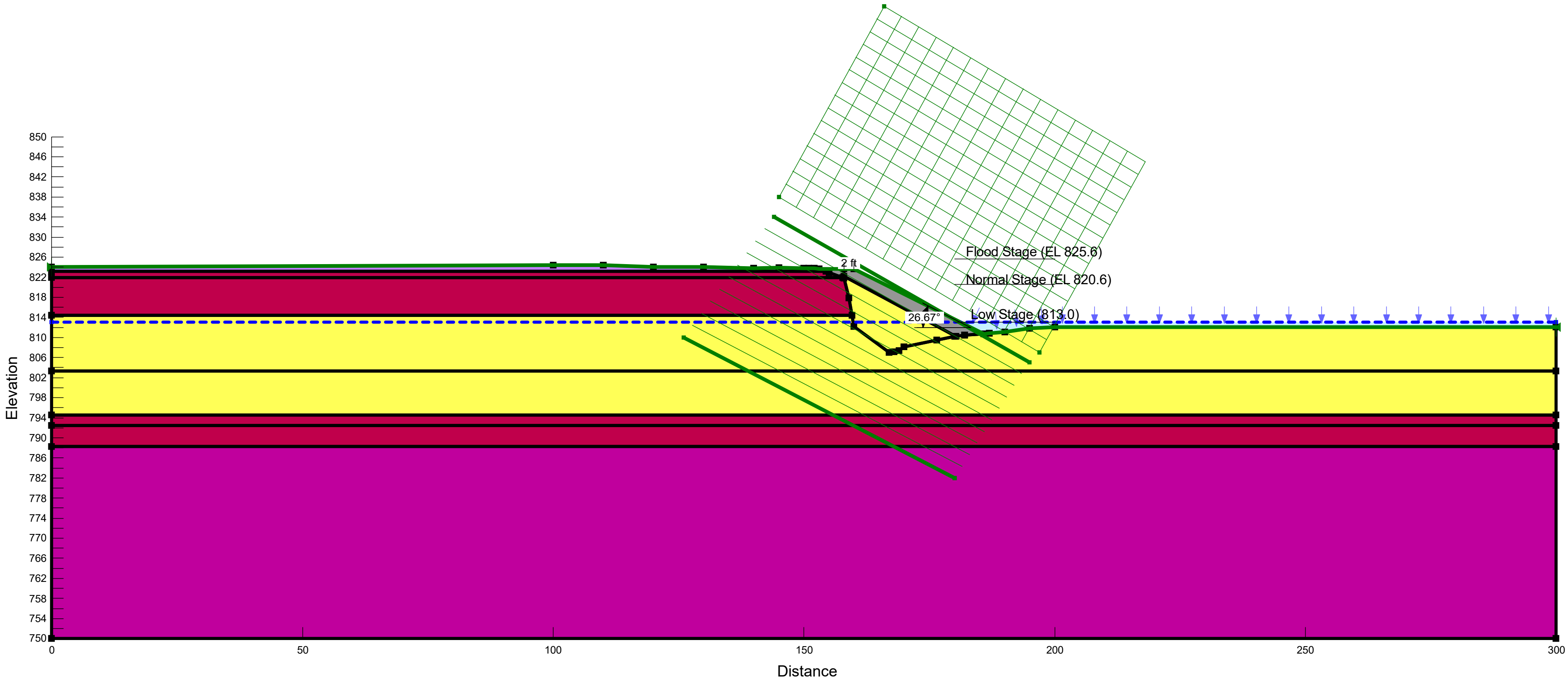
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Flood Stage - LT - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

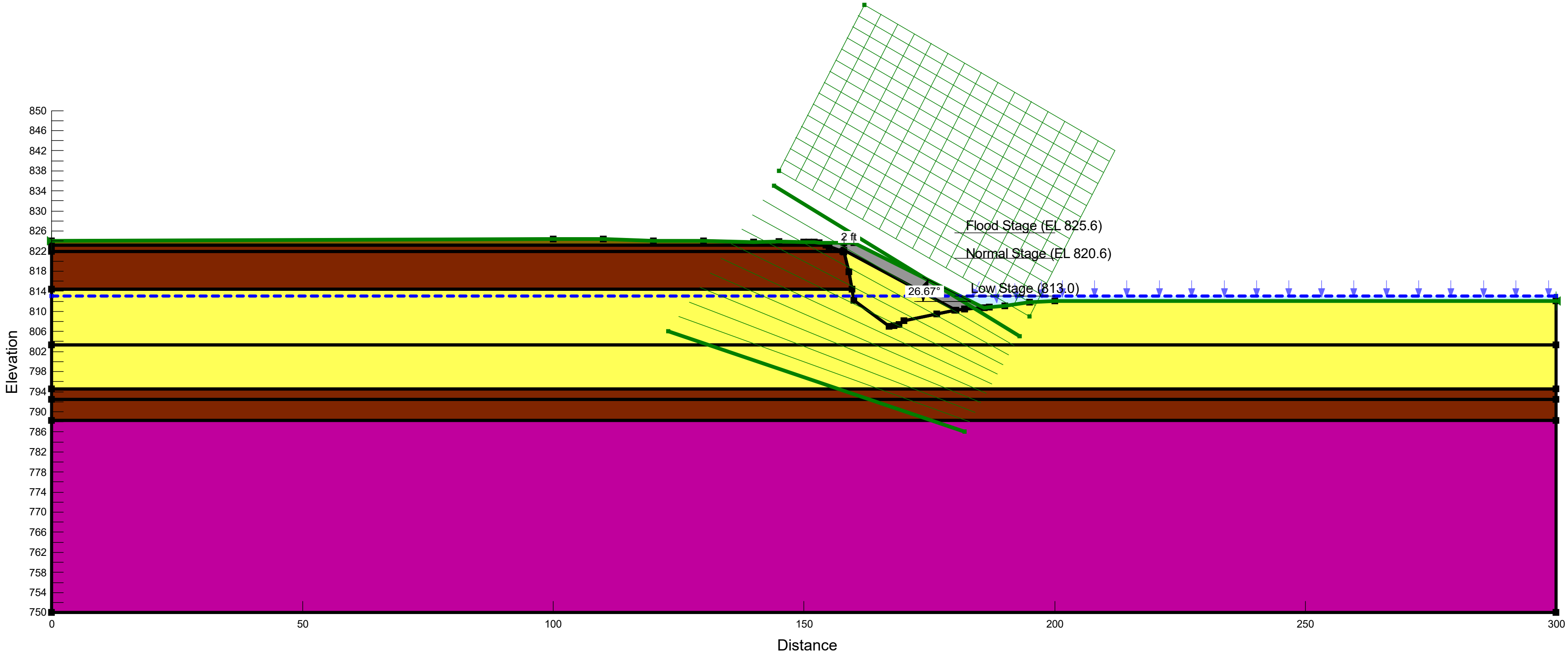
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Low Stage - EOC - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

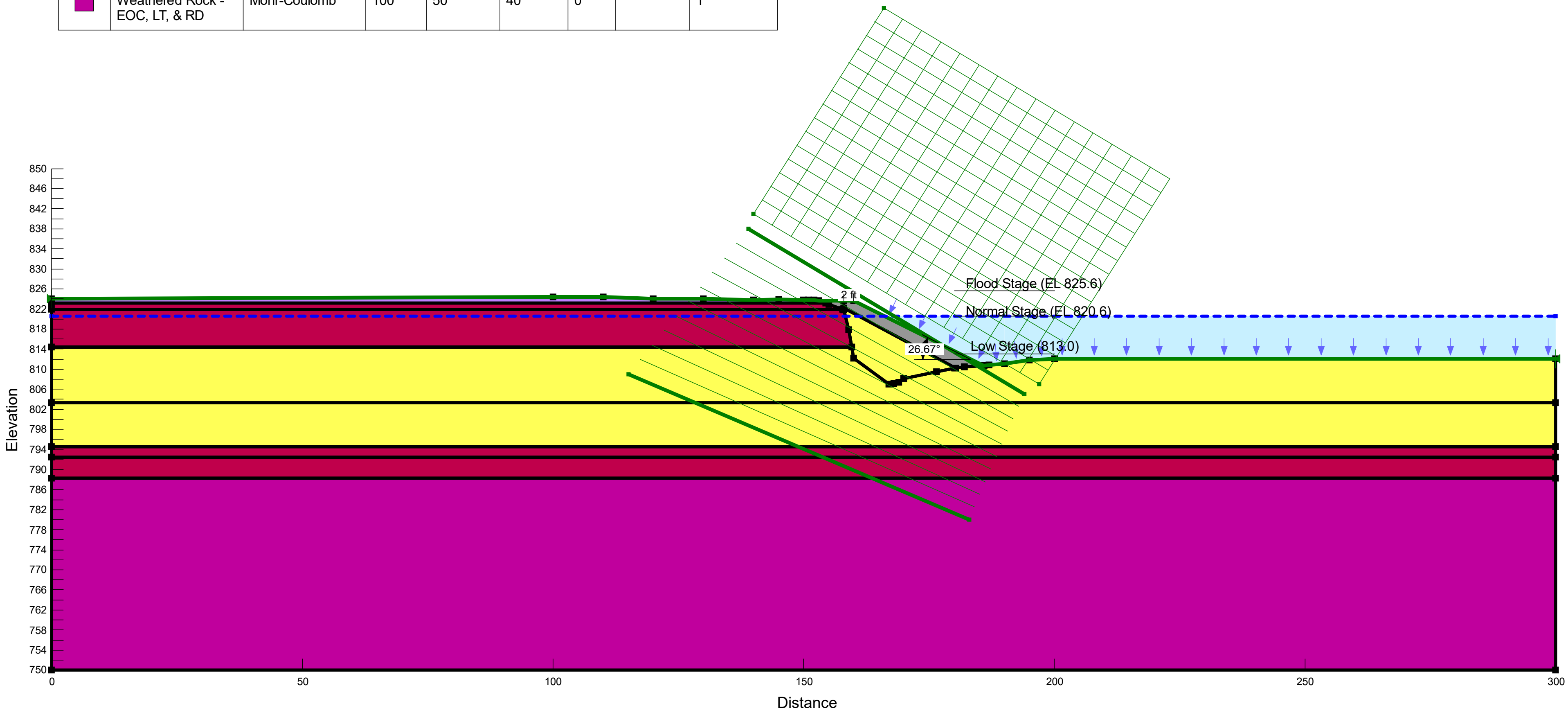
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
◼	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Low Stage - LT - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

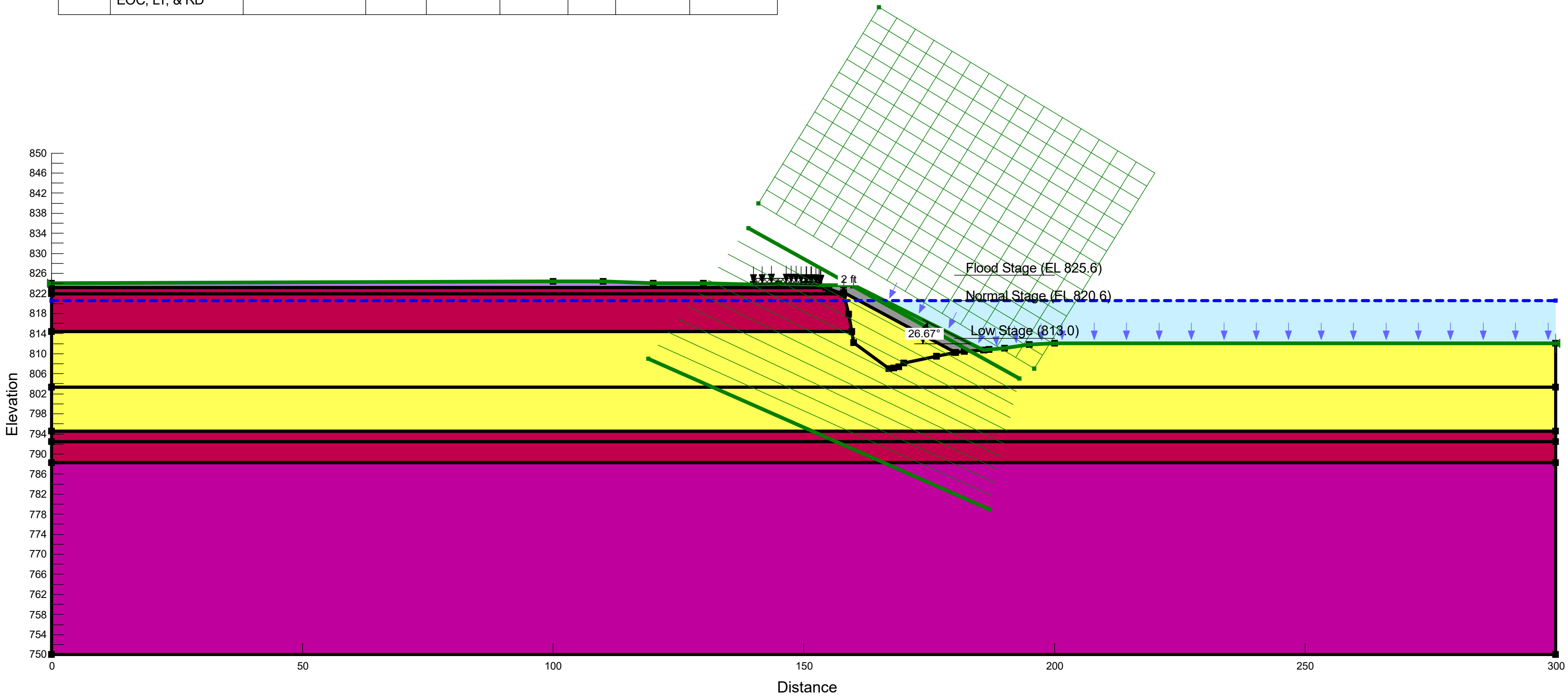
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Normal Stage - EOC - Alt3 (9)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

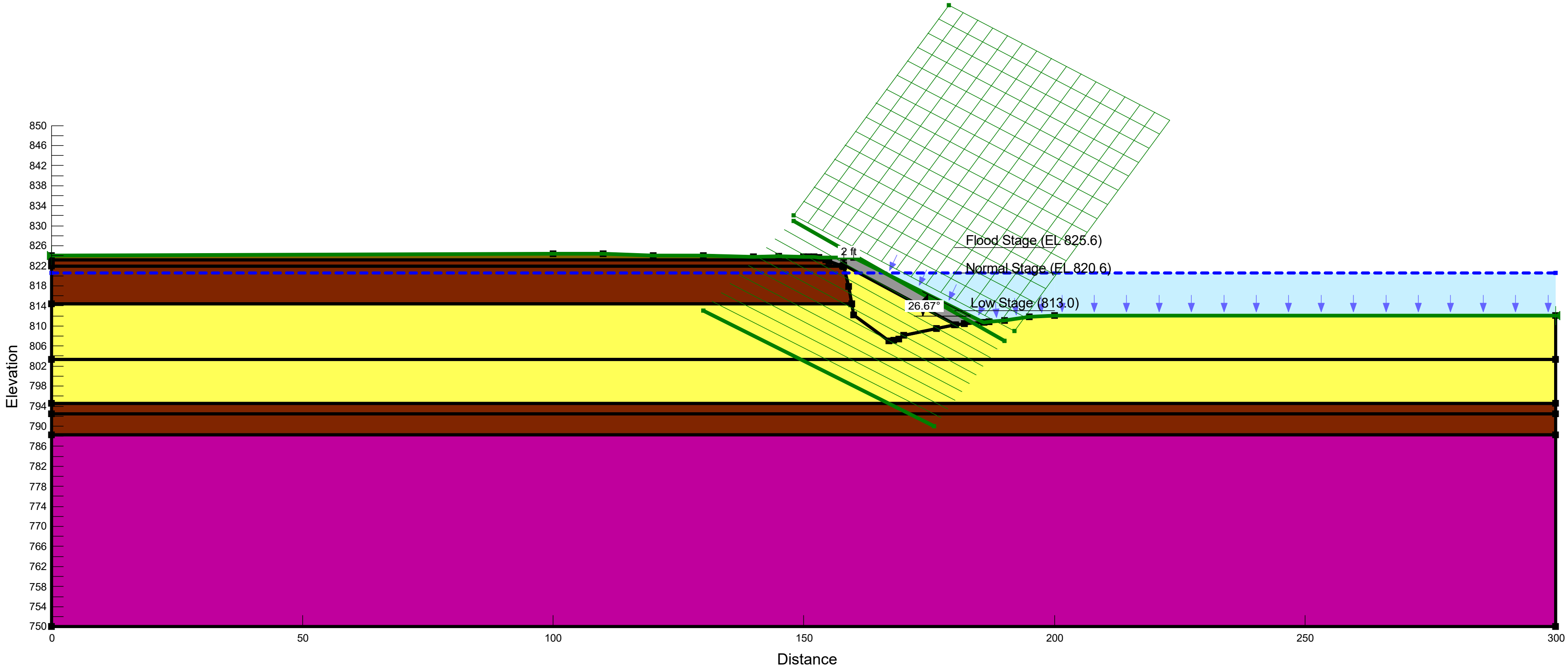
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1



Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Normal Stage - EOC - Surcharge - Alt3 (9)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

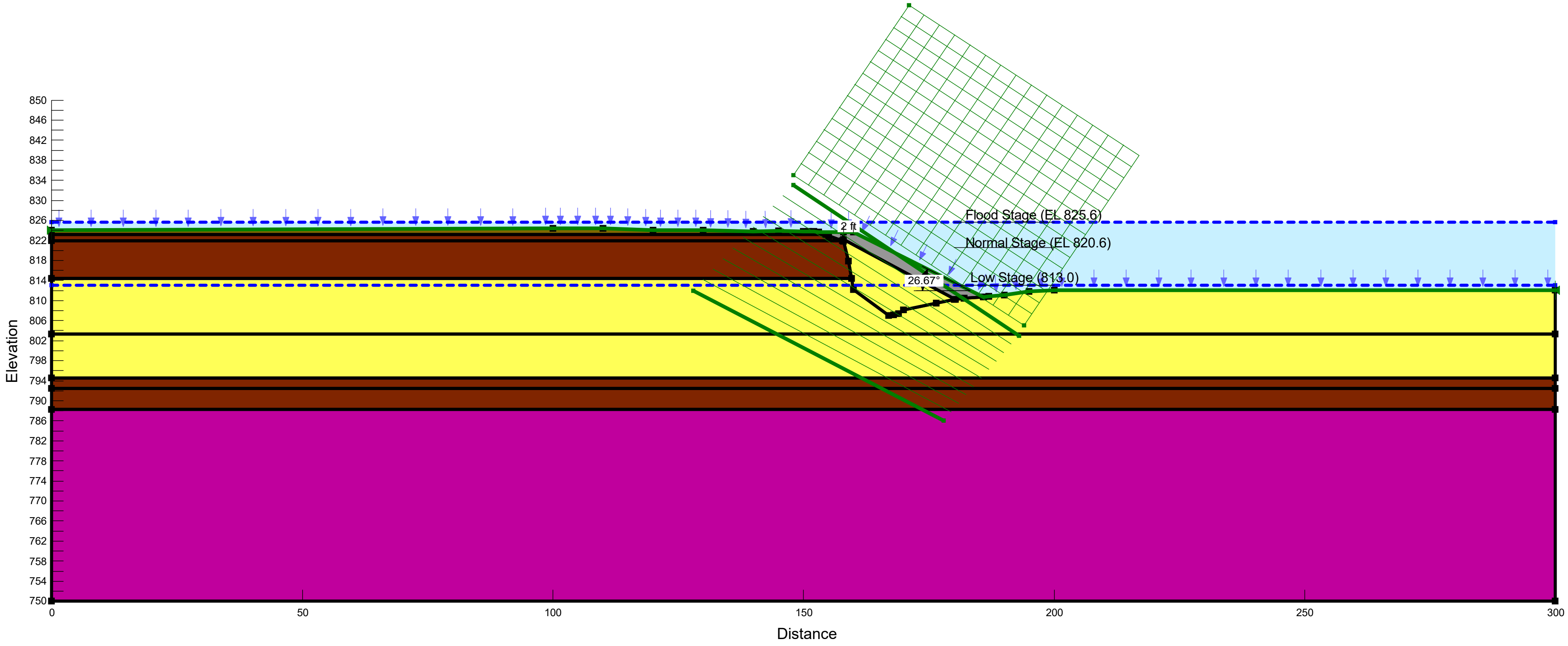
Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1



Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Normal Stage - LT - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	0	35	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2

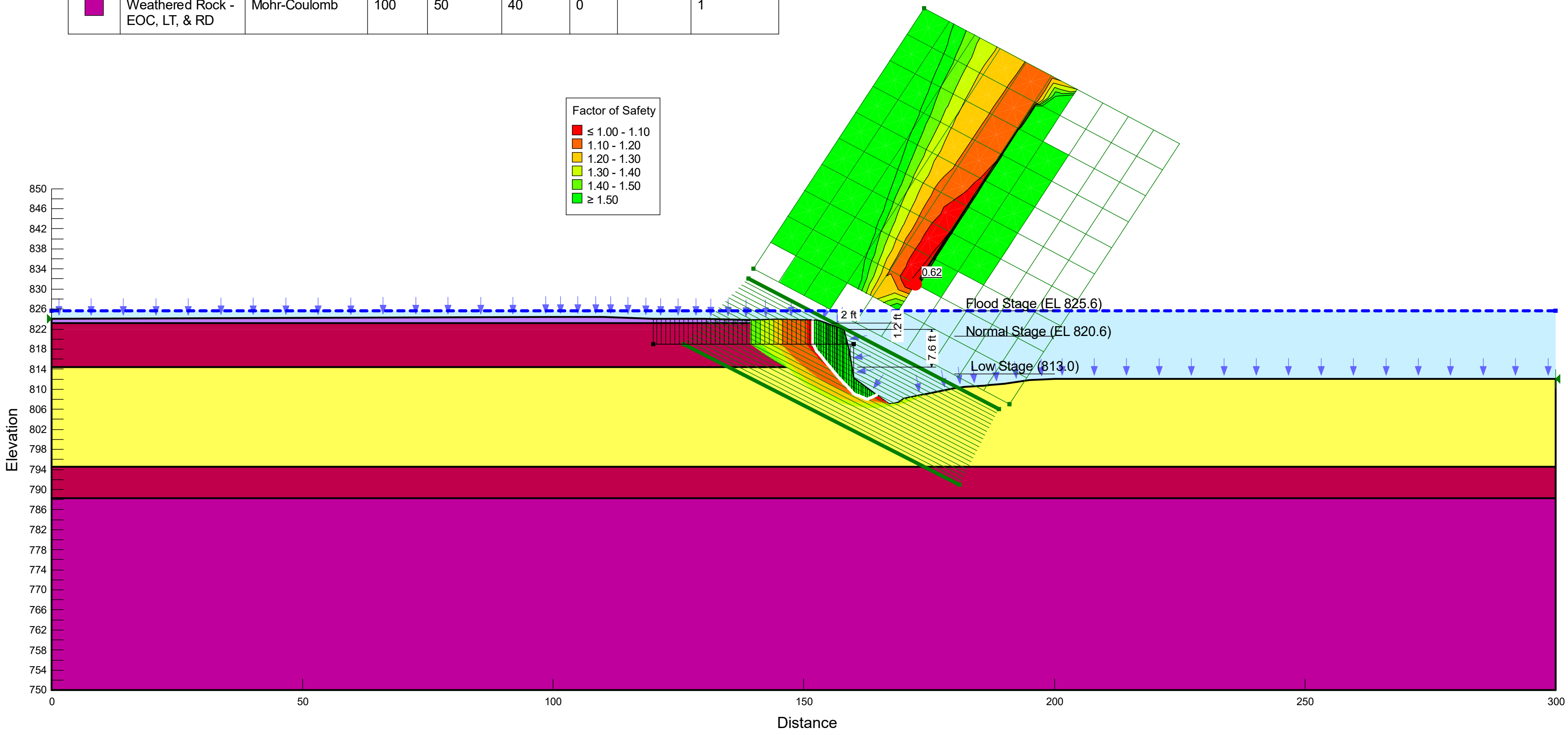


Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Varied PZ Line - RD - F to L - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,542 slip surfaces
Factor of Safety: 0.62

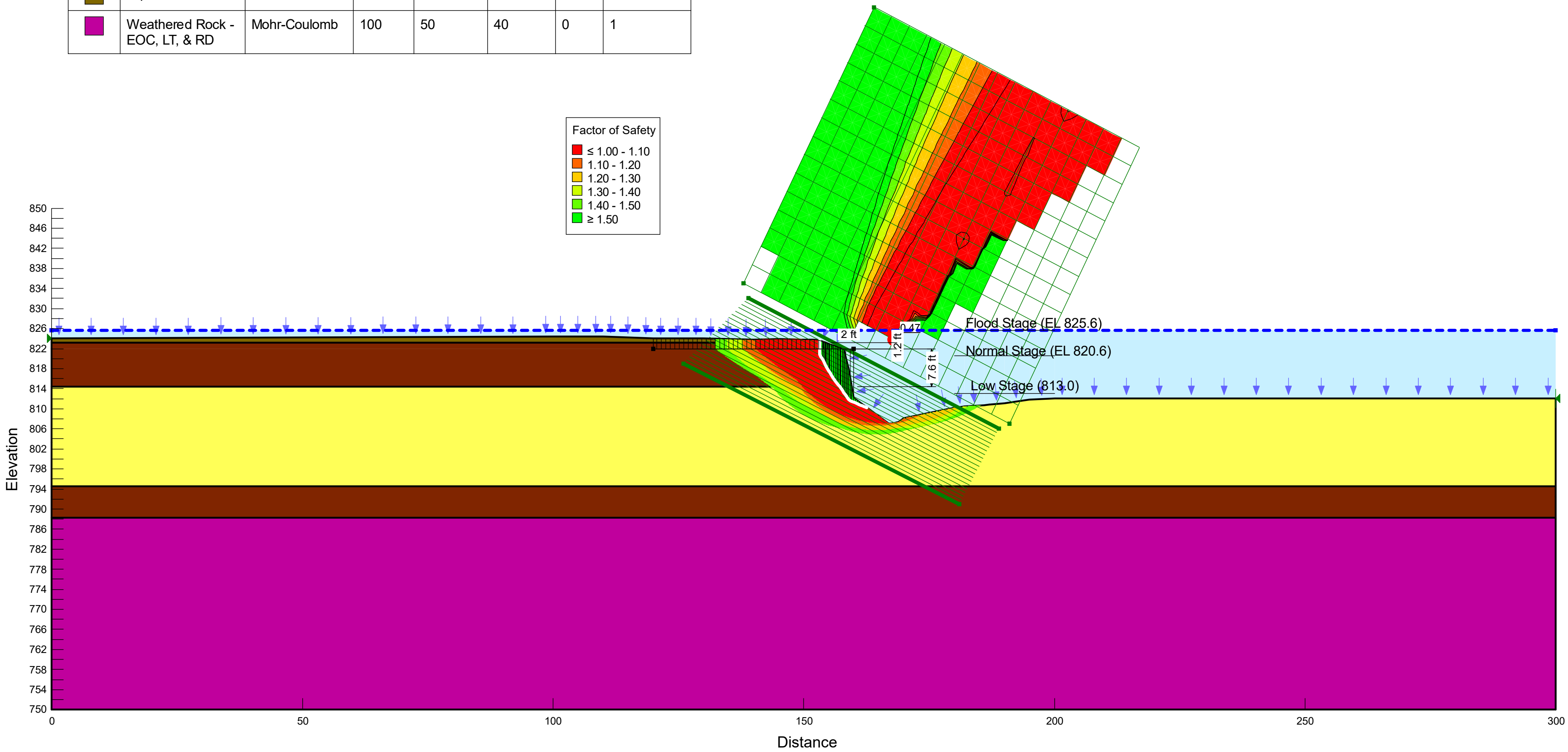


Name: 1 - Existing Conditions
Name: Flood Stage - EOC - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 5,377 slip surfaces
Factor of Safety: 0.47

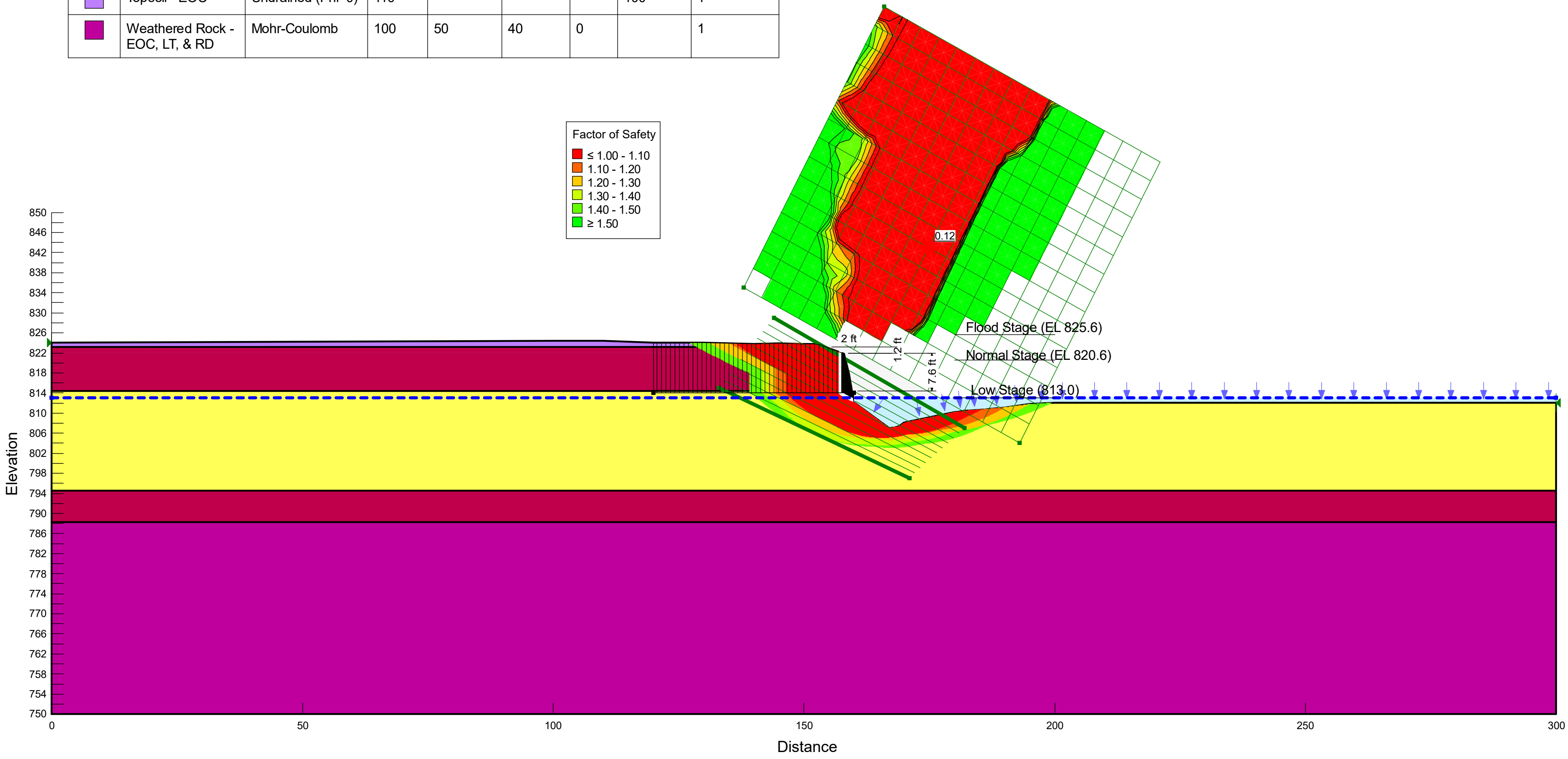


Name: 1 - Existing Conditions
Name: Flood Stage - LT - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.12

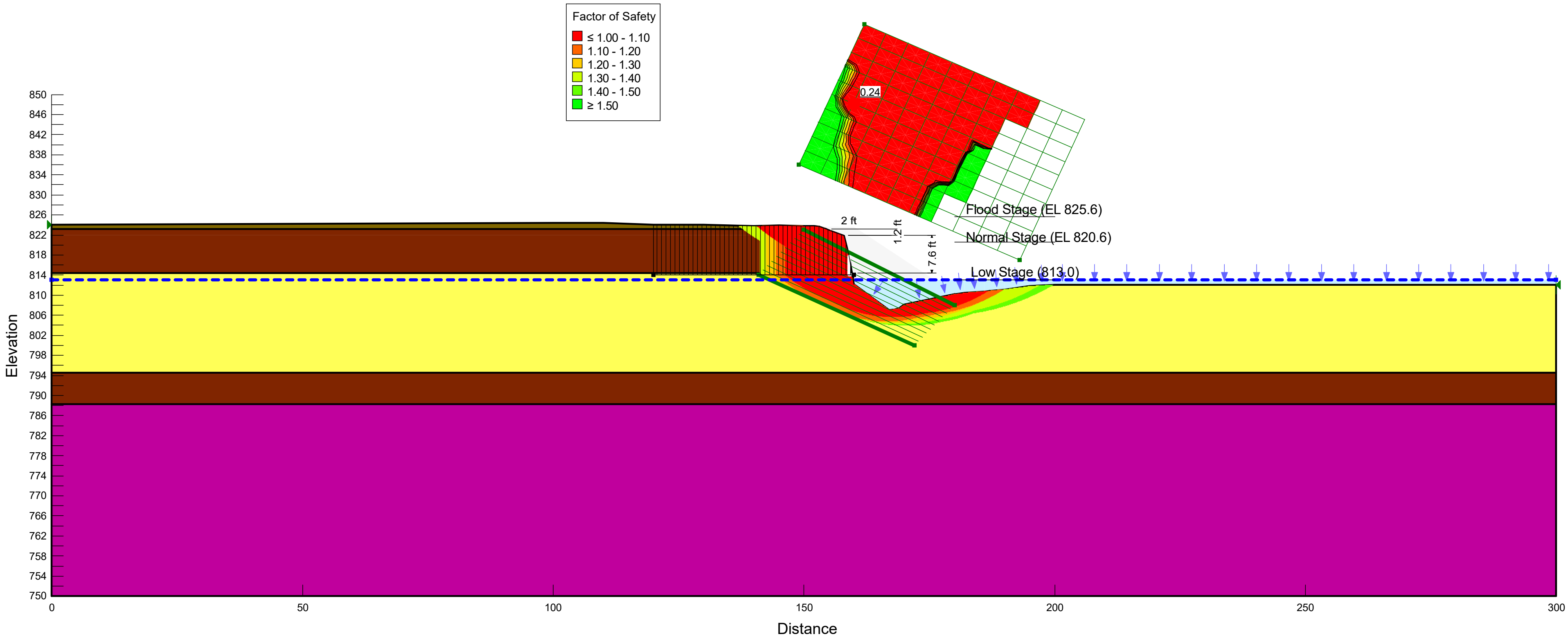


Name: 1 - Existing Conditions
Name: Low Stage - EOC - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 1,332 slip surfaces
Factor of Safety: 0.24

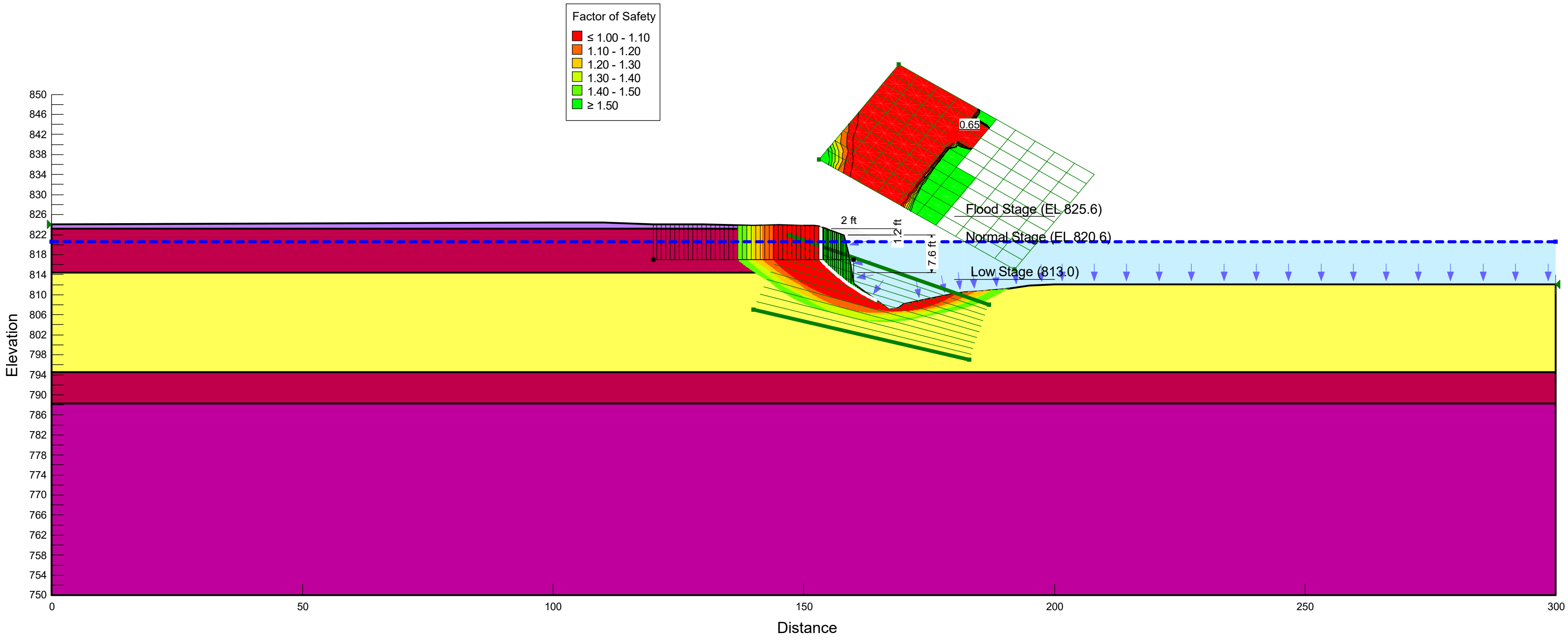


Name: 1 - Existing Conditions
Name: Low Stage - LT - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 1,332 slip surfaces
Factor of Safety: 0.65

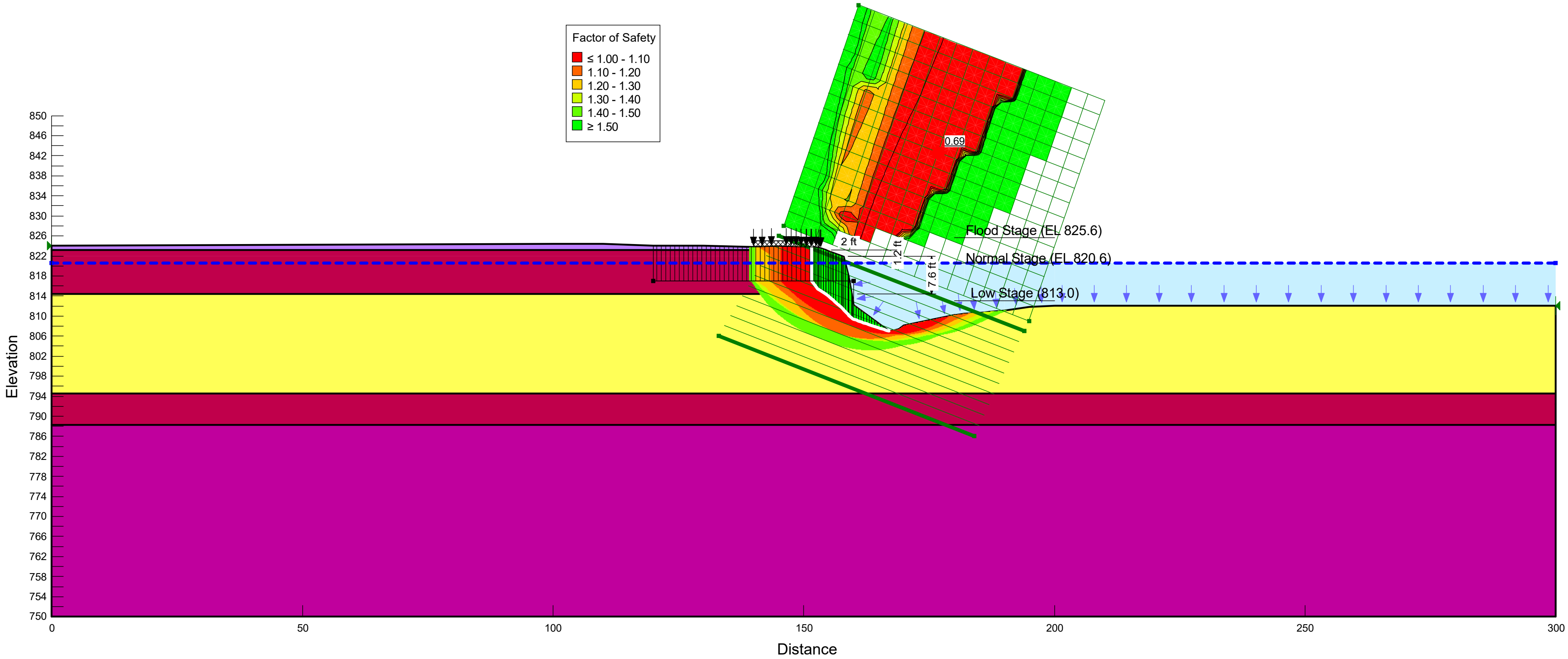


Name: 1 - Existing Conditions
Name: Normal Stage - EOC - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.69

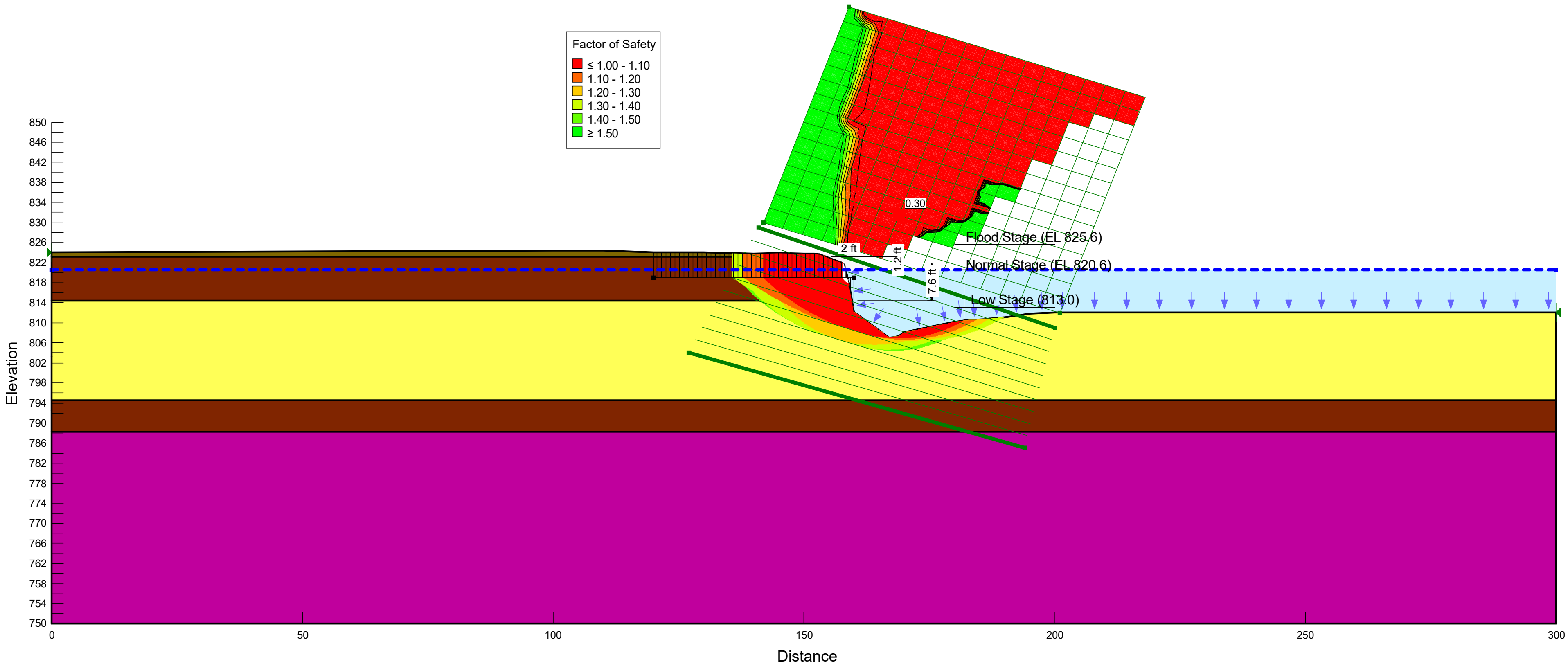


Name: 1 - Existing Conditions
Name: Normal Stage - EOC - Surcharge - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.30

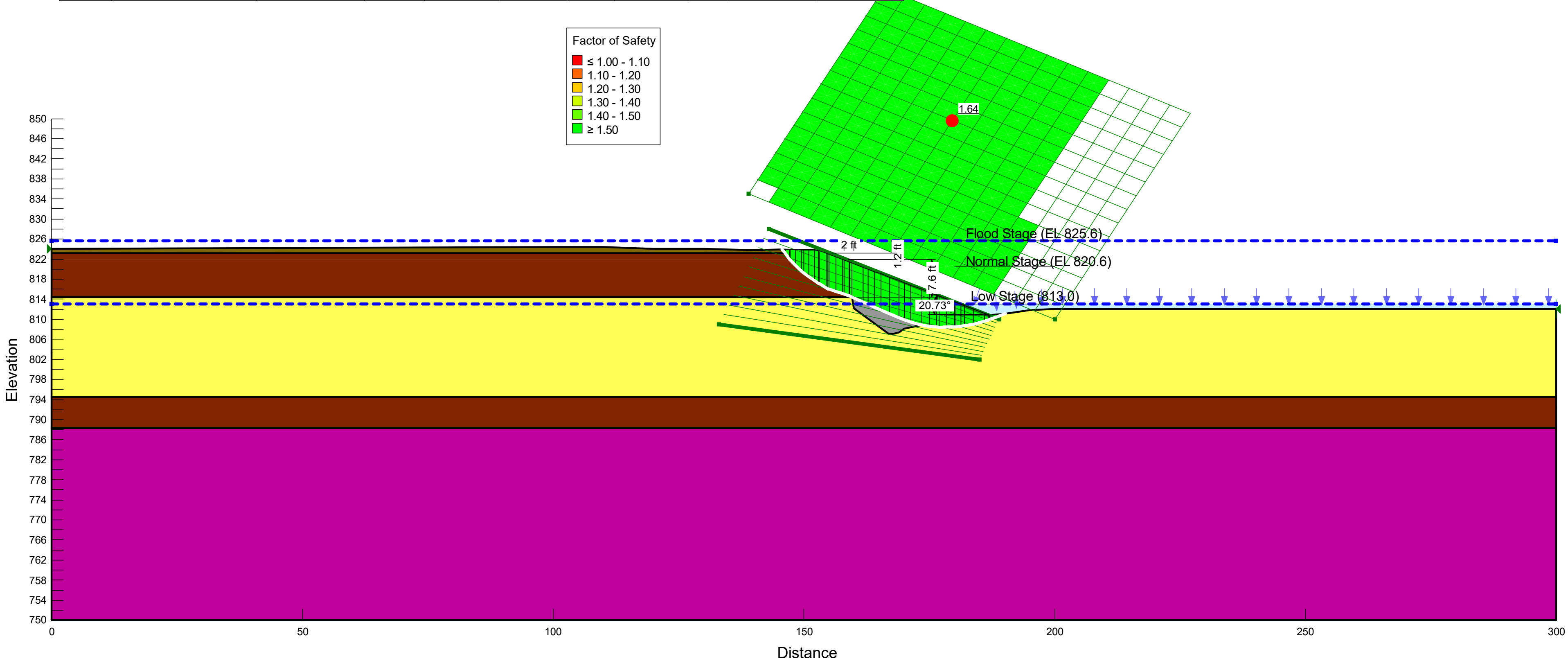


Name: 1 - Existing Conditions
Name: Normal Stage - LT - ExCon
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	0	35	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2

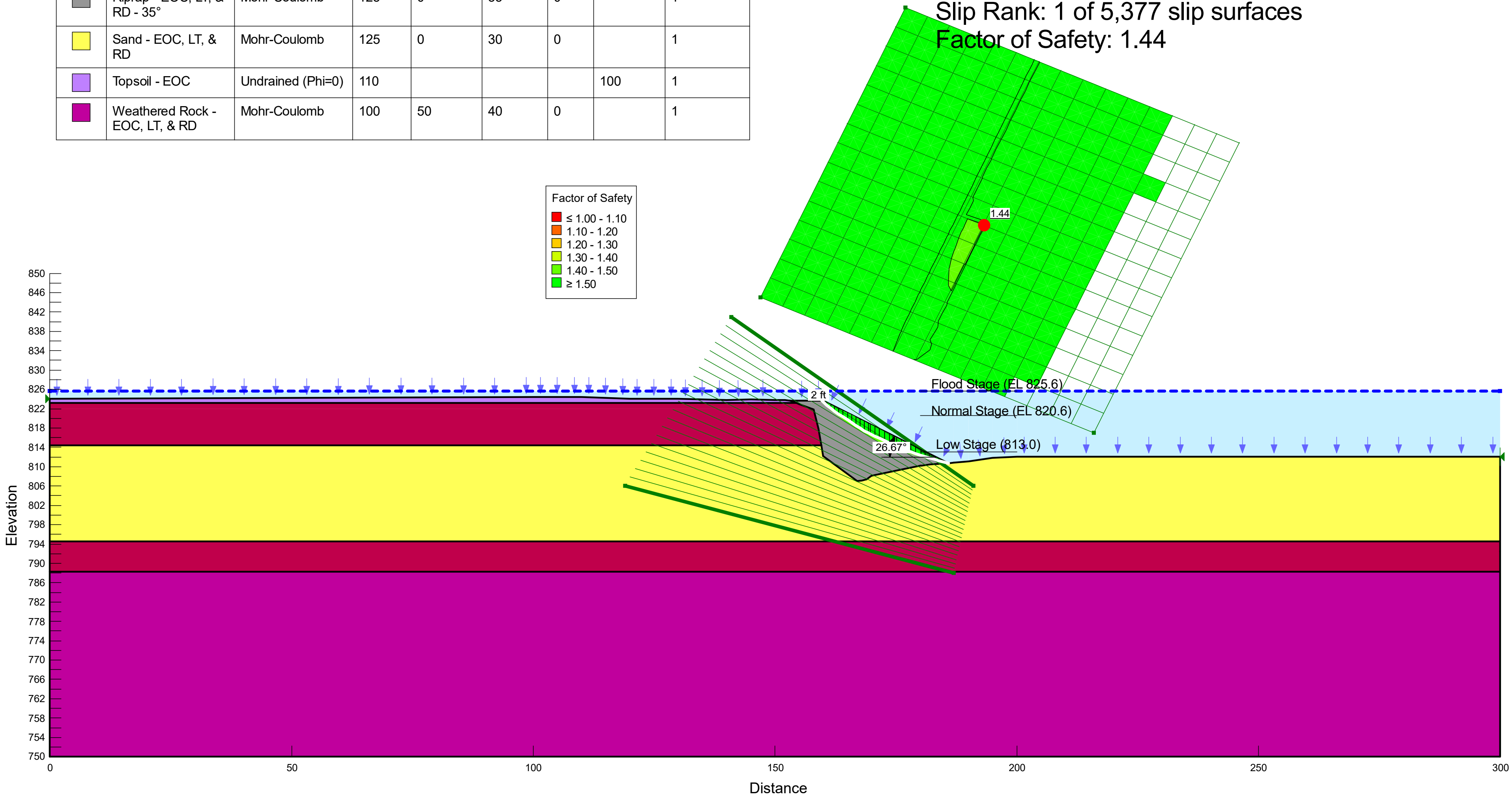
Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.64



Name: 4 - Alternative 3 - Post-Flood-Shaping - 35° Riprap - 2V:5H
Name: Varied PZ Line - RD - F to L - Alt3 (3)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

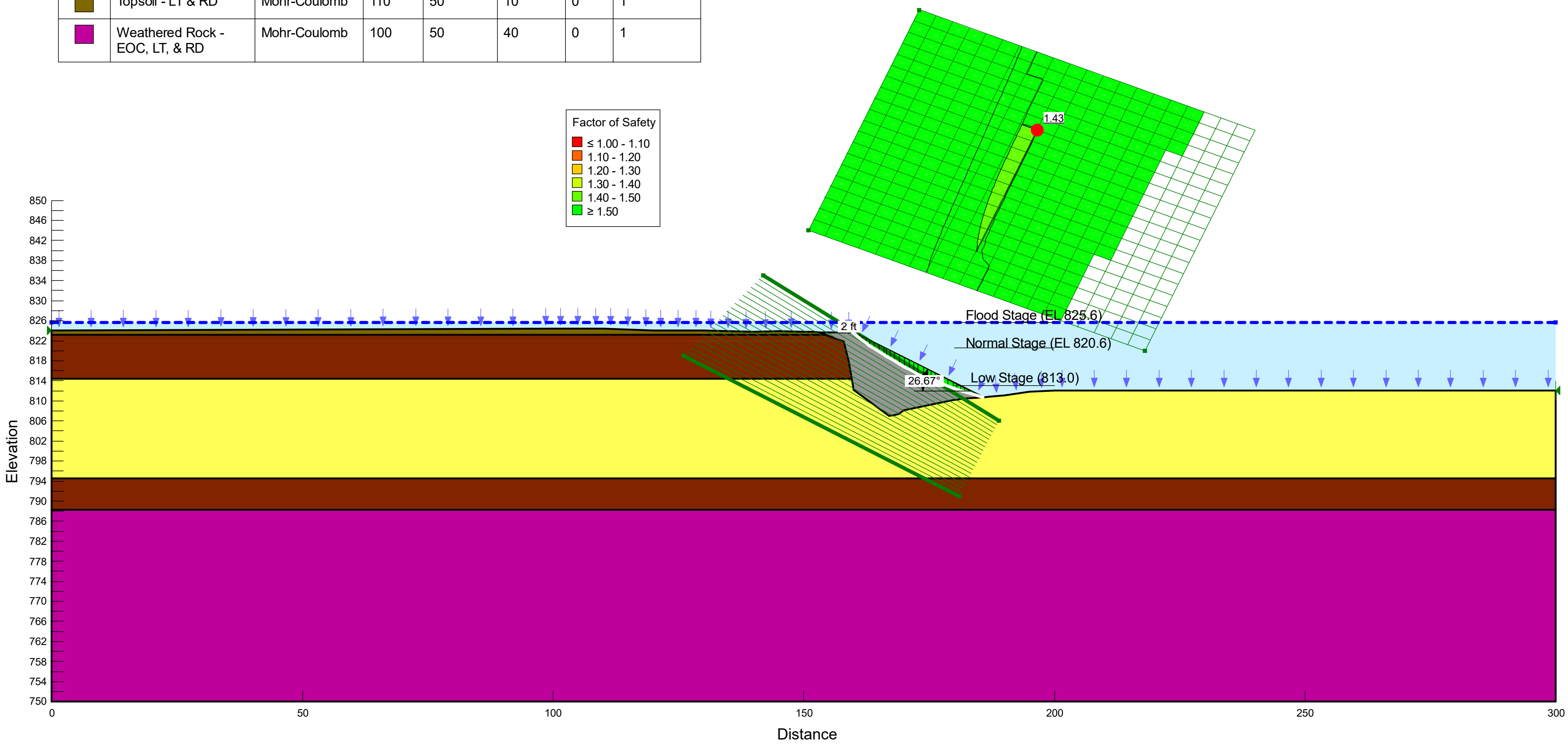


Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Flood Stage - EOC - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 9,262 slip surfaces
Factor of Safety: 1.43

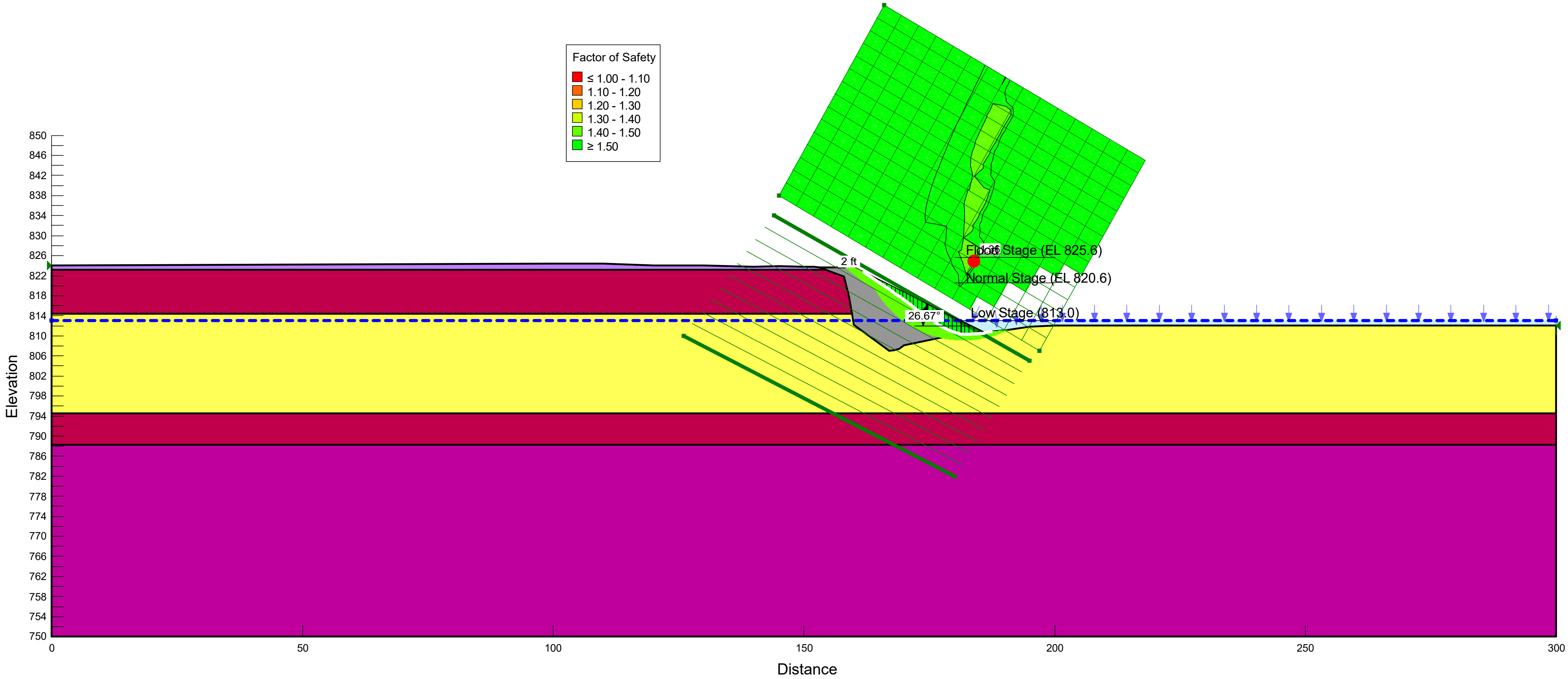


Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Flood Stage - LT - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
▨	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.36

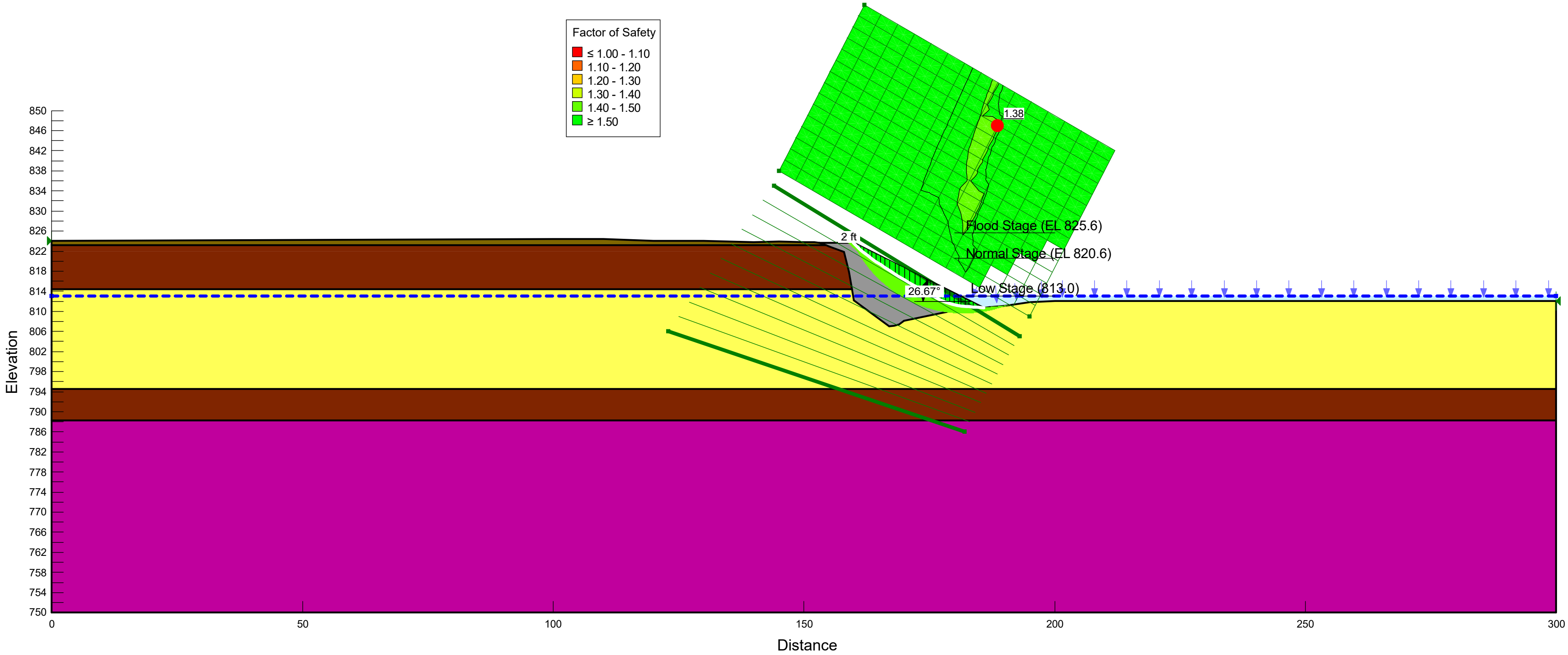


Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Low Stage - EOC - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.38

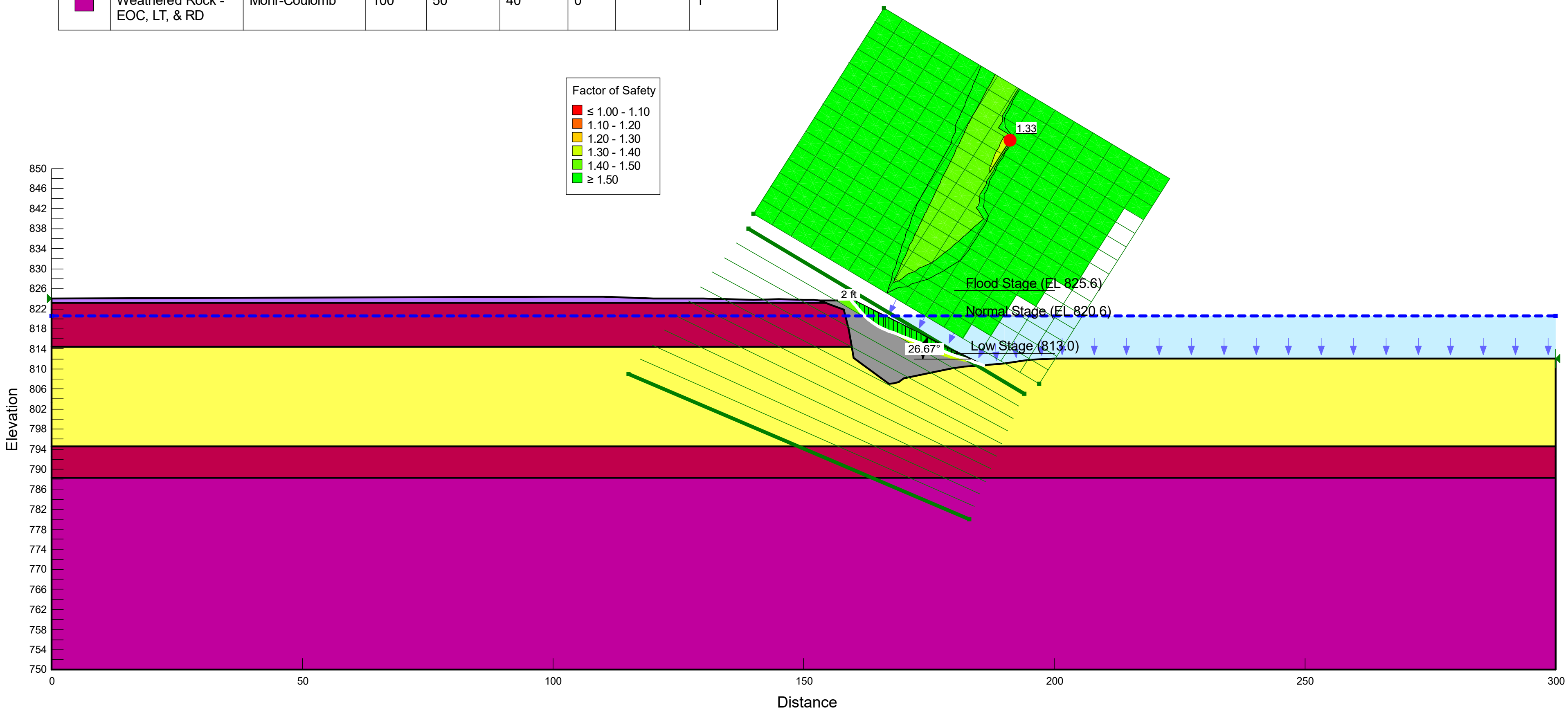


Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Low Stage - LT - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.33

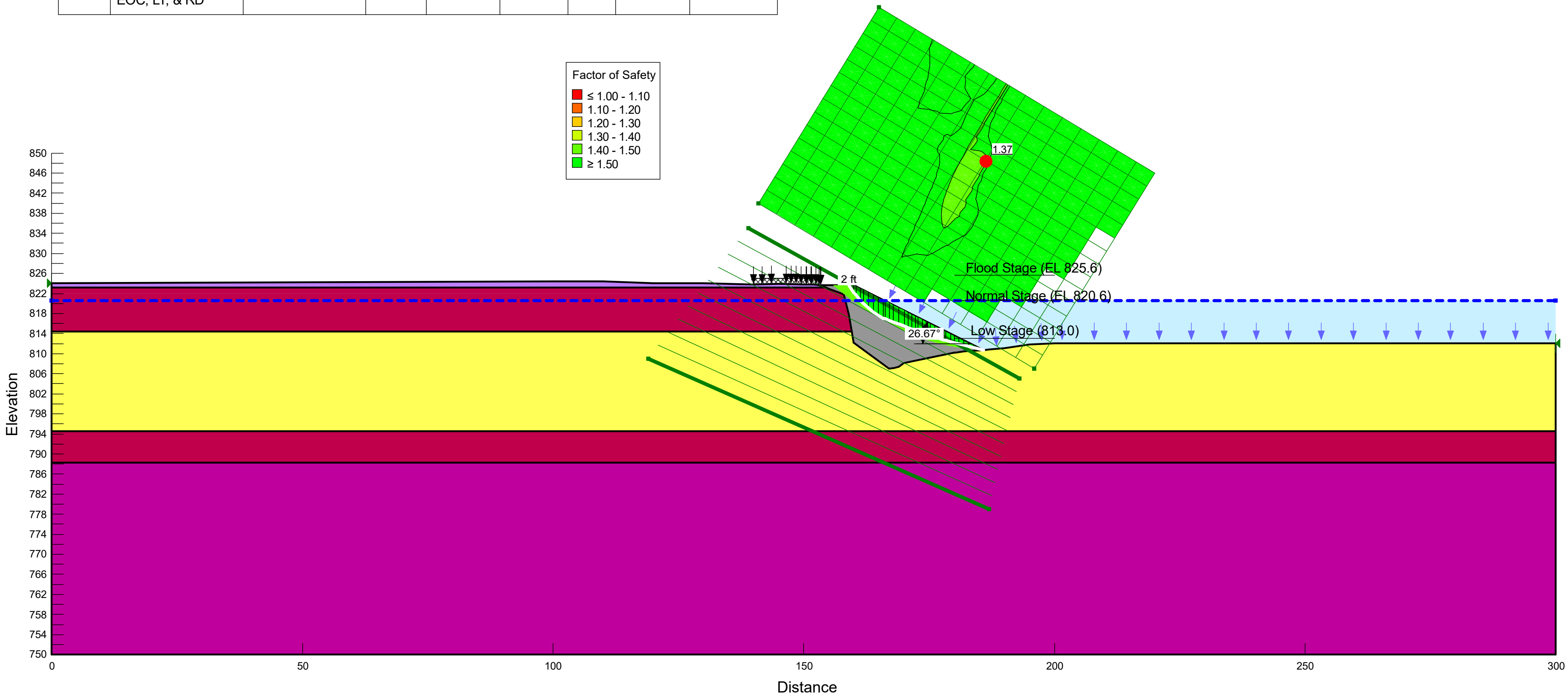


Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Normal Stage - EOC - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.37

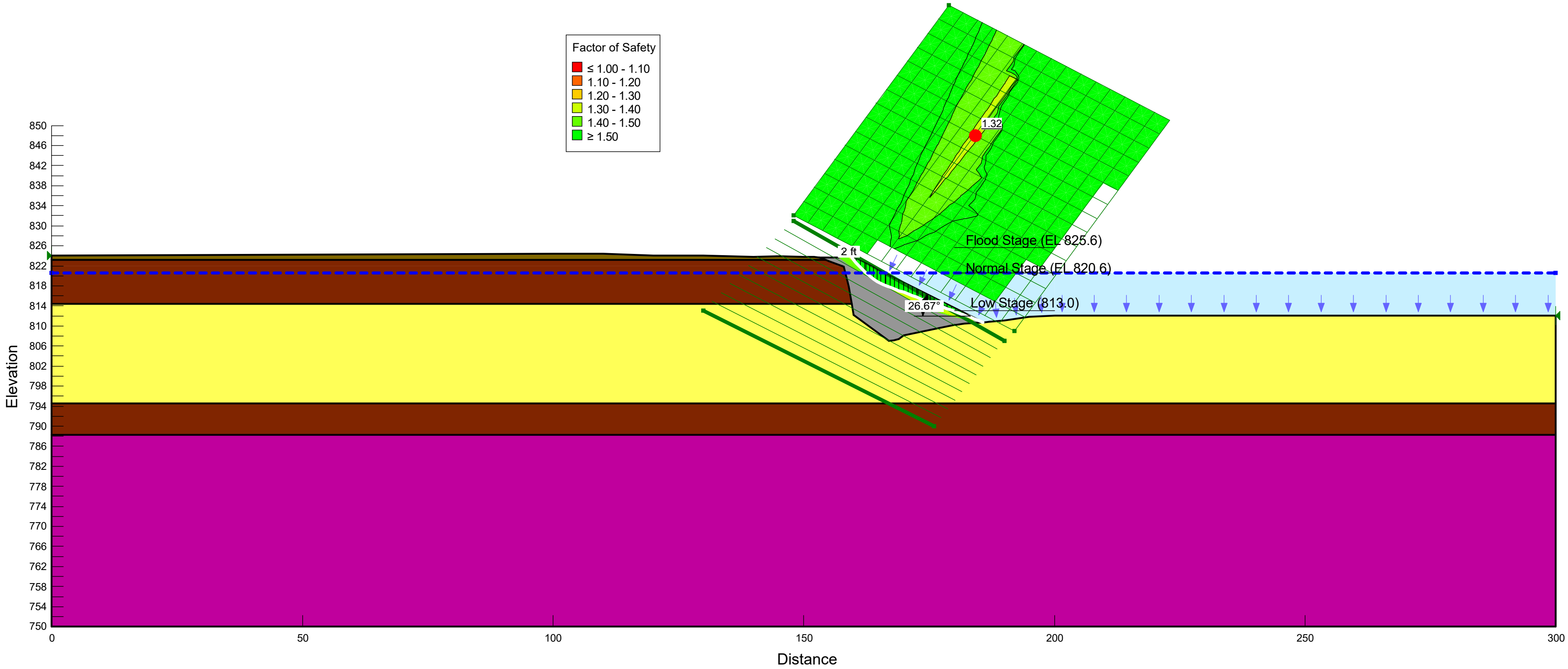


Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Normal Stage - EOC - Surcharge - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
■	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.32

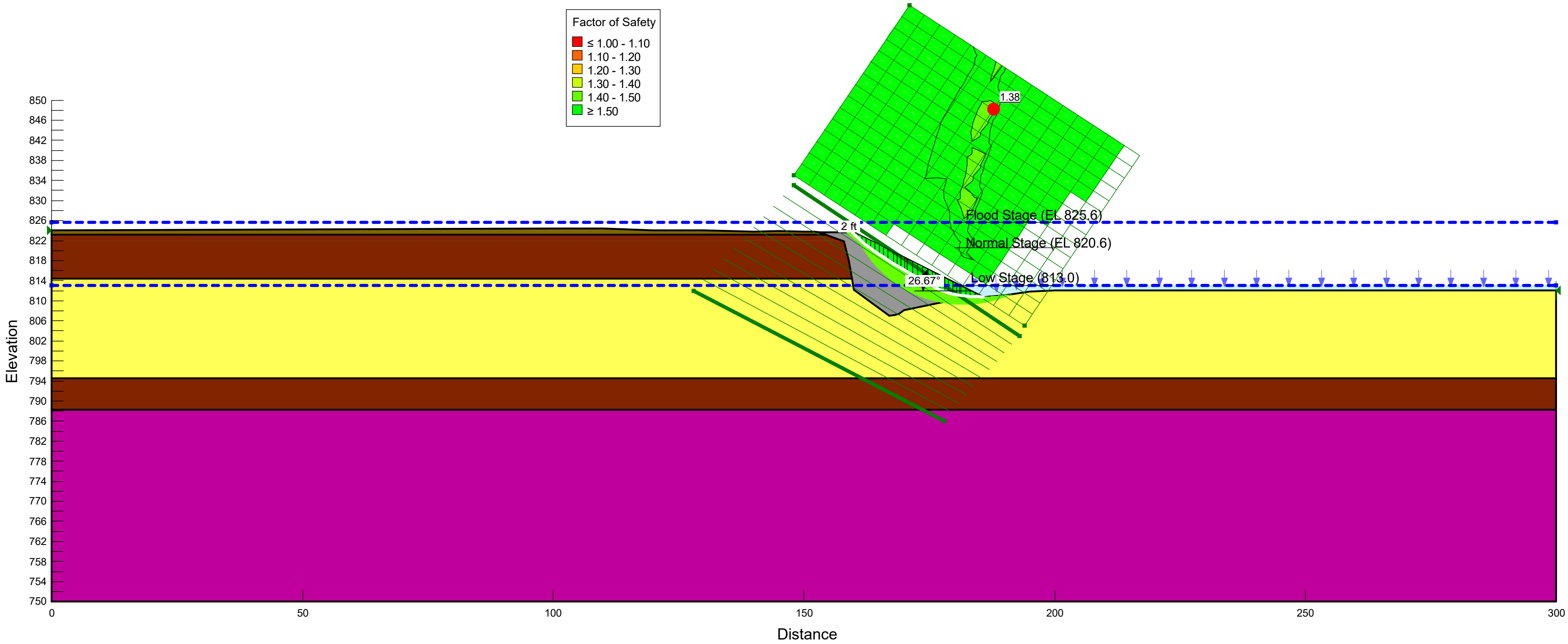


Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Normal Stage - LT - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
▩	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	0	35	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2

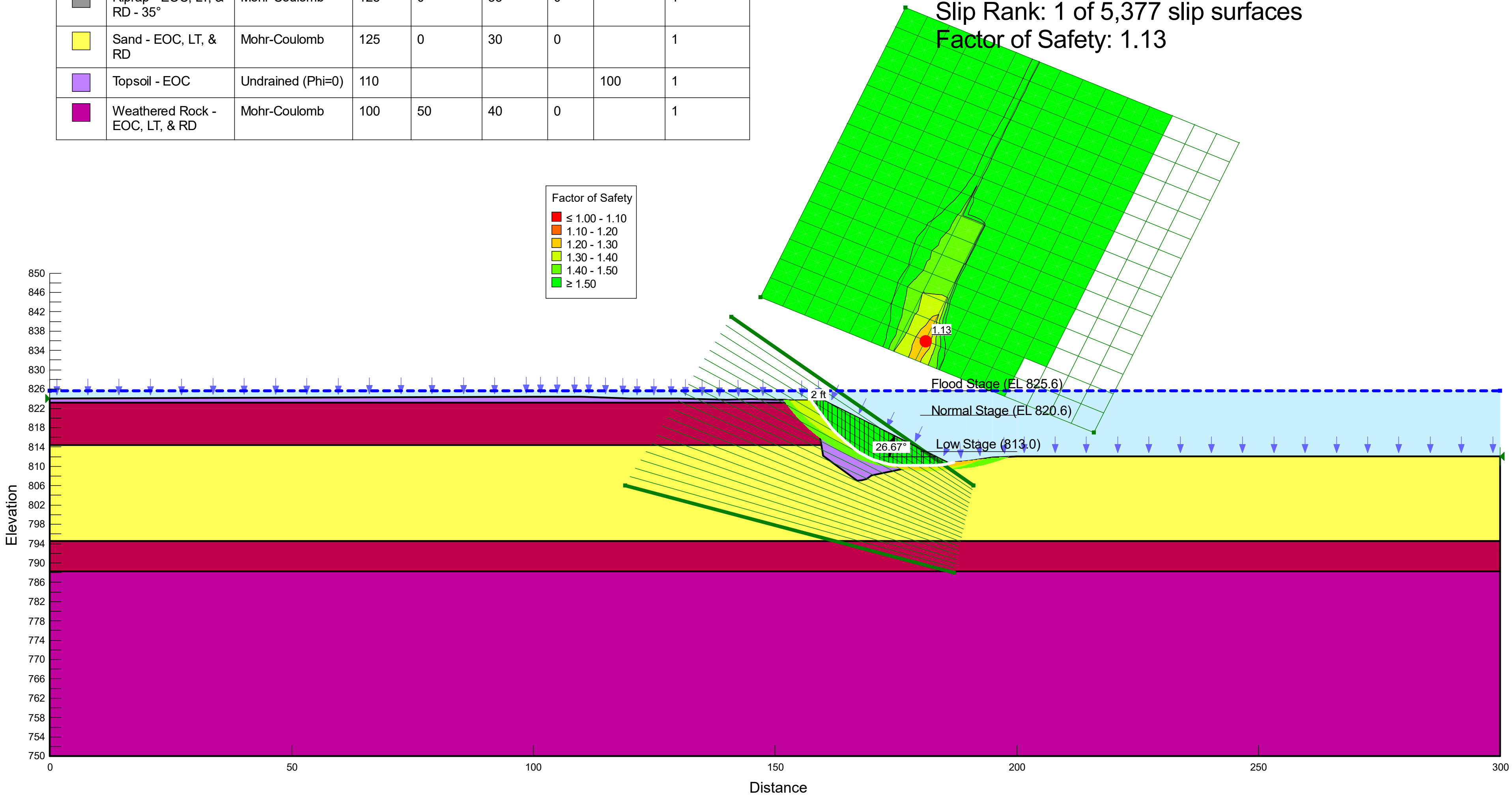
Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.38



Name: 5 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H
Name: Varied PZ Line - RD - F to L - Alt3 (5)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

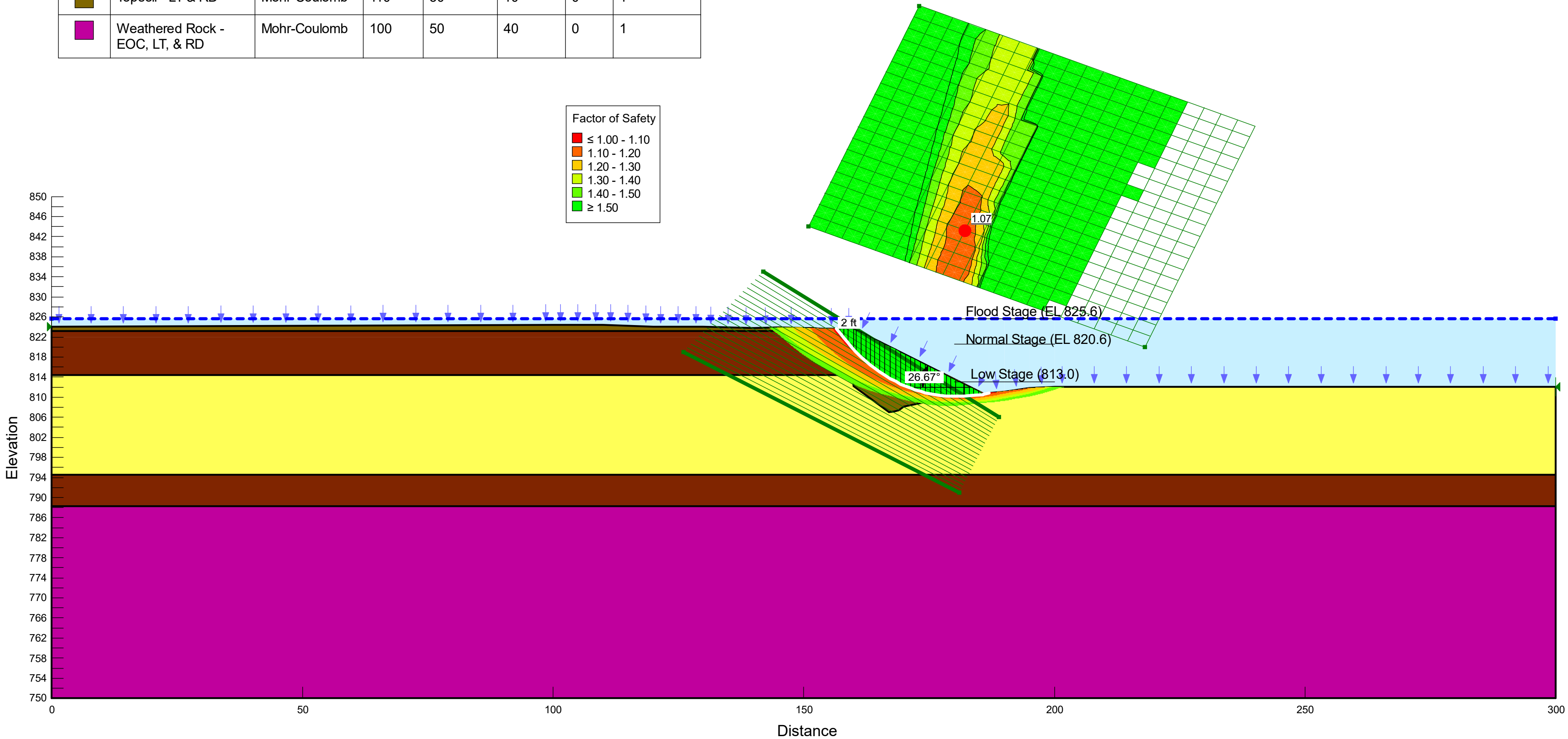


Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Flood Stage - EOC - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 9,262 slip surfaces
Factor of Safety: 1.07

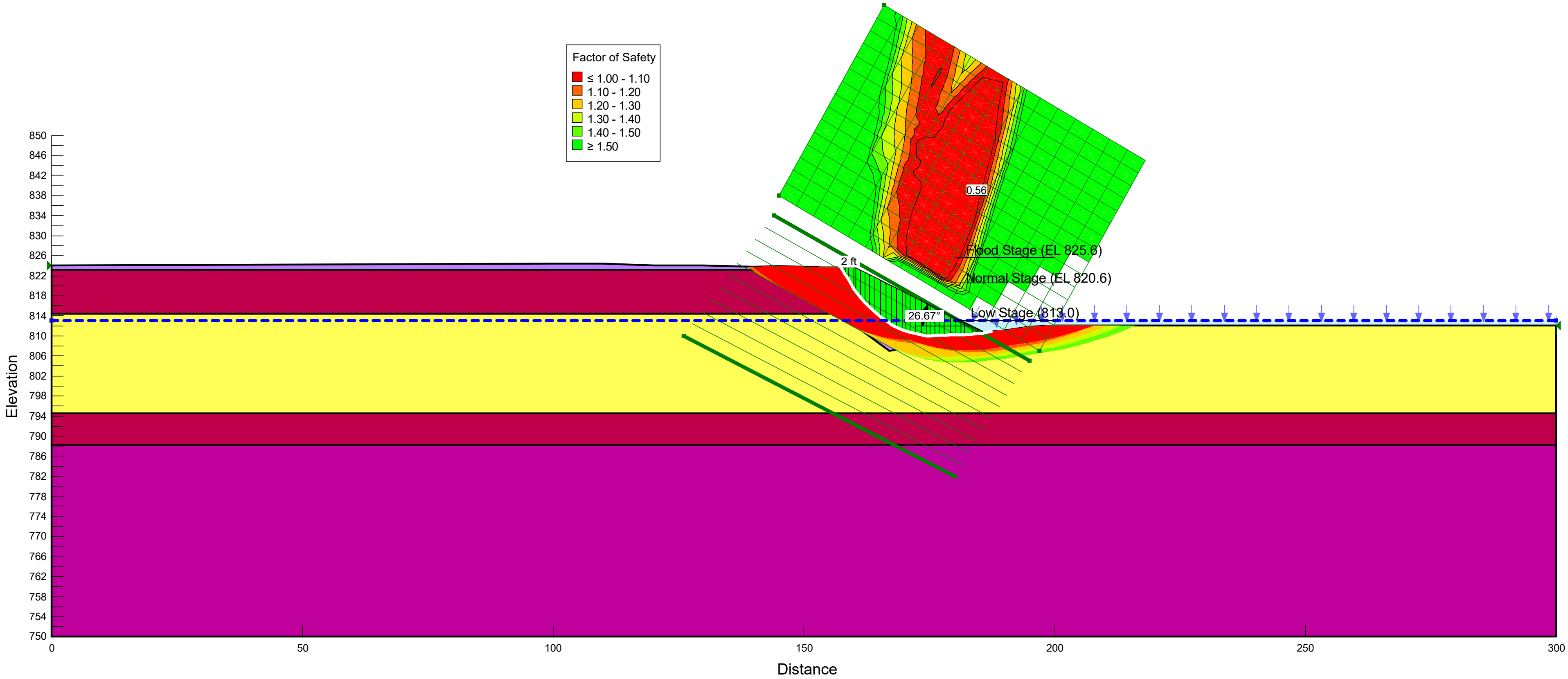


Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Flood Stage - LT - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.56

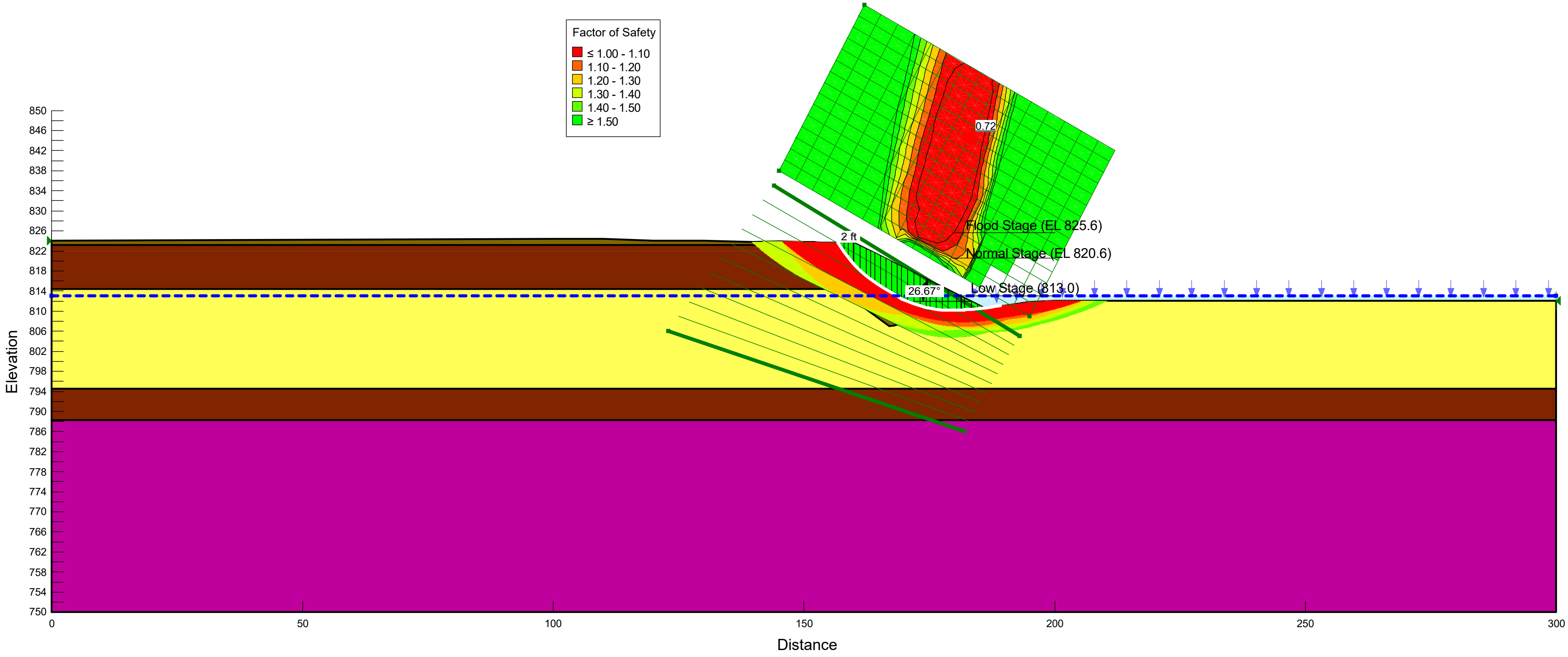


Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Low Stage - EOC - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.72

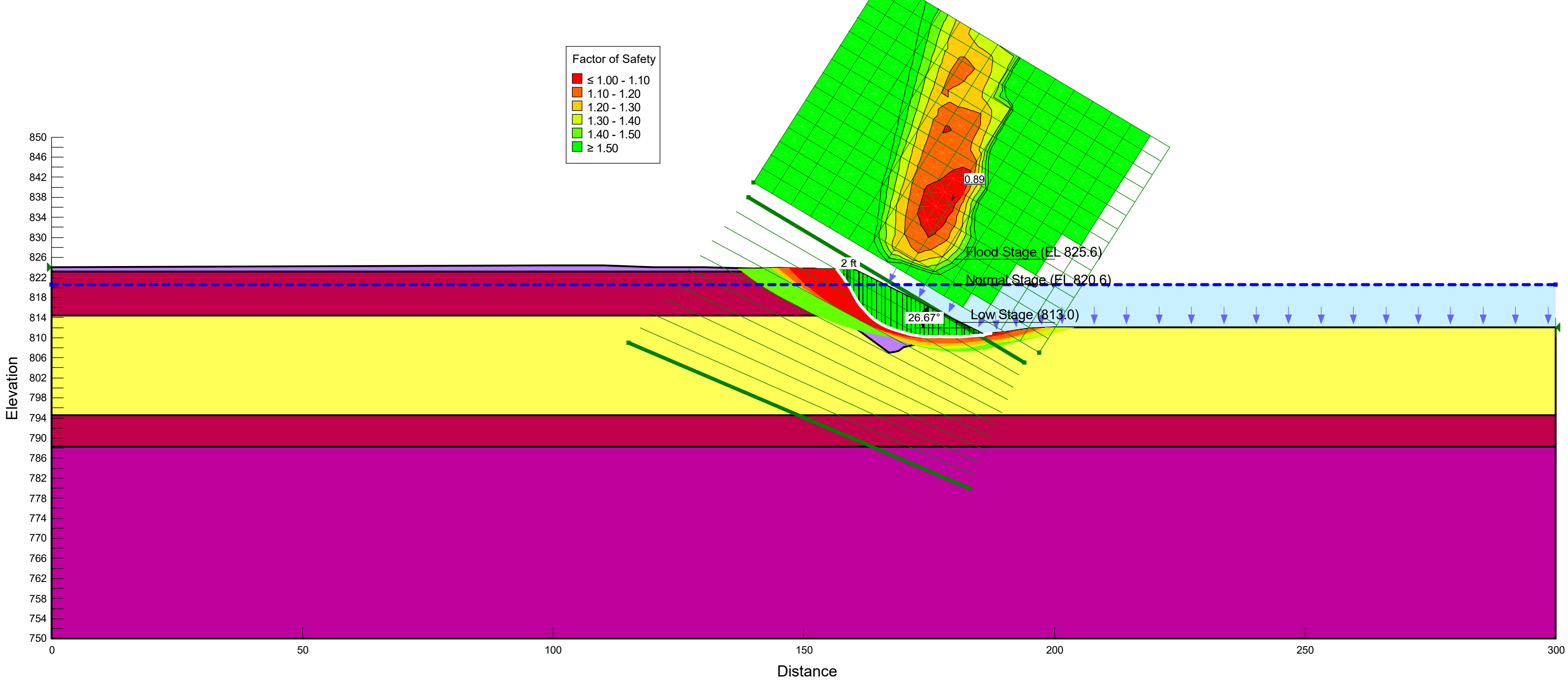


Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Low Stage - LT - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.89

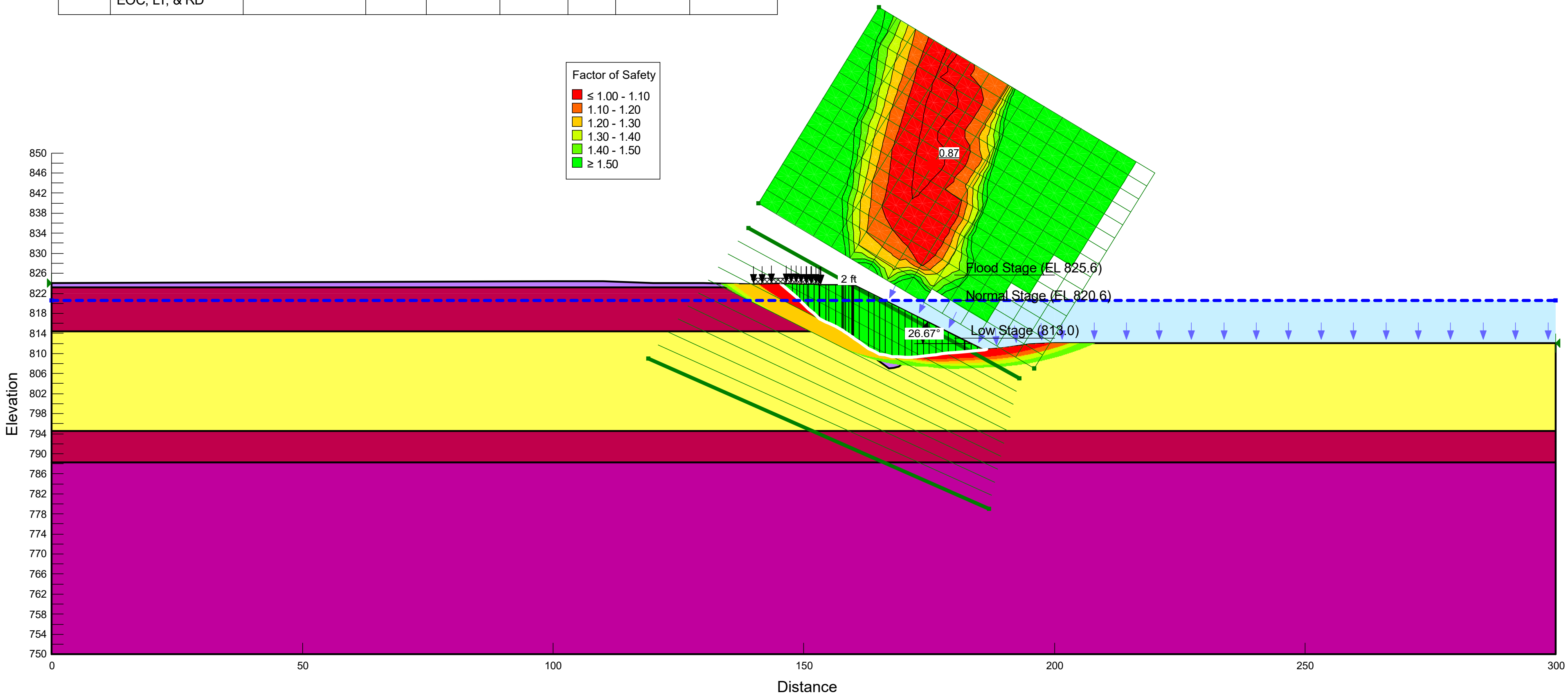


Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Normal Stage - EOC - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.87

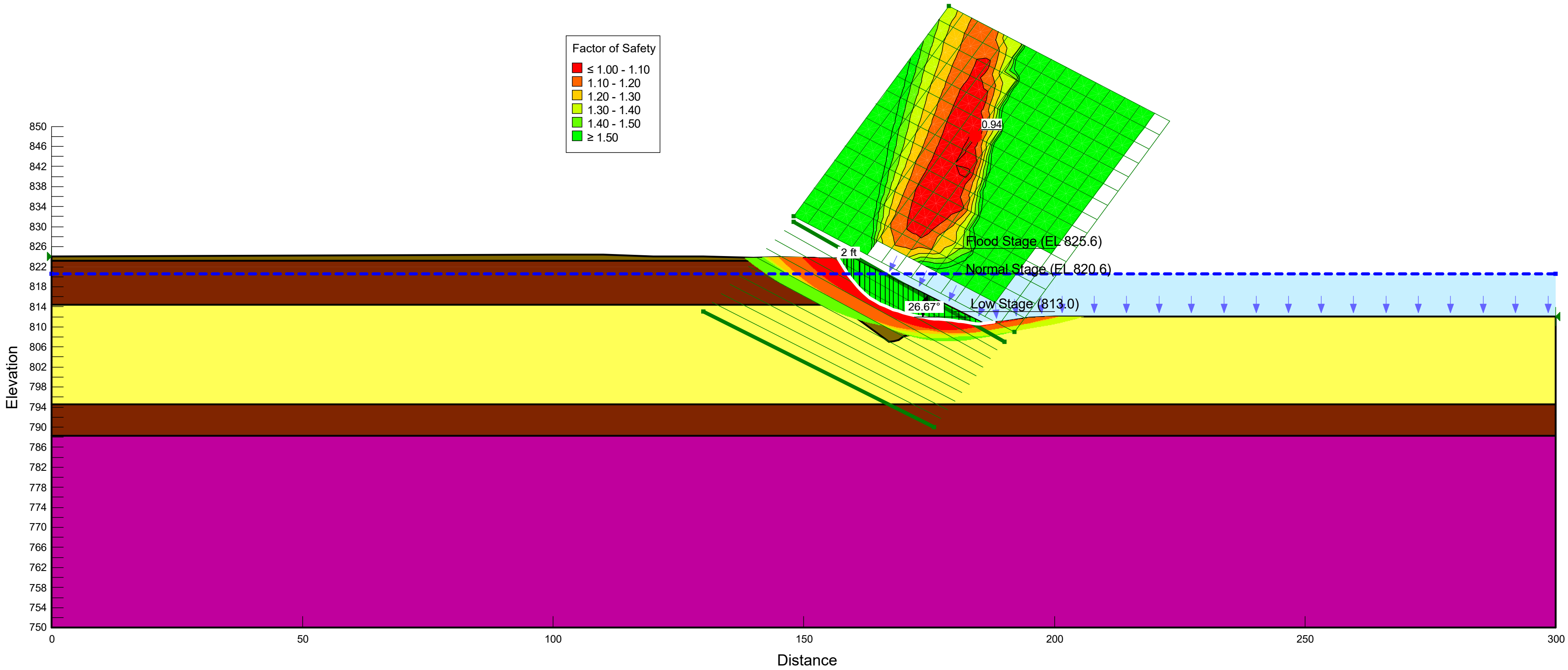


Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Normal Stage - EOC - Surcharge - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.94

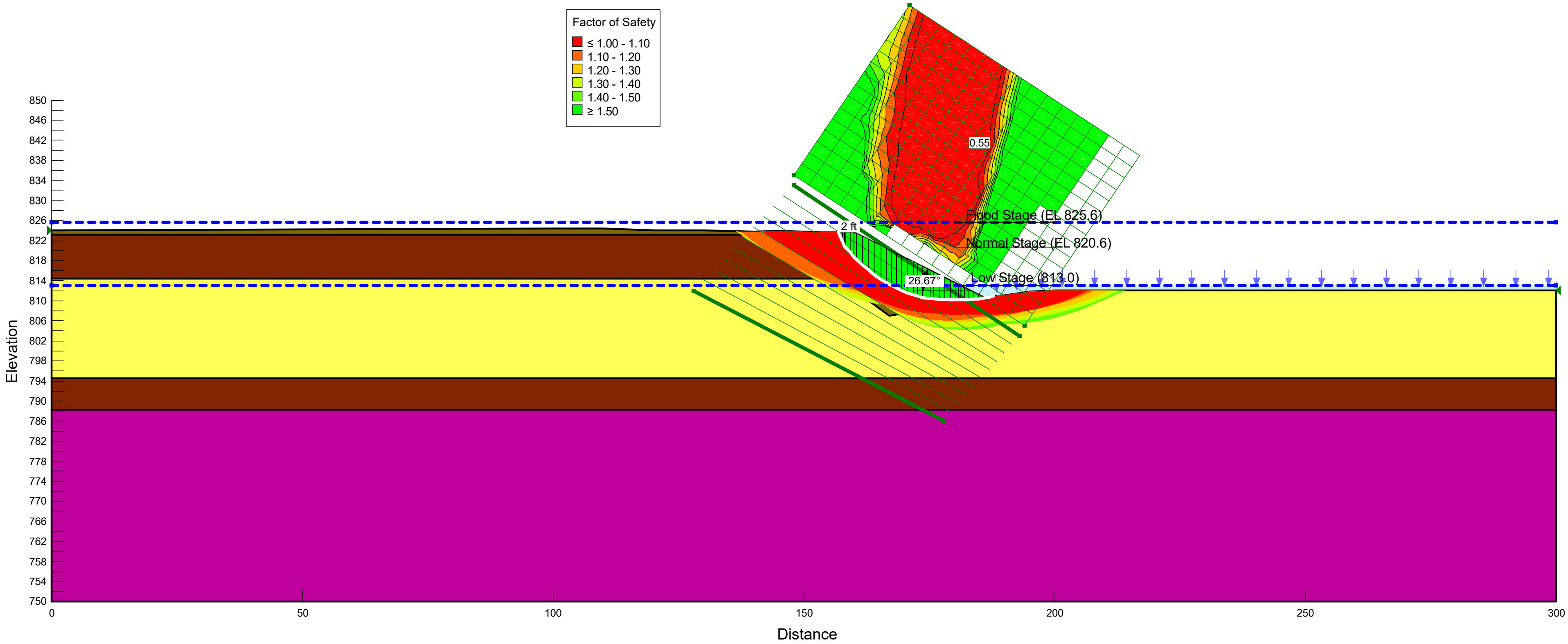


Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Normal Stage - LT - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	0	35	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2

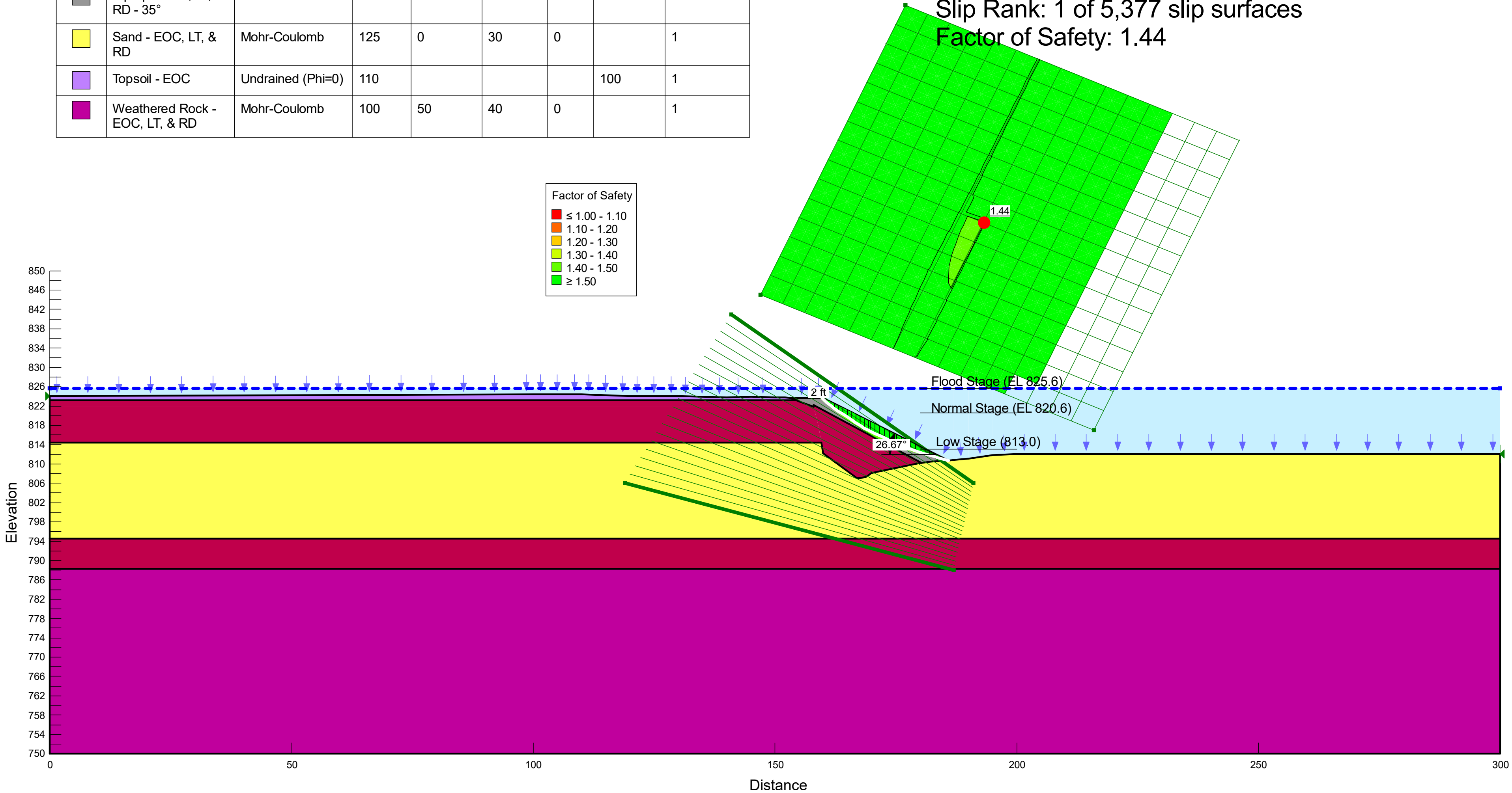
Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.55



Name: 6 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Topsoil
Name: Varied PZ Line - RD - F to L - Alt3 (6)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

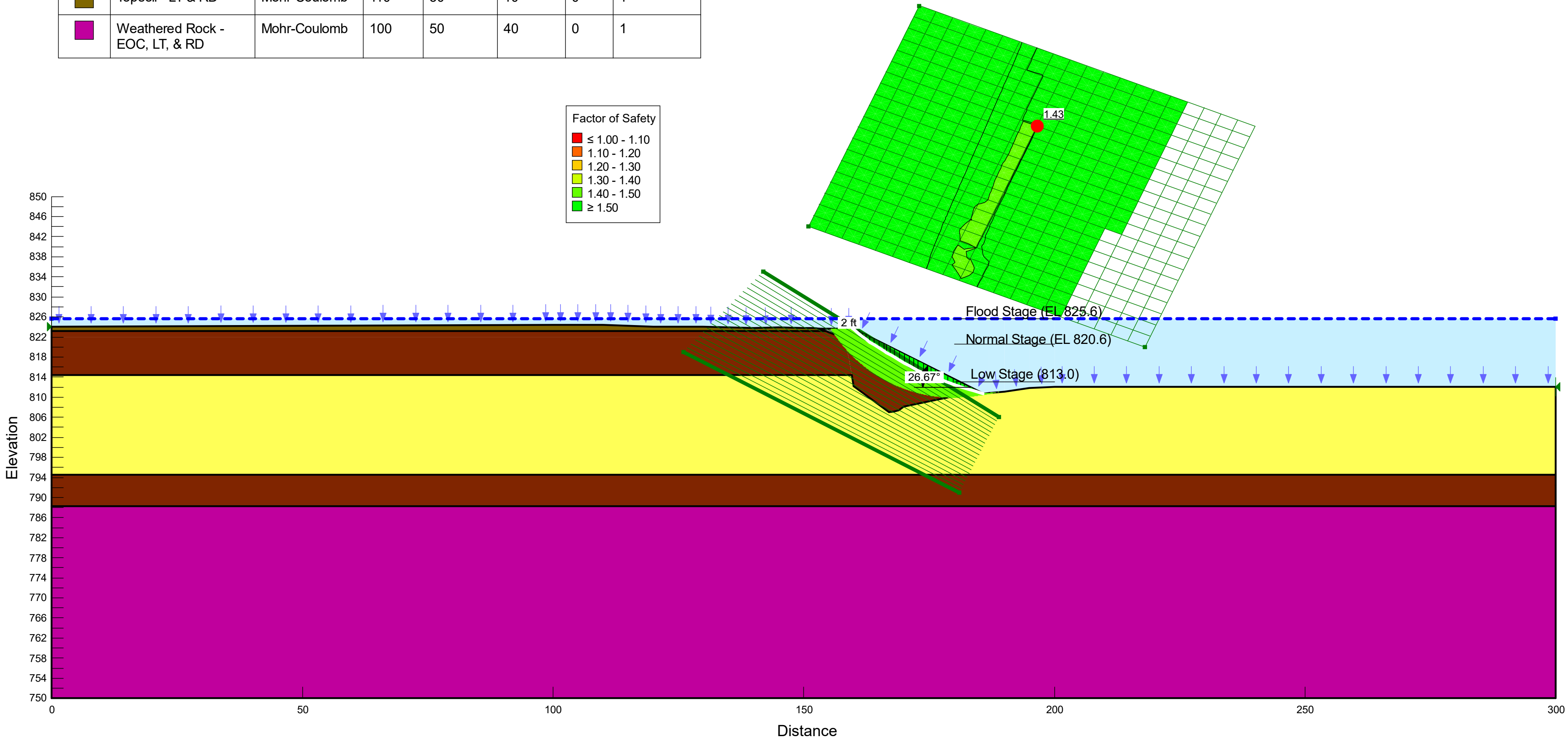


Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Flood Stage - EOC - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 9,262 slip surfaces
Factor of Safety: 1.43

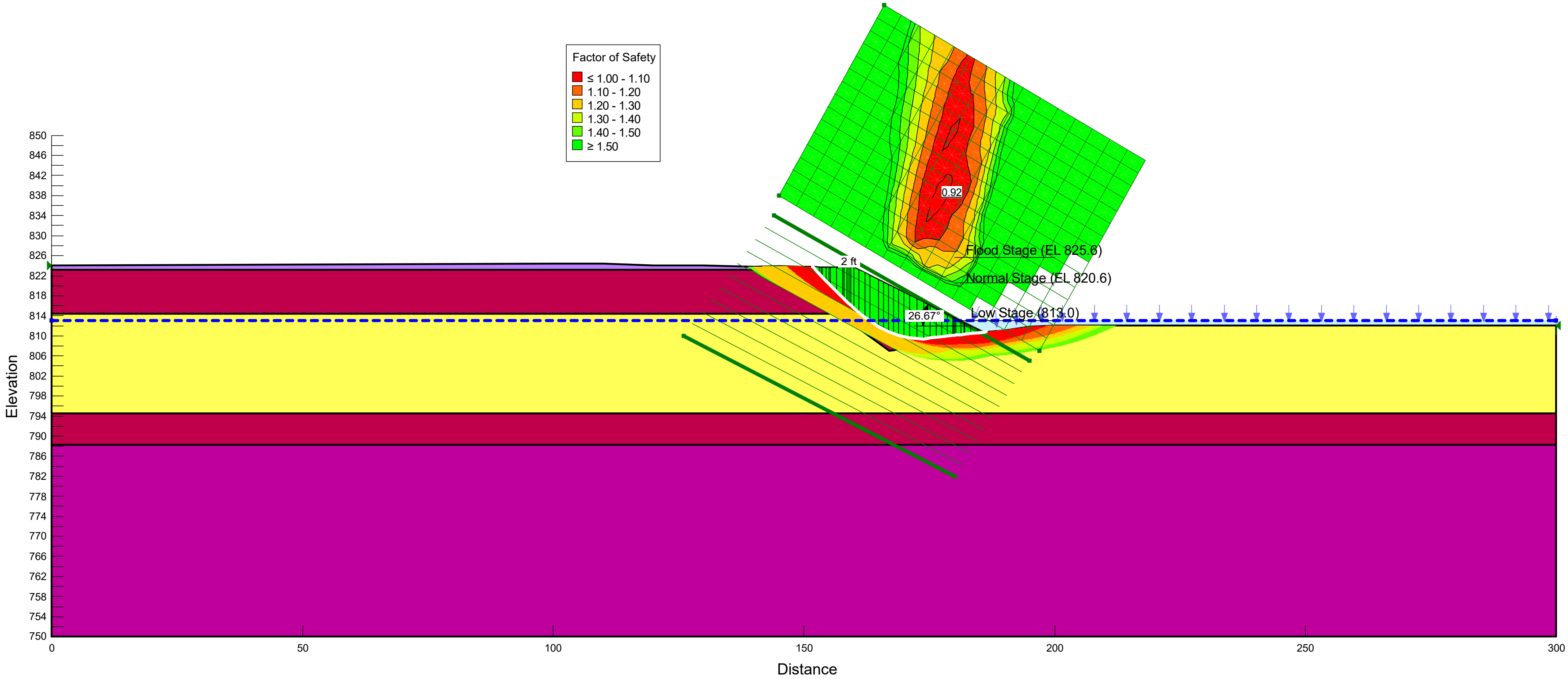


Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Flood Stage - LT - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.92

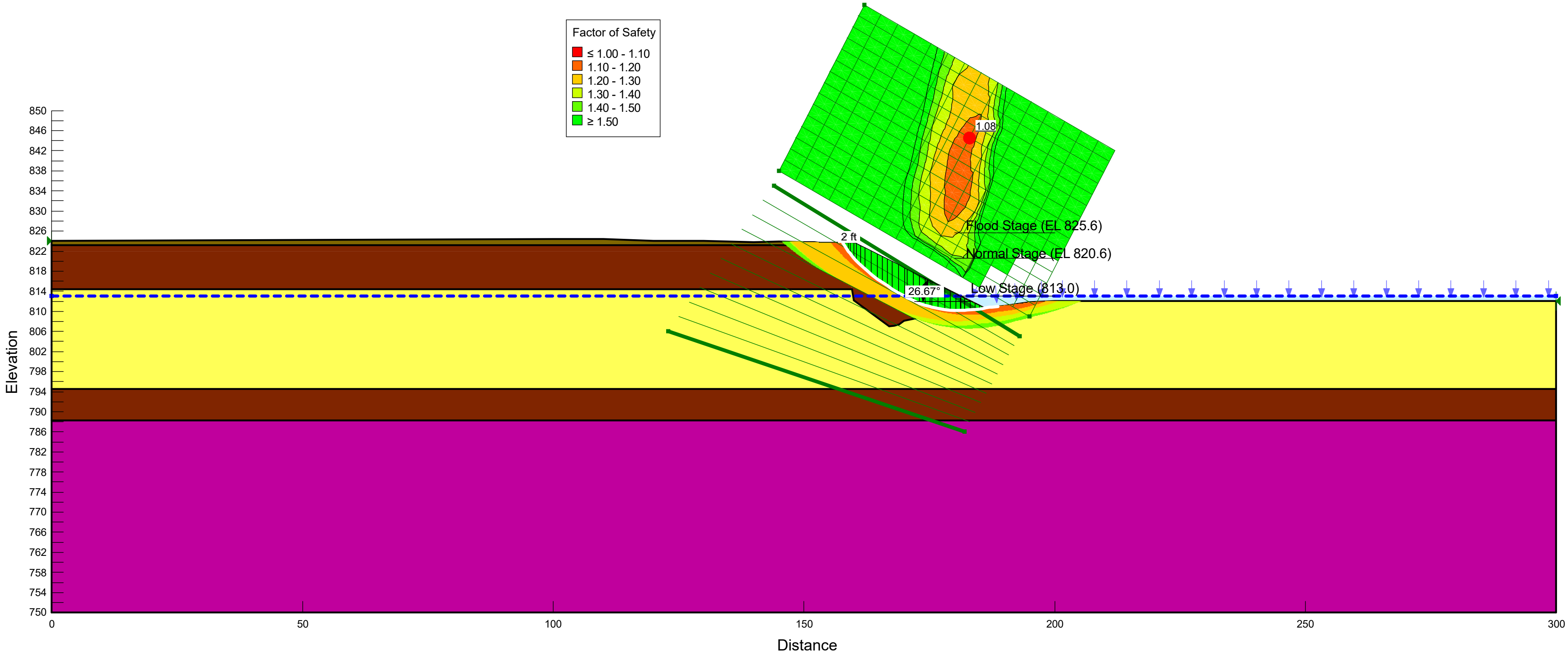


Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Low Stage - EOC - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.08

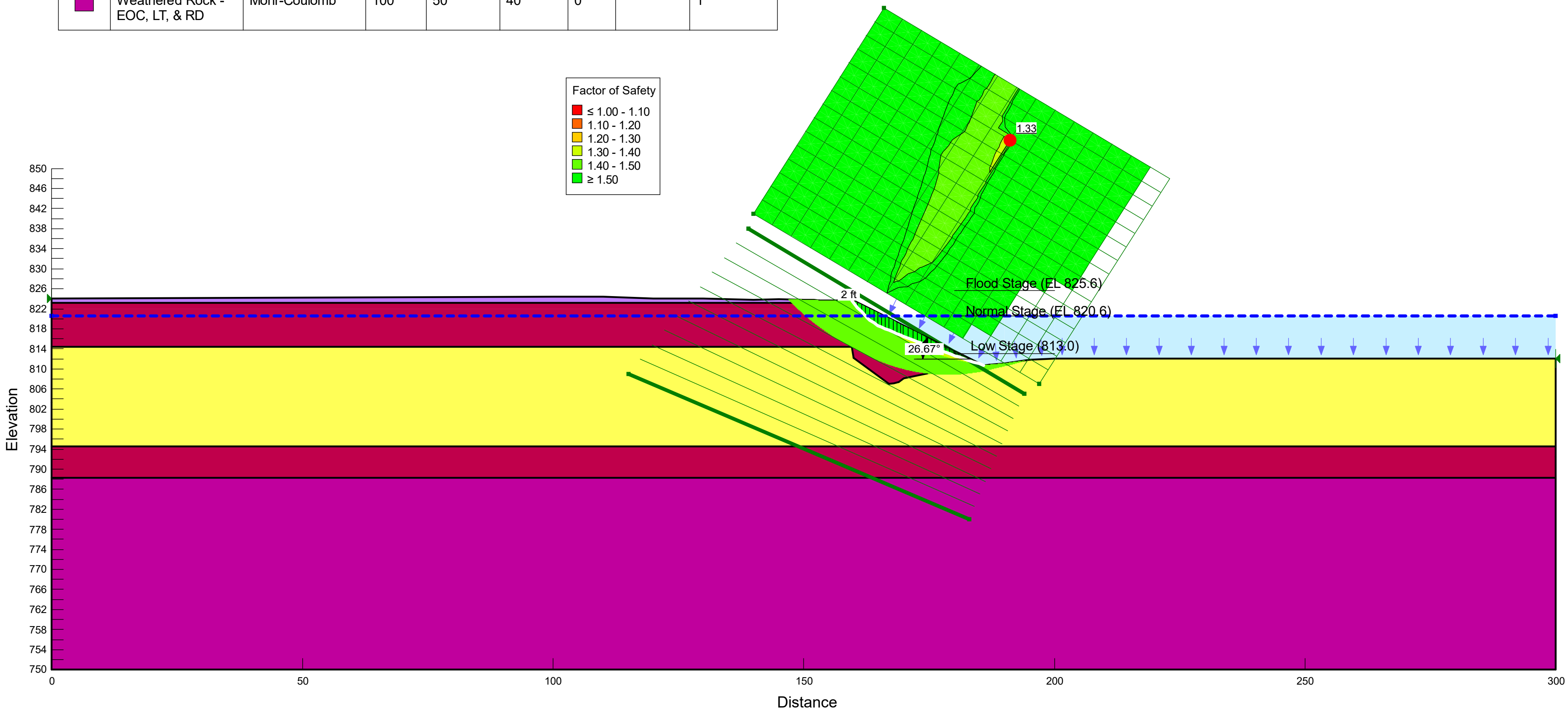


Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Low Stage - LT - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.33

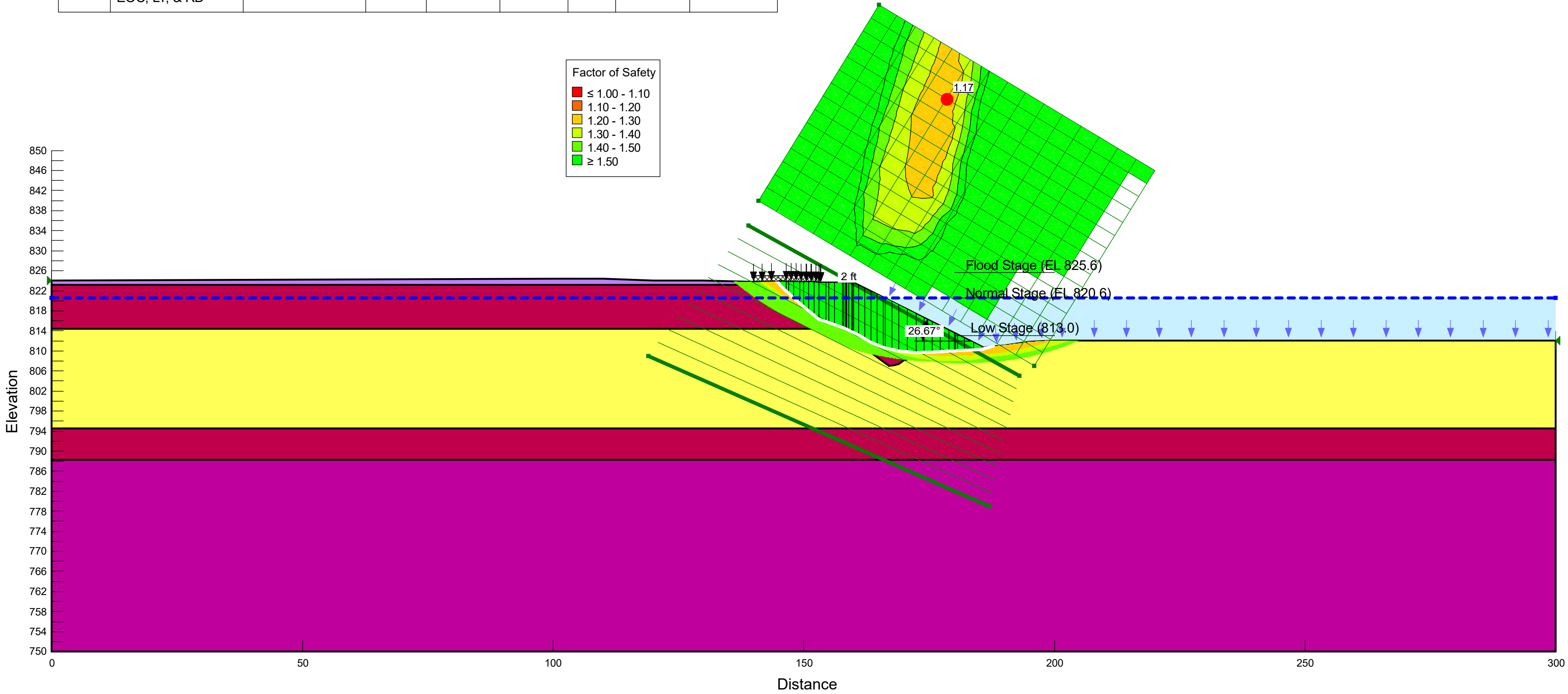


Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Normal Stage - EOC - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.17

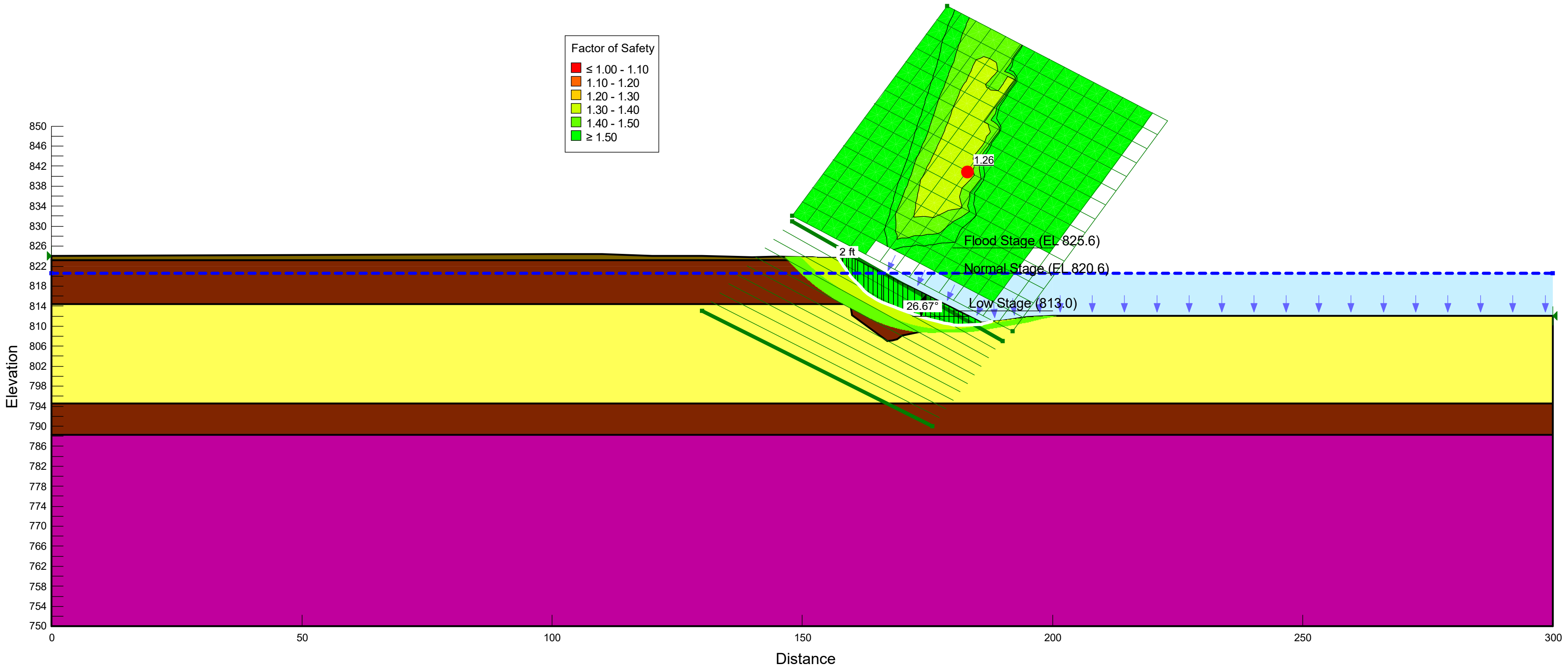


Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Normal Stage - EOC - Surcharge - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.26

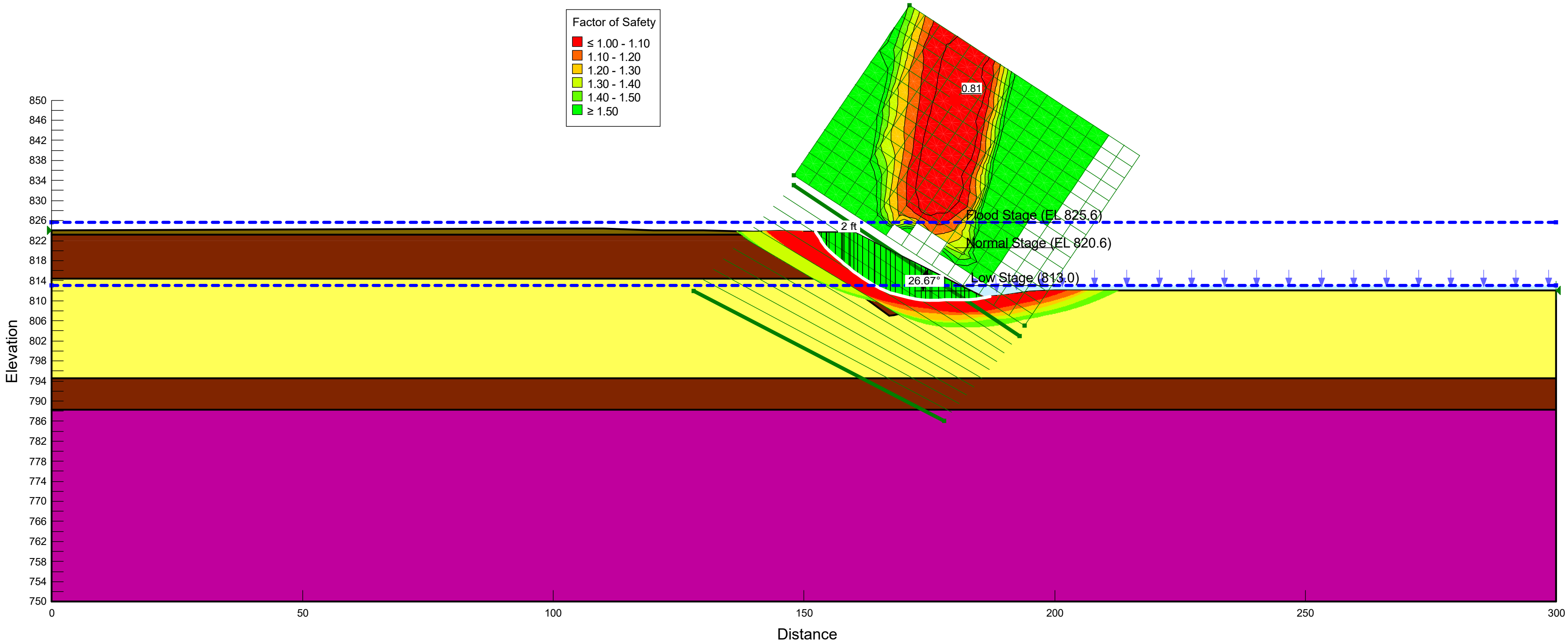


Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Normal Stage - LT - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
◼	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	0	35	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2

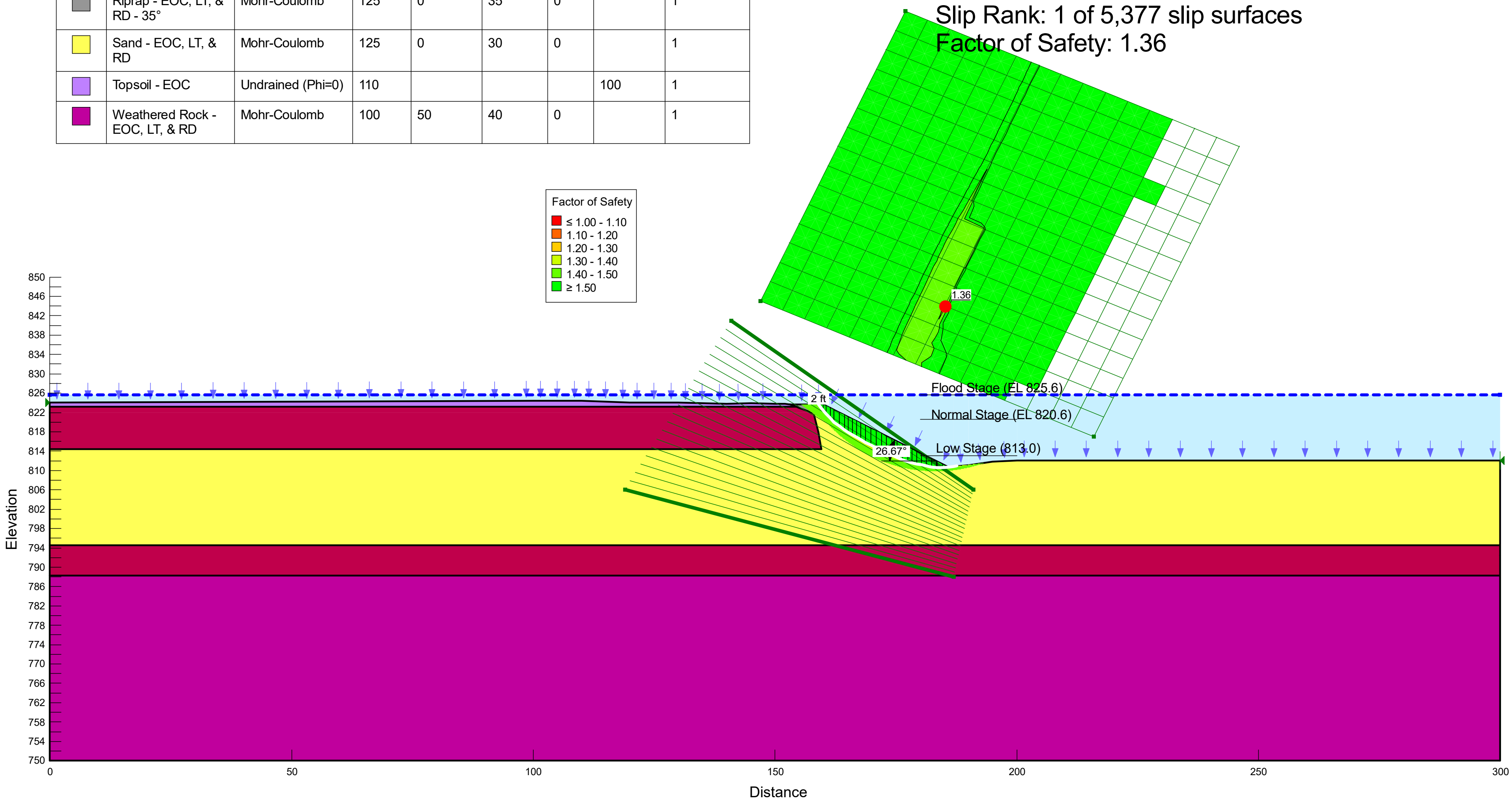
Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 0.81



Name: 7 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Clay
Name: Varied PZ Line - RD - F to L - Alt3 (7)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

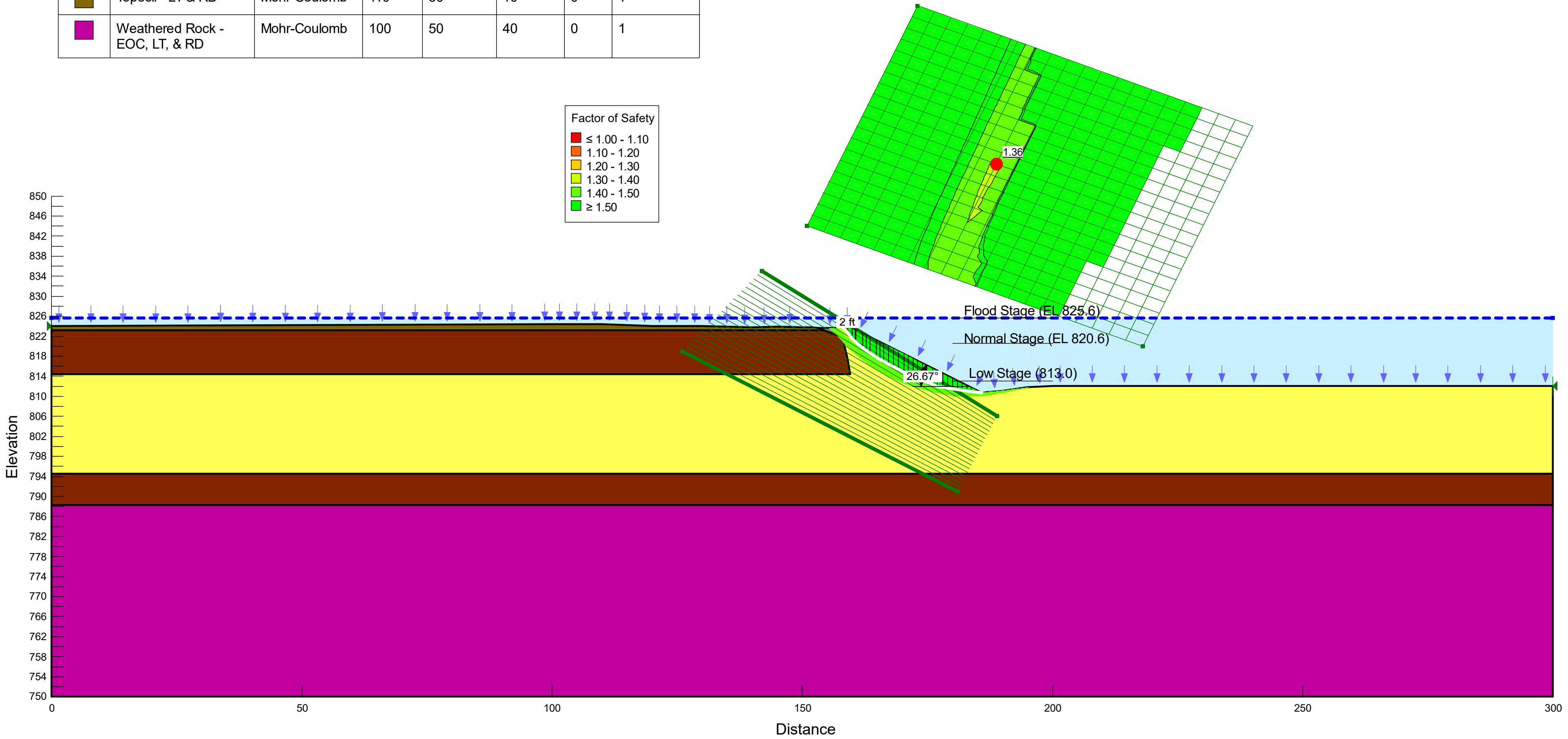


Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Flood Stage - EOC - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
◼	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 9,262 slip surfaces
Factor of Safety: 1.36

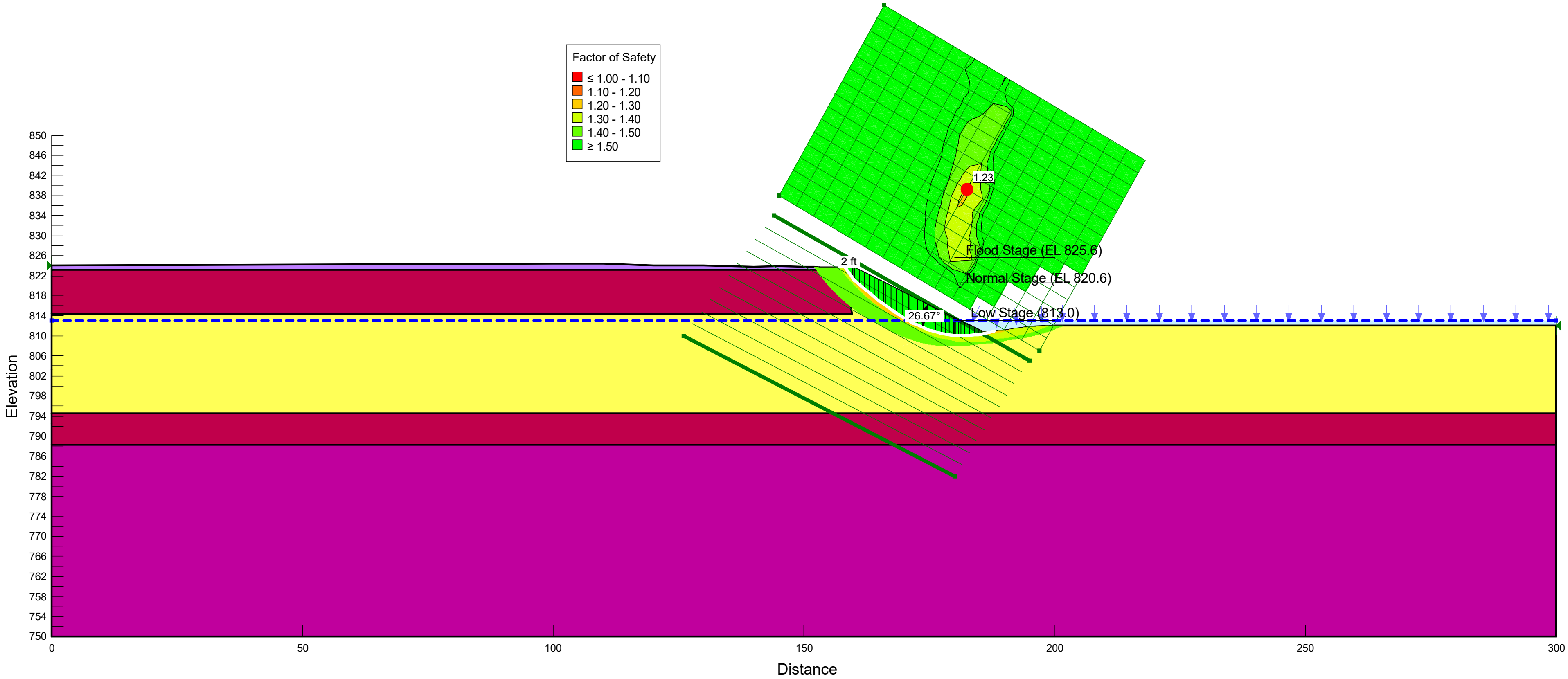


Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Flood Stage - LT - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬛	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.23

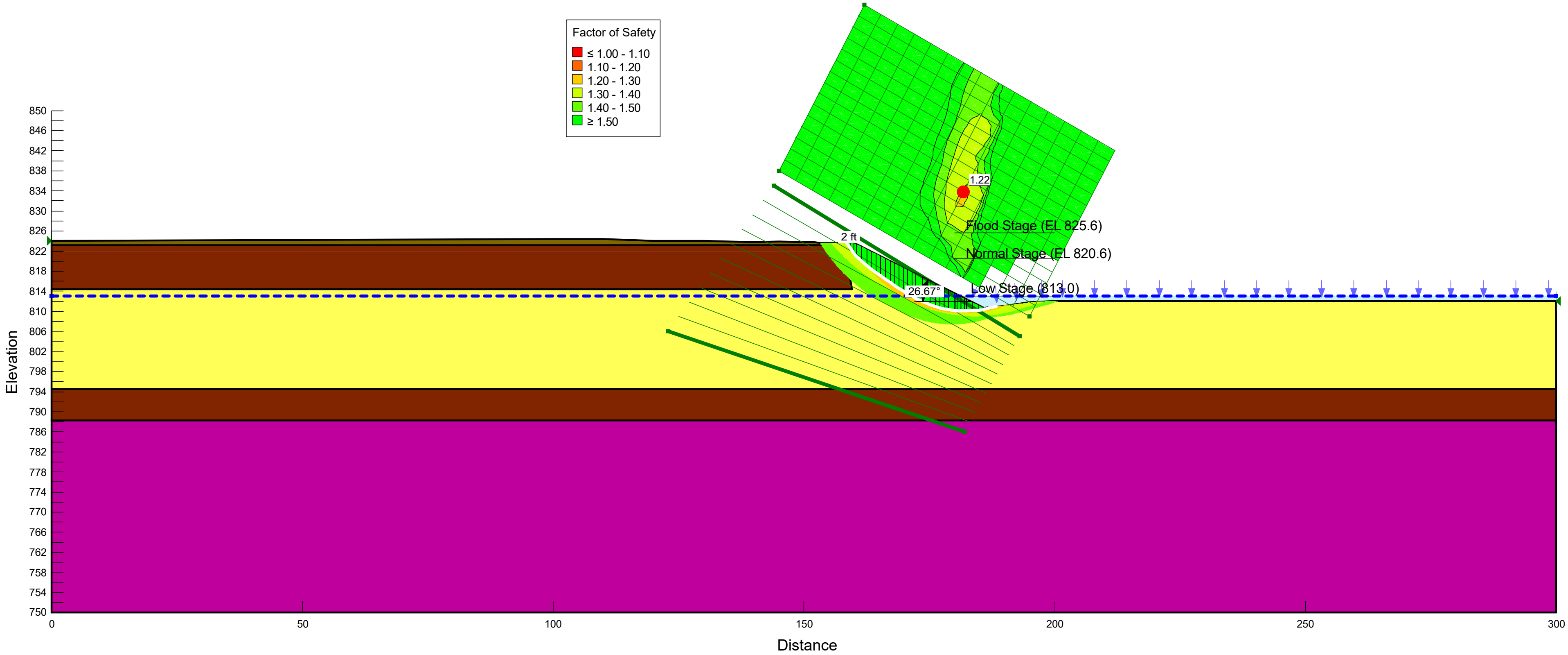


Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Low Stage - EOC - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.22

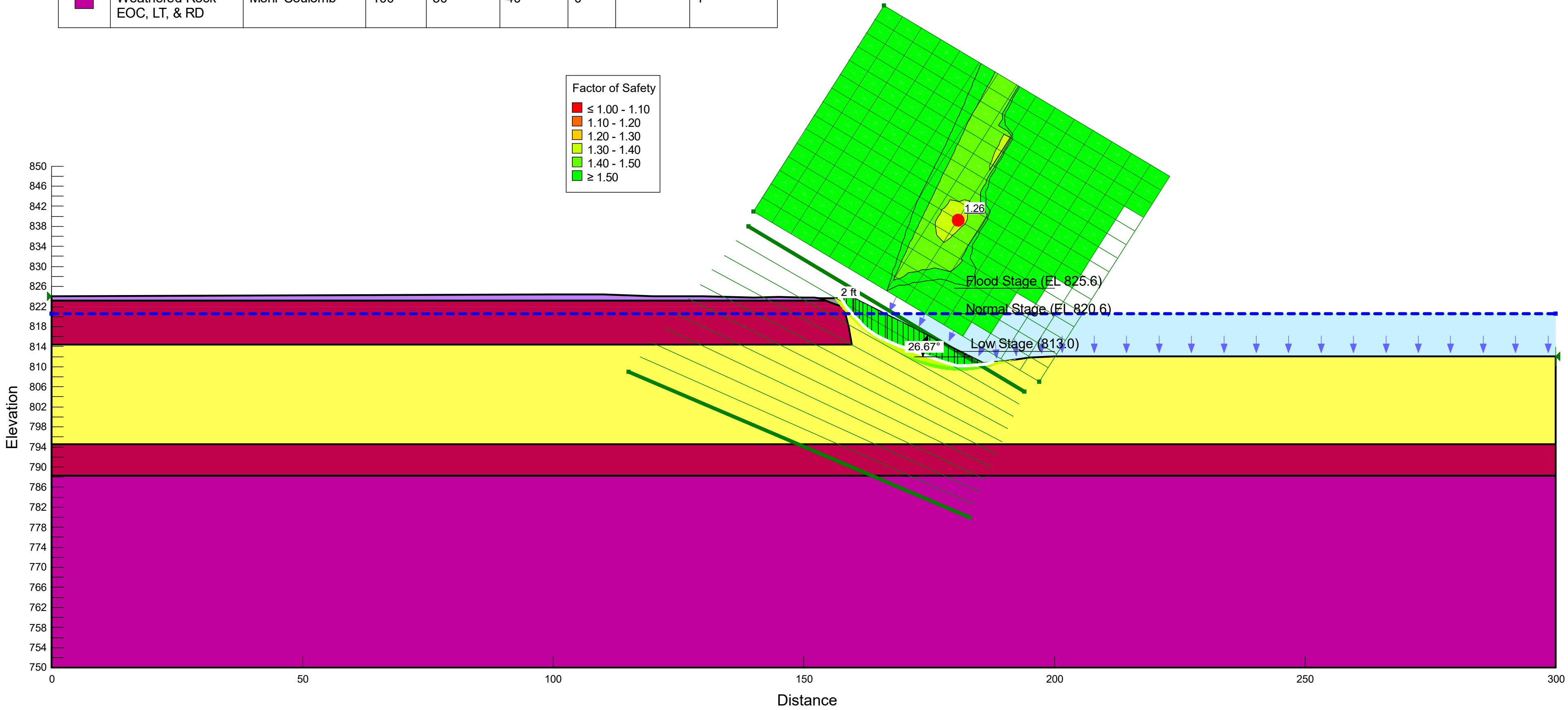


Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Low Stage - LT - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
■	Clay - EOC	Undrained (Phi=0)	115				200	1
■	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
■	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
■	Topsoil - EOC	Undrained (Phi=0)	110				100	1
■	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.26

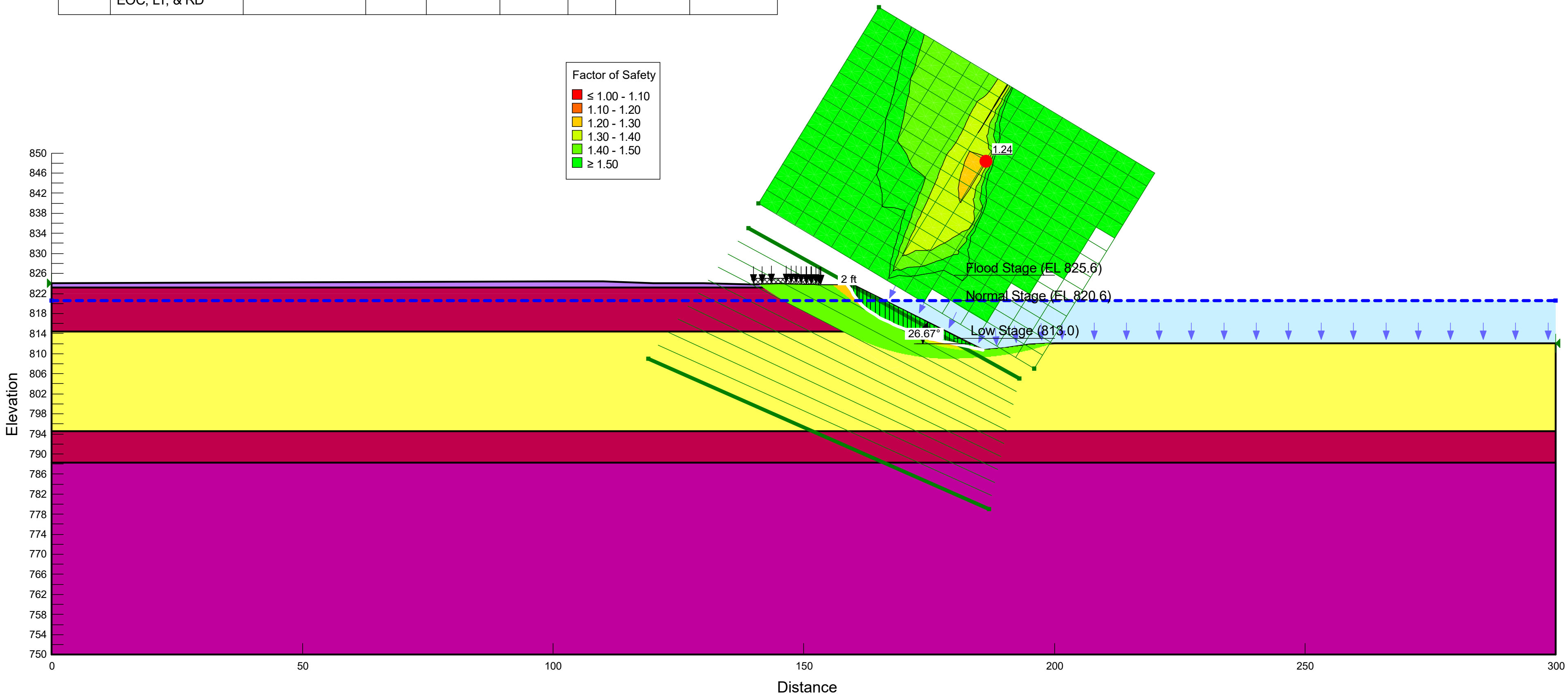


Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Normal Stage - EOC - Alt3 (9)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Total Cohesion (psf)	Piezometric Line
🟥	Clay - EOC	Undrained (Phi=0)	115				200	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0		1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0		1
🟪	Topsoil - EOC	Undrained (Phi=0)	110				100	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0		1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.24

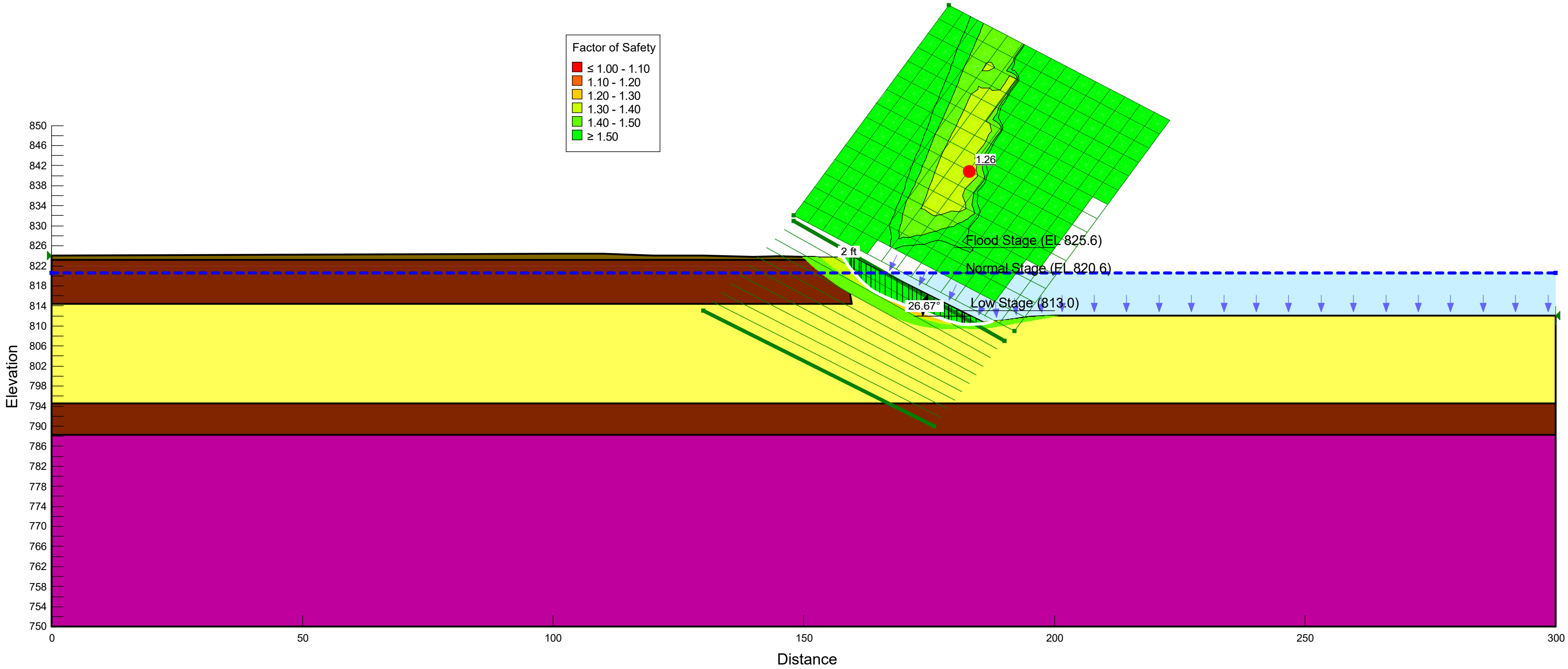


Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Normal Stage - EOC - Surcharge - Alt3 (9)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Line
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	1
⬜	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	1
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	1
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	1
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	1

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.26

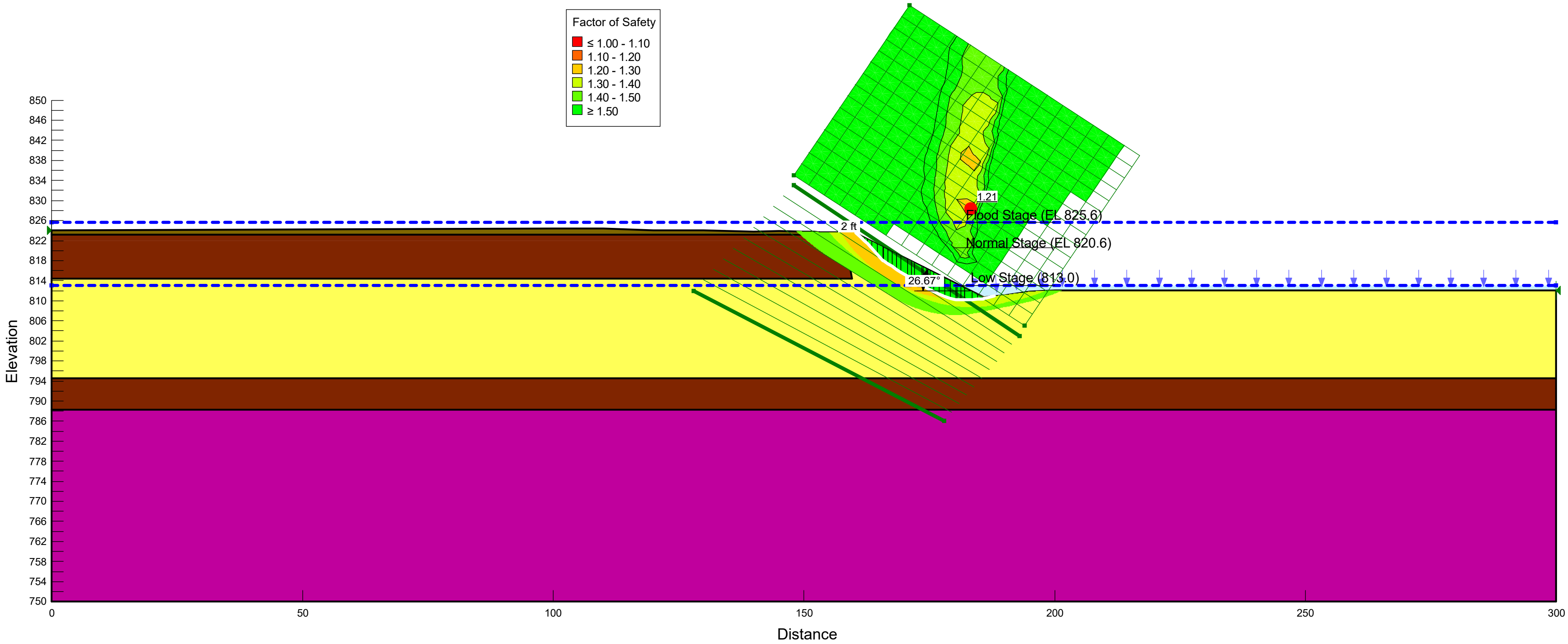


Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Normal Stage - LT - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius

Color	Name	Slope Stability Material Model	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)	Phi-B (°)	Cohesion R (psf)	Phi R (°)	Piezometric Line	Piezometric Line After Drawdown
🟫	Clay - LT & RD	Mohr-Coulomb	115	50	20	0	200	0	1	2
▨	Riprap - EOC, LT, & RD - 35°	Mohr-Coulomb	125	0	35	0	0	35	1	2
🟨	Sand - EOC, LT, & RD	Mohr-Coulomb	125	0	30	0	0	30	1	2
🟫	Topsoil - LT & RD	Mohr-Coulomb	110	50	10	0	100	0	1	2
🟪	Weathered Rock - EOC, LT, & RD	Mohr-Coulomb	100	50	40	0	50	40	1	2

Slip Rank: 1 of 2,817 slip surfaces
Factor of Safety: 1.21



Name: 8 - Alternative 3 - During- and Post-Construction - 35° Riprap - 1V:2H - Random Fill as Sand
Name: Varied PZ Line - RD - F to L - Alt3 (8)
F of S Calculation Option: Constant

Lower Sioux Indian Community - Feasibility Study
Method: Spencer
Slip Surface Option: Grid and Radius