KNIFE RIVER ELBEE BEND BANK STABILIZATION
KNRI 257081

APPENDIX B

Geotechnical Recommendations Report for Knife River - Elbee Bend Bank Stabilization Project, Knife River Indian Villages National Historic Site, Stanton, ND, October 22, 2024 prepared by Stantec Consulting Services Inc.

Knife River – Elbee Bend – Geotechnical Report

Stantec Consulting Services Inc.

Prepared for:
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Acronyms / Abbreviations

ASTM	American Society for Testing and Materials
CPT	Cone Penetration Test
ft	feet
FOS	Factor of Safety
in	inch
kPa	Kilopascal
LE	Limit Equilibrium
LL	Liquid Limit
Mm	millimeters
NPS	National Park Service
NP	Not Performed
%	Percentage
pcf	pounds per cubic foot
PL	Plastic Limit
PI	Plasticity Index
2D	Two dimensional
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USCS	Unified Soil Classification System

1 Introduction and Overview

1.1 Scope and Purpose

This Geotechnical Report is prepared in accordance with the Knife River Elbee Bend Bank Stabilization Project ("Project") Scope of Work, subtask 0.5: Geotechnical Recommendations, to support the design and includes:

- Data interpretation, analysis, and summaries
- Preliminary geotechnical design parameters for slope stability analysis
- Slope stability analysis
- Filter/ granular bedding design and compatibility

The geotechnical interpretation is based on data and information provided in the geological investigation at the Knife River – Elbee Bend Bank Stabilization Project (USACE, 2022) submitted to National Park Service (NPS). This Geotechnical Report presented herein should be read and considered in conjunction with USACE (2022). The purpose of this Geotechnical Report is to first provide an initial characterization (interpretation) of the geologic, geotechnical, and groundwater conditions, and selection of preliminary design parameters for use in the slope stability analysis of the Elbee Bend bank stabilization at the Knife River (presented in **Section 1** and **Section 2**). Also, the slope stability analysis was performed for the Elbee Bend considering different embankment configurations to select the best configuration that meet the minimum factor of safety (FOS) of the embankment against slope stability failure (presented in **Section 3**). Then, filter design and compatibility were performed for granular bedding at the selected embankment configuration (presented in **Section 4**).

This Geotechnical Report is not a construction contract document but is intended for use by the design team in design development of the Project. The interpretation of subsurface conditions presented herein includes interpolation between the completed subsurface explorations. The drill holes and Cone Penetration Test (CPT) depict subsurface conditions at the indicated locations and dates. Non-uniform conditions may occur between drill holes and CPT and, as a result, the distribution of subsurface conditions encountered may differ from those presented in this report.

1.2 Project Description

The Knife River is a tributary of the Missouri River with the Elbee Bend site on the Knife River located approximately two miles from the confluence of the two rivers. The recent changes in channel migration rates and patterns are postulated to be related to river base-level modifications caused by dam/reservoir development on the Missouri River and associated fluvial-backwater development (Ellis, L., 2006; USACE , 2018). Several of the Knife River meander bends have increased channel migration (meander) rates in the past few decades with the Elbee Bend being the focus of this study. Cutbank erosion rates of 1.0 to 3.5 feet per year (Sexton, C, 2012) within the past several decades threaten an archaeological site within the Knife River Indian Villages Historical Site (**Figure 1**).

The NPS was previously contracted with USACE (2020-2024) to design and construct a revetment to stabilize the cutbank of Elbee Bend. A subsurface geotechnical investigation was undertaken to collect relevant information on soil characteristics and potential borrow material from the left bank. The sides of the river are named (right or left) relative to a view downstream. Soil investigation was completed on the right and left banks of Elbee Bend - Knife River in support of a bank stabilization project near Stanton, ND (USACE, 2022). However, these investigations and studies did not document the slope stability recommendations for the proposed revetment slope. In early 2024, NPS ended the contract with USACE and awarded the Architect-Engineer (A/E) contract to Stantec Consulting Services Inc. to prepare Construction Documents.

Stantec provided a phased approach to inform the Project. First, a geotechnical interpretation of the previous geological investigation was performed. Second, slope stability analyses were performed to evaluate the stability of the proposed Elbee Bend bank section. Stability analysis was also performed considering a flatter slope and different embankment configuration. A filter design and compatibility were also completed.

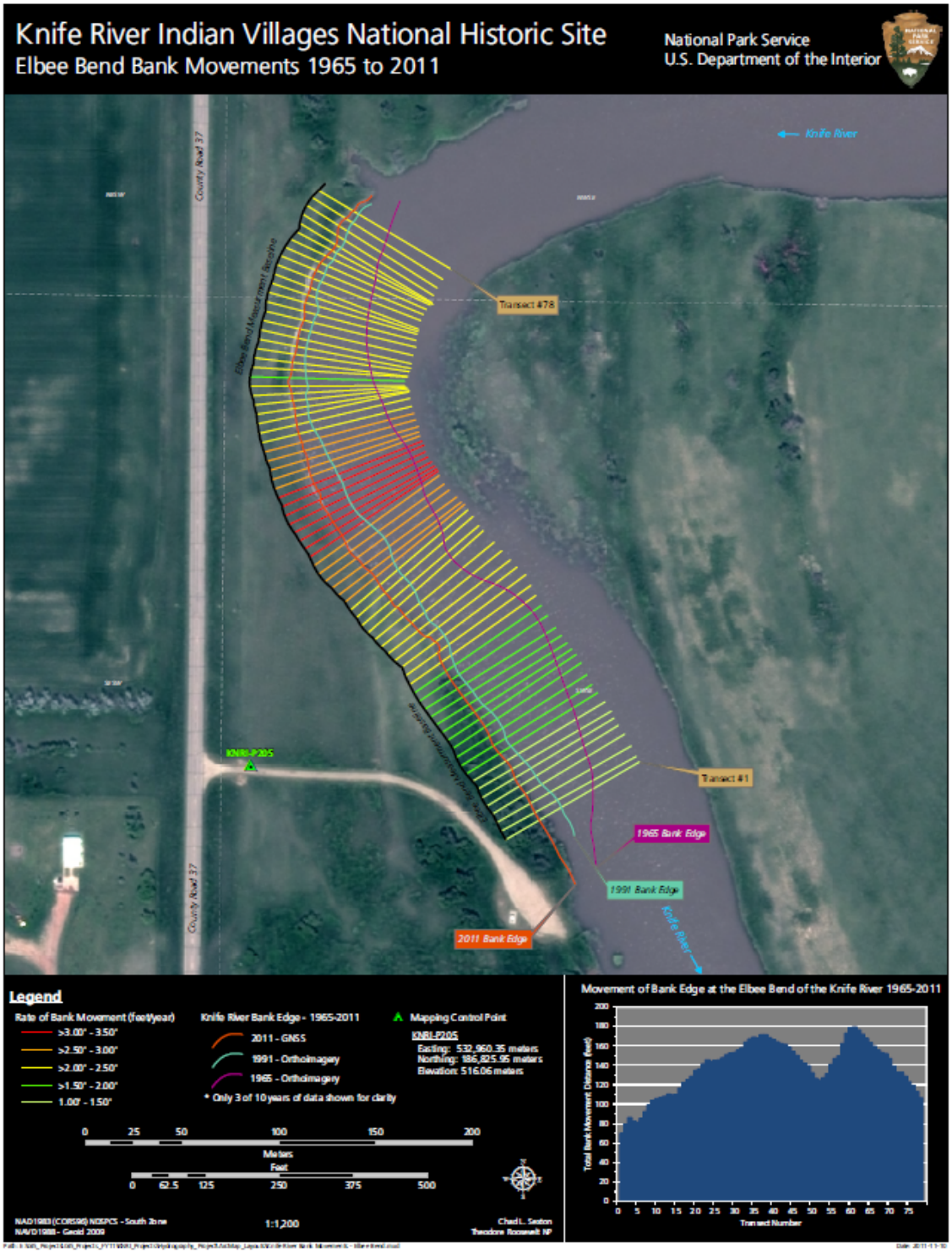


Figure 1 Elbee Bend Bank Movements 1965 to 2011

2 Subsurface Conditions and Interpretations

Geotechnical field investigation was conducted on the right bank (cutbank/outer) and left bank (pointbar/inner bend) of the Elbee Bend Knife River between December 1, 2024 through December 9, 2021. The fieldwork consisted of pushing twelve (12) cone penetration tests (CPTs) and drilling six (6) auger boring holes (BH) to obtain lithologic and groundwater information. CPT and auger boring locations are shown on **Figure 2**. Fifteen (15) samples of disturbed and undisturbed soil were collected and tested in the laboratory. More information about the geotechnical field investigation is presented in USACE (2022). CPT processed data from USACE (2022), and boring information were used to determine the lithology of the Elbee Bend. As soil from the left bank of the Elbee Bend will be excavated and used as compacted fill to build the proposed stabilized right bank, the geologic and geotechnical interpretation is focused on the left bank of the Elbee Bend. CPT-01, CPT-02, CPT-03, CPT-04, CPT-05, CPT-07, BH-01, BH-03, BH-04, BH-05, and the laboratory test for the samples collected in the inner bend (as summarized in **Table 1**) were used to determine the lithology of the left bank. Dry density tests were not performed for any samples collected from the left bank; however, one dry density test (91.6 pcf) was performed on poorly graded sand sample in the right bend at depth between 18 ft and 20 ft (USACE, 2022).

Fluvial geomorphology analysis was performed on the left bank of the Elbee Bend to understand the interactions between river shape, water, and sediment transport processes. The depositional environment is an inner meander bend, point bar system. As such, it is highly dynamic and variable even within a small area. Deposition generally occurs along historical flow paths with fines prevalent on the downstream end of the meander bend, where flows are slowed and eddies form. Therefore, sediments at CPT-06 and CPT-07 were likely deposited at different times and are part of a separate meander deposition belt than the rest of the CPT locations.

Four (4) profiles were constructed to display the fluvial geomorphology analysis based on CPT, boreholes, and laboratory data. The alignments of these profiles are shown in red on **Figure 2.** Profile A and profile D illustrate North to South left bank subsurface materials, and Profile B, and Profile C illustrate cross-valley left bank (perpendicular to profiles A and D) subsurface materials. Profiles A, B, C, and D are shown on **Figures 3**, **4**, **5**, and **6** respectively. These figures show that the soil in the left bank is mainly sandy with clay and silt lenses.

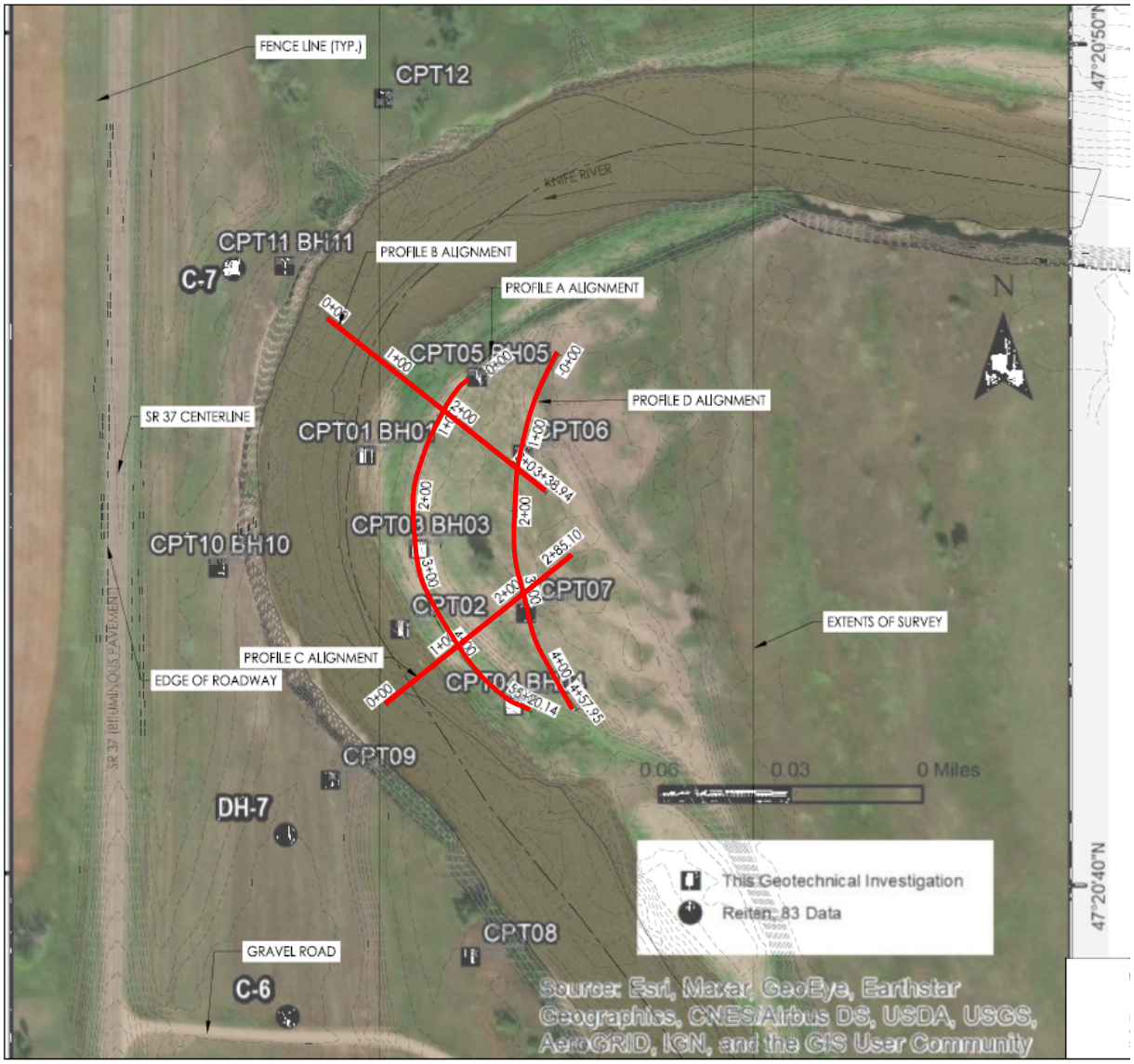


Figure 2 Profiles (in red) used for the geomorphology analysis (modified from USACE, 2022).

Table 1 Summary of Laboratory Testing on Samples Collected in the Left Bank of the Elbee Bend (USACE, 2022)

Boring and Sample Nos.	Depth (ft)	Description	USCS[1]	Sieve % Passing								Atterberg			Moisture content
				1/2 in	3/8 in	#4	#10	#20	#40	#80	#200	LL[2]	PL[3]	PI[4]	%
KN-FY21-CPT01-D-1	3.0-4.5	2.5Y 5/2 Olive Gray Poorly Graded Sand with Silt	SP-SM		100.0	99.9	99.3	96.9	80.2	11.0	5.9	-	-	-	24.7
KN-FY21-CPT03-D-1	6.0-6.5	2.5Y 5/2 Olive Gray Silty Sand	SM			100.0	99.6	97.8	89.5	38.1	22.2				25.2
KN-FY21-CPT03-D-2	6.5-7.5	2.5Y 5/4 Olive Poorly Graded Sand	SP			100.0	100.0	99.8	95.0	21.6	2.5	NP	NP	NP	15.0
KN-FY21-CPT04-D-1	6.0-6.6	5YR 4/2 Dark Reddish Gray Silty Sand	SM			100.0	99.8	99.2	93.2	45.1	19.9	NP	NP	NP	18.8
KN-FY21-CPT04-D-2	6.6-7.5	2.5Y 5/2 Grayish Brown Silty Sand	SM			100.0	100.0	99.2	90.4	51.7	36.1	20	19	1	37.1

[1] Unified Soil Classification System (USCS). The first letter in the naming describes the major constituents of the soil (G-gravel, S-sand, M-silt, C-clay, O-organic). The second letter describes characteristics of the soil. For coarse-grained, the second letters are: P-poorly graded (uniform particle sizes), W-well-graded (diversified particle sizes), M-silty fines, and C-clayey fines.
[2] The Liquid Limit (LL) is the water content of the soil at which it changes from a plastic to liquid consistency.
[3] The Plastic Limit (PL) is the water content of the soil at which it changes from a brittle/crumble consistency to a plastic consistency.
[4] The Plasticity Index (PI) is the range over which a soil has a plastic consistency and is calculated as the Liquid Limit minus the Plastic Limit.

KN-FY21-CPT05-D-1	4.0-4.6	2.5Y 6/8 Olive Yellow Poorly Graded Sand	SP		100.0	99.4	98.5	93.2	65.5	7.2	3.2				4.6
KN-FY21-CPT05-D-2	4.6-5.5	2.5Y 6/1 Gray Fat Clay with Sand	CH		100.0	98.4	97.6	96.2	91.7	81.4	74.7	61	21	40	43.3

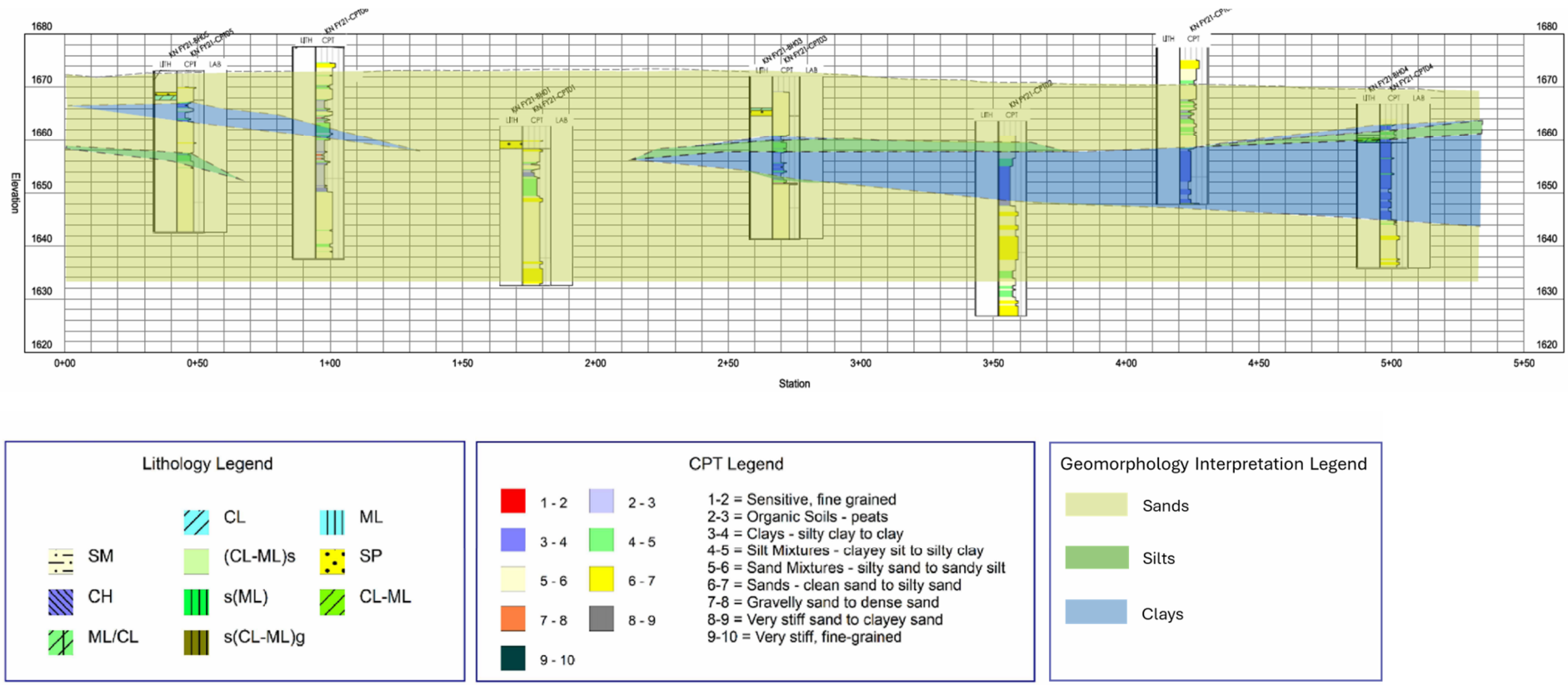


Figure 3 Profile A showing geomorphology interpretation based on the displaced CPT, boreholes, and laboratory data (vertical exaggeration 2 to 1). The location of profile A is shown on **Figure 2**.

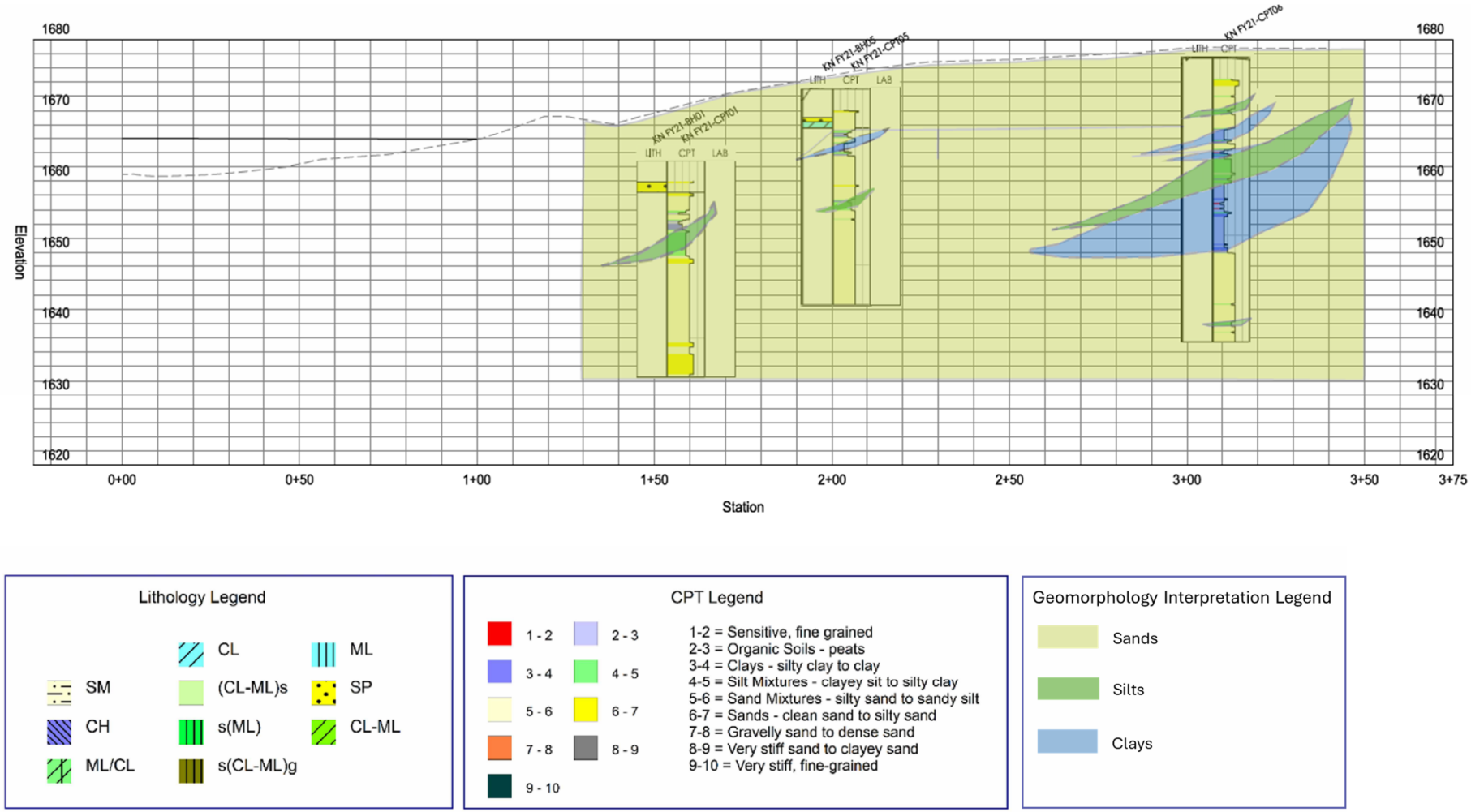


Figure 4 Profile B showing geomorphology interpretation based on the displaced CPT, boreholes, and laboratory data (vertical exaggeration 2 to 1). The location of profile B is shown on **Figure 2**.

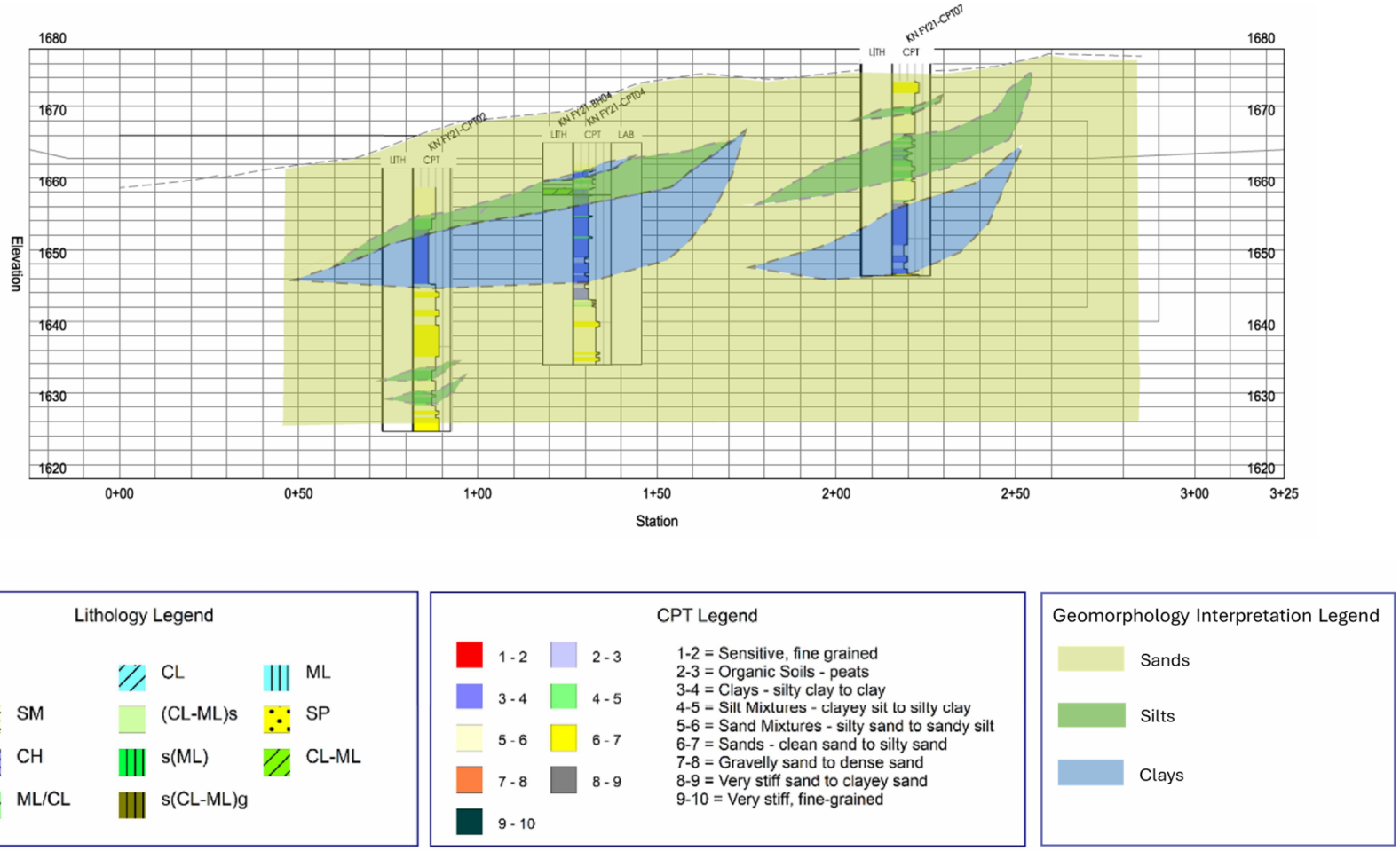


Figure 5 Profile C showing geomorphology interpretation based on the displaced CPT, boreholes, and laboratory data (vertical exaggeration 2 to 1). The location of profile C is shown on **Figure 2**.

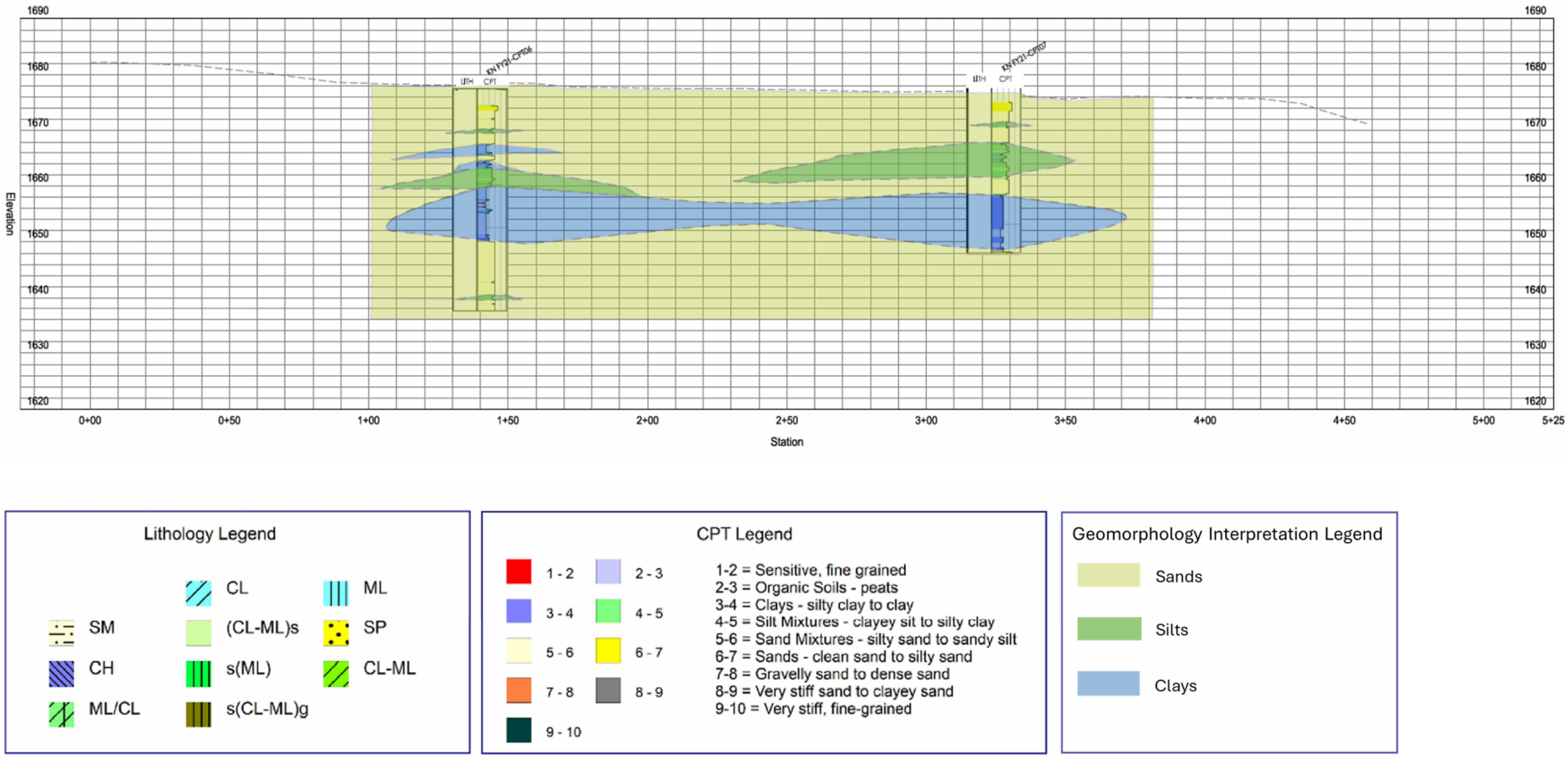


Figure 6 Profile D showing geomorphology interpretation based on the displaced CPT, boreholes, and laboratory data (vertical exaggeration 2 to 1). The location of profile D is shown on **Figure 2**.

3 Slope Stability Analysis

3.1 Model Geometry

Slope stability analysis was performed at the right bank of the Elbee Bend for the proposed stabilized embankment configuration. The maximum section of the right bank, shown in **Figure 7,** was considered for slope stability analyses. The foundation at the maximum section consists mainly of sand as interpreted from the CPT and boreholes data provided in USACE (2022). The embankment height at the maximum section measured from the riverbed to the embankment crest is around 32 feet.

The different configurations of the Elbee Bend are shown in **Figure 8** through **Figure 13** considered two different slope gradients of 3.0H:1.0V and 2.5H:1.0V (refer to **Table 2**). The slope is identified as ratio of horizontal (H) to vertical (V). The design components of the stabilized embankment consist of:

- Subsurface rock toe protection (which consists of void filled riprap),
- Longitudinal peak stone for toe protection (which consists of void filled riprap),
- Inboard of the peak stone, underwater fill and compacted fill will be added. Underwater fill will consist of void filled riprap. The compacted fill will be excavated material from the right bank of the Elbee Bend and possibly from borrow on site,
- Six (6) inch layer of filter/ granular bedding will be added between the void filled riprap and compacted fill, and between soil filled riprap and compacted fill,
- A 10 foot wide bench is incorporated into the slope at an elevation of 1,672 feet,
- A three and three-quarters (3.75) foot thick layer of soil-filled riprap topped with six (6) inches of topsoil will be installed. **Table 2** considered different options for the riprap extension,
- Landward of the bench will be fitted with erosion control blanket,
- The entire slope, bench, and disturbed areas will be seeded,
- At the upstream tie in point, a 10-ft wide trench of buried rock (which consists of void filled riprap) is installed starting at elevation 1,661 feet up to final grade for the entire embankment section. The buried rock trench has two purposes. The rock trench holds the existing upstream slope in place while the stabilized embankment is constructed downstream of the buried rock trench. The other purpose is to prevent future flanking of the constructed embankment. This design component was not explicitly modeled.

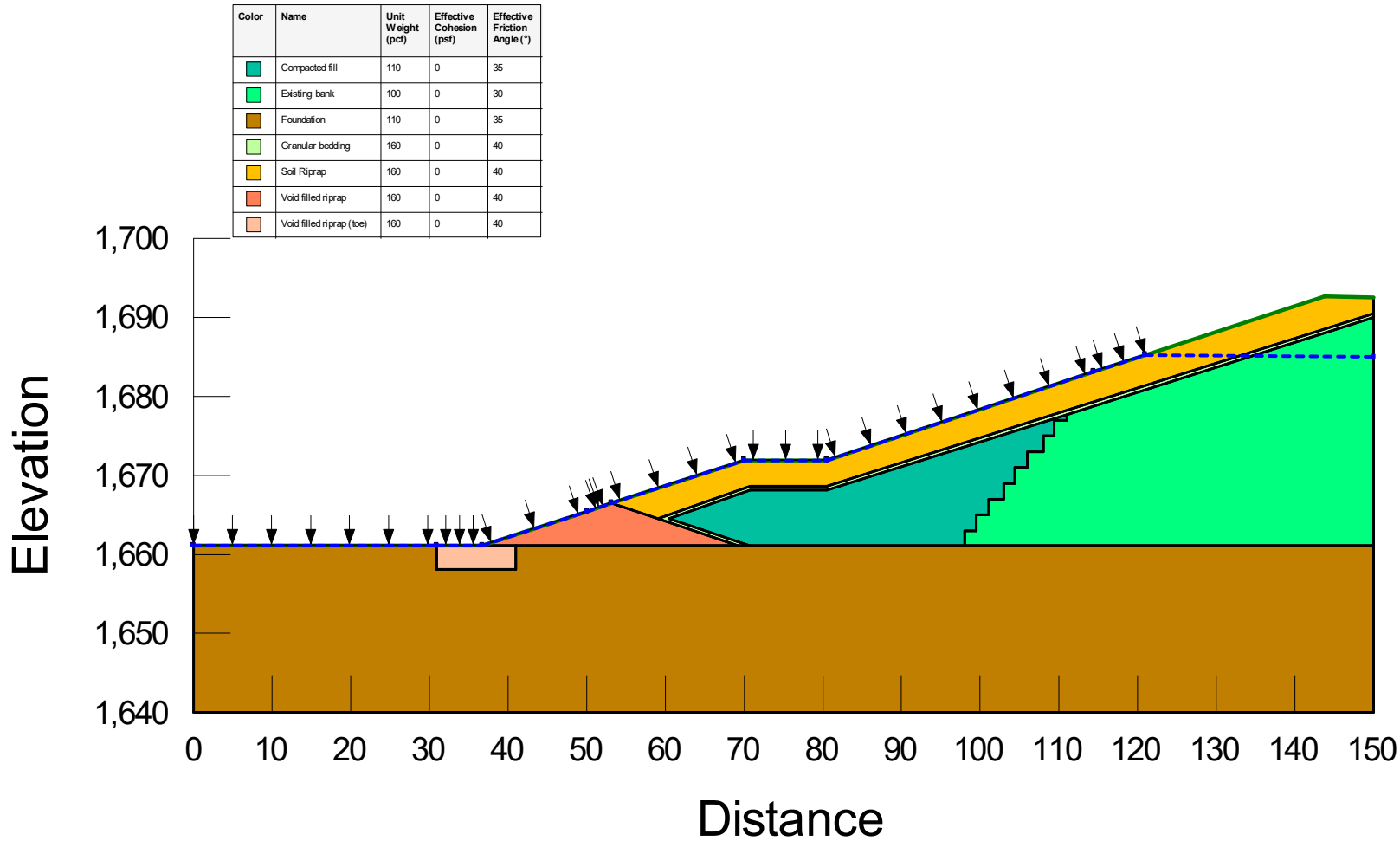
In the stability analysis model, foundation excavation was assumed within the riverbed to reach a top foundation level of around 1,661 feet elevation. Different cases were considered for the stabilized embankment slope as described in **Table 2** to assess the FOS change with riprap extend through the slope, the riprap unit weight, the embankment slope, and the embankment configuration. The profiles for the cross-section analyzed for each of the different cases, including material designations, are shown in

through **Figure 13**. Additionally, the phreatic surface used in the stability models is based on 100-year water surface elevation of 1,685.3 feet and is shown as a blue dashed line in these figures. The phreatic surface is the upper surface of the saturated zone in soil or rock, where all voids are filled with water.

Table 2 Summary of Different Cases

Case ID	Slope	Riprap	Filter/ Granular Bedding
Case 1 (see Figure 8)	3.0H:1.0V	- Void filled riprap (3 ft x 10 ft) will be constructed for subsurface rock toe protection - Soil filled riprap will be constructed above the longitudinal peak stone and along the slope to the crest	- Filter/ granular bedding will be constructed between compacted fill and soil filled riprap, between compacted fill and void filled riprap, and between existing bank and void filled riprap.
Case 2 (see Figure 9)	3.0H:1.0V	- Void filled riprap (3 ft x 10 ft) will be constructed for subsurface rock toe protection - Soil filled riprap will be constructed above the longitudinal peak stone until reaching the bench elevation of 1,672 ft	- Filter/ granular bedding will be constructed between compacted fill and soil filled riprap, and between compacted fill and void filled riprap.
Case 3 (see Figure 10)	3.0H:1.0V	- Void filled riprap (3 ft x 10 ft) will be constructed for subsurface rock toe protection - Soil filled riprap will be constructed above the longitudinal peak stone and along the slope to the crest. Riprap unit weight is 150 pcf above the bench and 160 pcf from the bench and below to assess using riprap with lower density.	- Filter/ granular bedding will be constructed between compacted fill and soil filled riprap, between compacted fill and void filled riprap, and between existing bank and void filled riprap.
Case 4 (see Figure 11)	3.0H:1.0V	- Void filled riprap (3 ft x 10 ft) will be constructed for subsurface rock toe protection. Void filled riprap will be also constructed behind the longitudinal peak stone until 1,664 ft level. - Soil filled riprap will be constructed above the longitudinal peak stone and along the slope to the crest. Riprap unit weight is 150 pcf above the bench and 160 pcf from the bench and below to assess using riprap with lower density.	- Filter/ granular bedding will be constructed between compacted fill and soil filled riprap, between compacted fill and void filled riprap, and between existing bank and void filled riprap.
Case 5 (see Figure 12)	2.5H:1.0V	- Void filled riprap (3 ft x 10 ft) will be constructed for subsurface rock toe protection - Soil filled riprap will be constructed above the longitudinal peak stone and along the slope to the crest	Rock will be installed at the toe and base of the slope
Case 6 (see Figure 13)	3.0H:1.0V	- Void filled riprap (inverse trapezoidal shape: top 18.6 ft (top) x 4ft (base) x 3 ft (height)) will be constructed for subsurface rock toe protection. Void filled riprap will be also constructed behind the longitudinal peak stone until the top of the longitudinal peak stone. - Soil filled riprap will be constructed above the longitudinal peak stone and along the slope to the crest	- Filter/ granular bedding will be constructed between compacted fill and soil filled riprap, between compacted fill and void filled riprap, and between existing bank and void filled riprap, and between foundation and void filled riprap.

Figure 7 Maximum Section location (indicated in red) at the Right Bend of the Elbee bend.



Color	Name	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)
	Compacted fill	110	0	35
	Existing bank	100	0	30
	Foundation	110	0	35
	Granular bedding	160	0	40
	Soil Riprap	160	0	40
	Void filled riprap	160	0	40
	Void filled riprap (toe)	160	0	40

Figure 8 Maximum Section Geometry at the Right Bank of the Elbee Bend – Case 1

Color	Name	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)
	Compacted fill	110	0	35
	Existing bank	100	0	30
	Foundation	110	0	35
	Granular bedding	160	0	40
	Soil Riprap	160	0	40
	Void filled riprap	160	0	40
	Void filled riprap (toe)	160	0	40

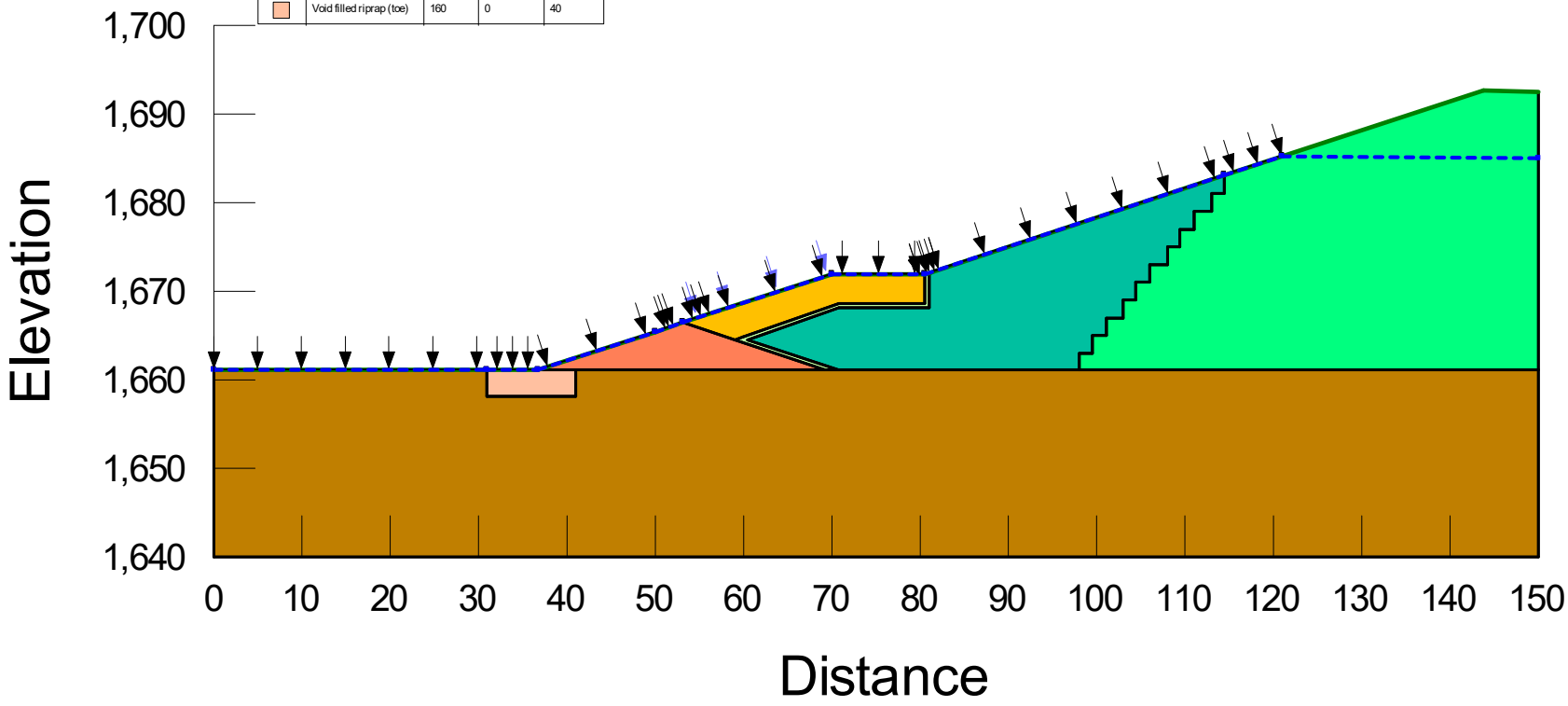


Figure 9 Maximum Section Geometry at the Right Bank of the Elbee Bend – Case 2

Color	Name	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)
	Compacted fill	110	0	35
	Existing bank	100	0	30
	Foundation	110	0	35
	Granular bedding	160	0	40
	Soil Riprap	160	0	40
	Soil riprap (lower density)	150	0	40
	Void filled riprap	160	0	40
	Void filled riprap (toe)	160	0	40

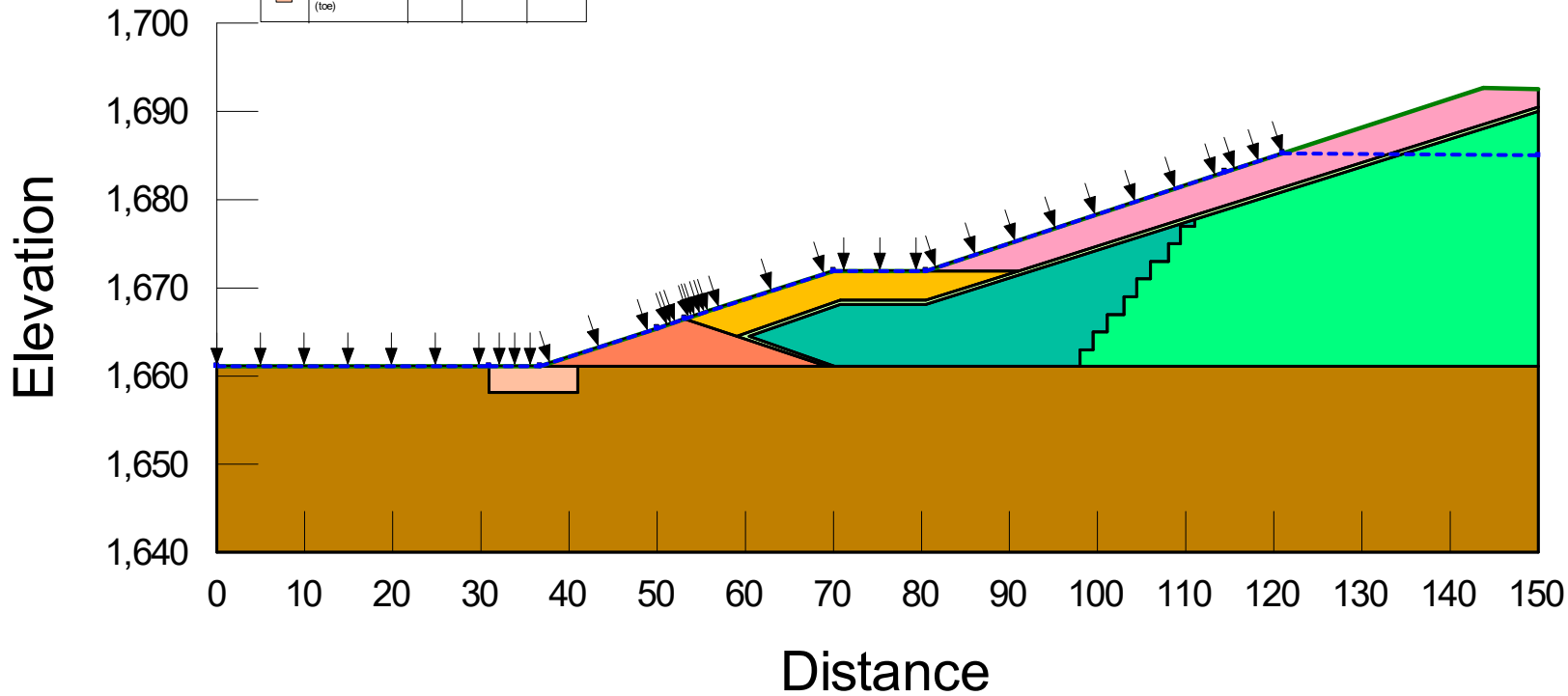


Figure 10 Maximum Section Geometry at the Right Bank of the Elbee Bend – Case 3

Color	Name	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)
	Compacted fill	110	0	35
	Existing bank	100	0	30
	Foundation	110	0	35
	Granular bedding	160	0	40
	Soil Riprap	160	0	40
	Soil riprap (lower density)	150	0	40
	Void filled riprap	160	0	40
	Void filled riprap (toe)	160	0	40

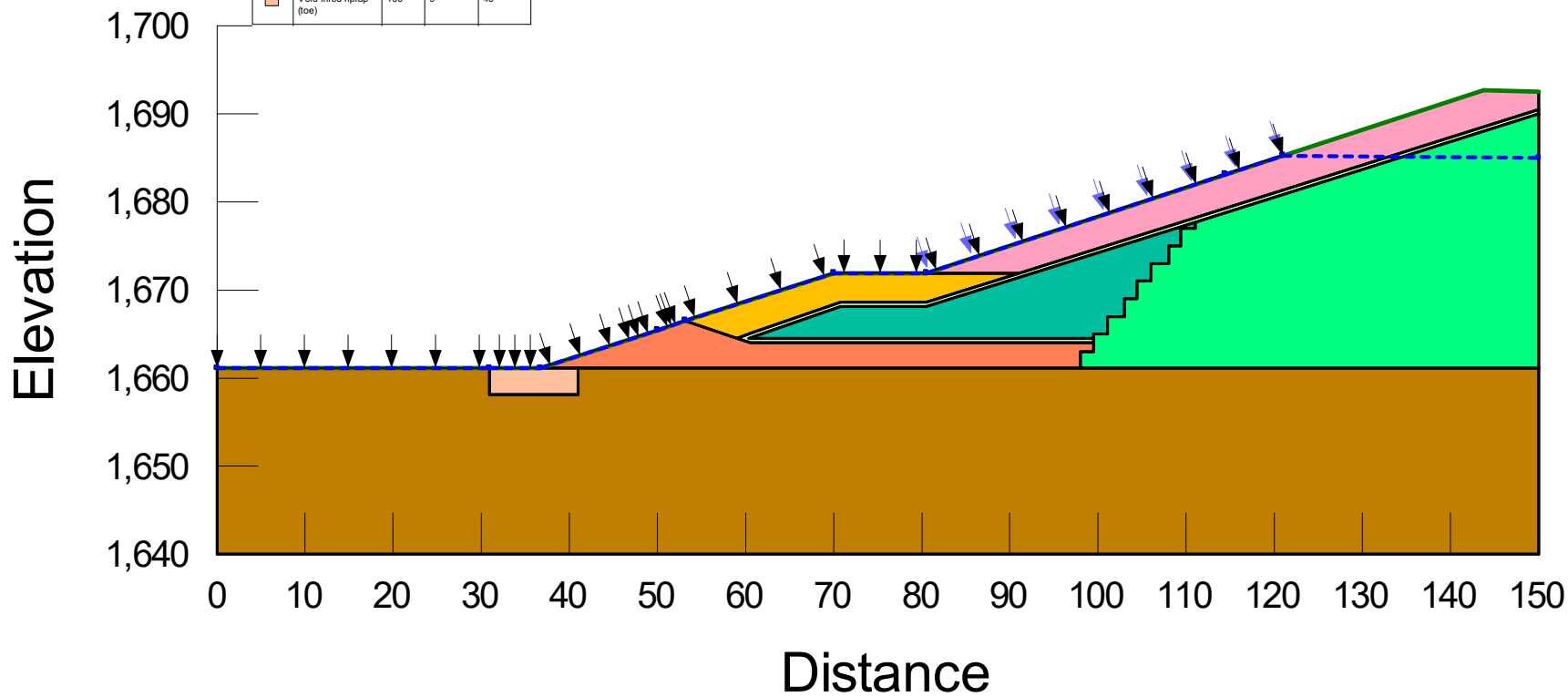


Figure 11 Maximum Section Geometry at the Right Bank of the Elbee Bend – Case 4

Color	Name	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)
	Compacted fill	110	0	35
	Existing bank	100	0	30
	Foundation	110	0	35
	Granular bedding	160	0	40
	Soil Riprap	160	0	40
	Void filled riprap	160	0	40
	Void filled riprap (toe)	160	0	40

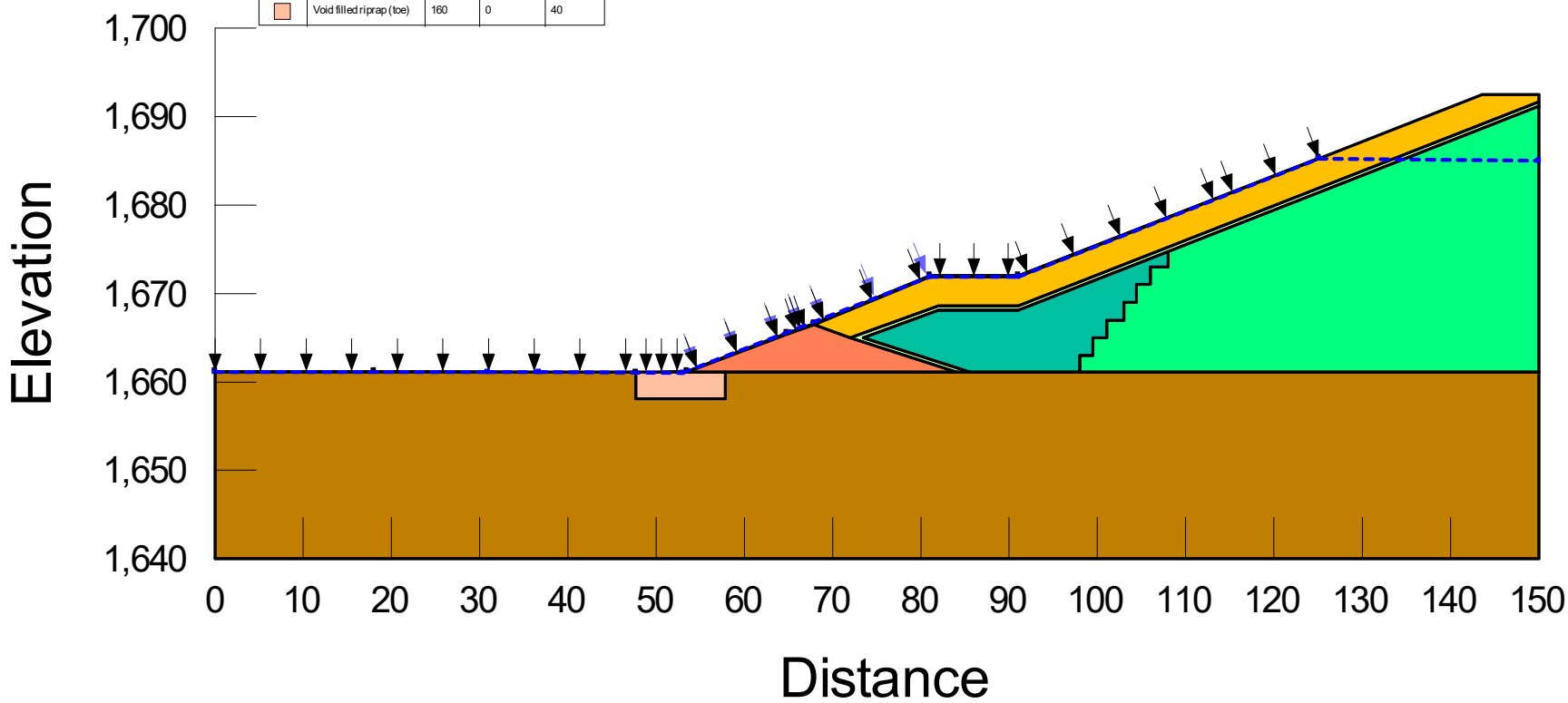
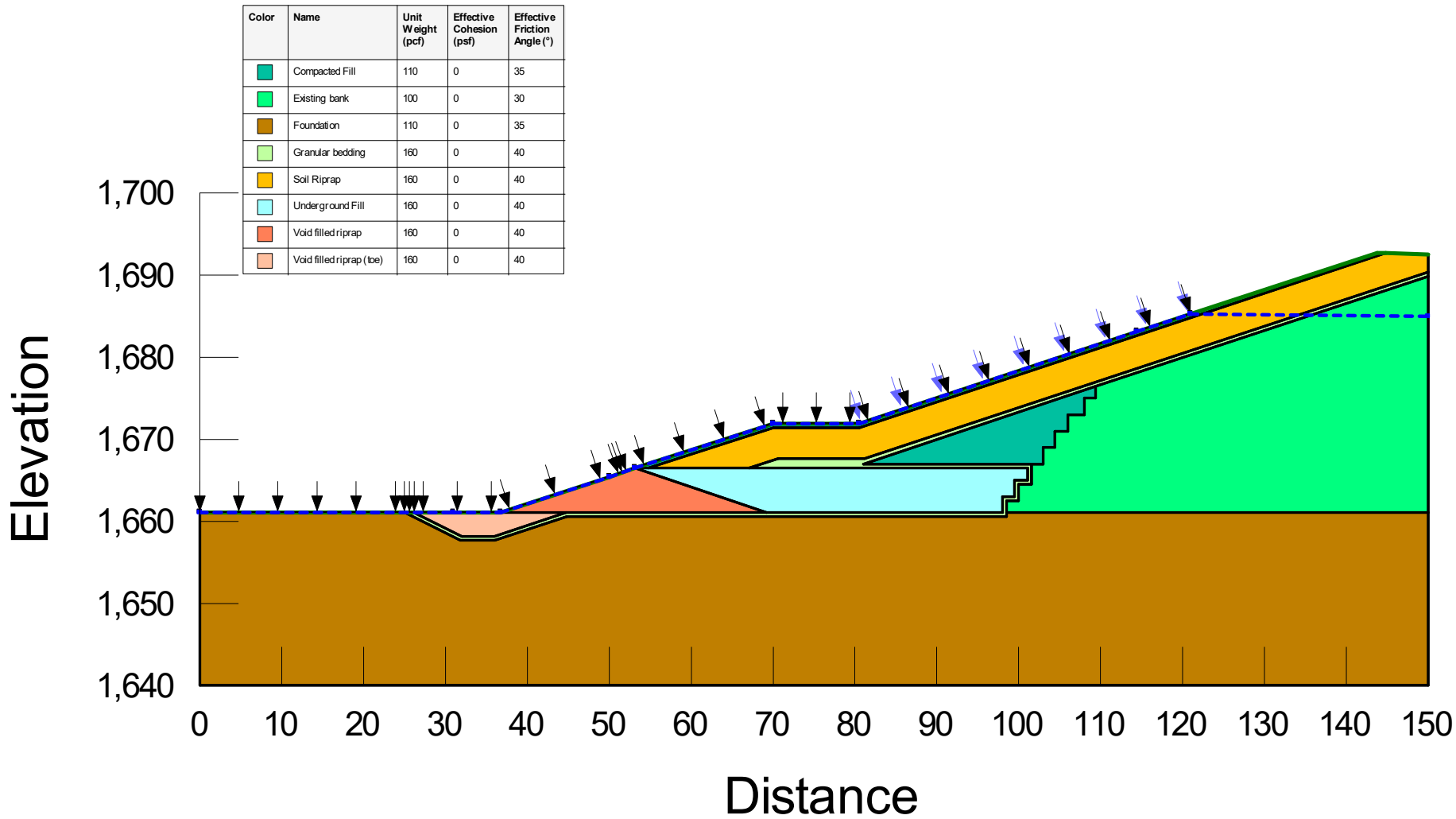


Figure 12 Maximum Section Geometry at the Right Bank of the Elbee Bend – Case 5



Color	Name	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)
	Compacted Fill	110	0	35
	Existing bank	100	0	30
	Foundation	110	0	35
	Granular bedding	160	0	40
	Soil Riprap	160	0	40
	Underground Fill	160	0	40
	Void filled riprap	160	0	40
	Void filled riprap (toe)	160	0	40

Figure 13 Maximum Section Geometry at the Right Bank of the Elbee Bend – Case 6

3.2 Methodology and Assumptions

The loading condition evaluated for the stability analysis and corresponding minimum FOS value is shown in **Table 3** and were adopted from applicable guidance documents, including Stability of Earth and Rockfill Dams (USACE, 2003).

Table 3 Loading Condition and Acceptable FOS

Loading Scenario	Minimum FOS	Reference
Flood Conditions	1.4	(USACE, 2003)

Flood conditions were evaluated using drained strength properties for all the materials, following the standard of practice (USACE, 2003). The flood level within the embankment is based on 100 year water surface elevation of 1,685.3 ft. The minimum recommended FOS for flood conditions is 1.4 (USACE, 2003).

The stability analysis was developed using SLOPE/W version 11.4.2.250 (Geo-Slope International, 2022). Limit Equilibrium (LE) analyses were performed to calculate the FOS of two-dimensional (2D) failure surfaces using the Morgenstern-Price Method (Morgenstern & Price, 1965), which is capable of rotational and translational failure surfaces and satisfies both moment and force equilibrium. The Entry and Exit method was used as the slip surface search method. The minimum FOS, as calculated by SLOPE/W, is often a shallow rotational failure surface representative of sloughing of non-cohesive soils along the slope face. These shallow slip surfaces represent surficial sloughing and are not considered to affect the overall stability of the embankment. To eliminate these surficial failure surfaces, the analyses discussed herein focus on failures deeper than 5.0 ft.

3.3 Material Parameters

The material parameters used in the stability analysis are based on typical values of similar materials. The material parameters are summarized in **Table 4** assuming drained strength properties for all the materials.

Table 4 Material Strength Properties Used for Stability Analysis

Materials	Unit Weight (pcf)	Strength Parameters
Void filled riprap Soil filled riprap	160(1)	c'= 0 kPa (4) ϕ' = 40 degrees (5)
Soil filled riprap (lower density)	150(2)	c'= 0 kPa (4) ϕ' = 40 degrees (5)
Filter/ Granular bedding	160(1)	c'= 0 kPa (4) ϕ' = 40 degrees (5)
Compacted fill	110(3)	c'= 0 kPa (4) ϕ' = 35 degrees (6)

(1) Typical unit weight of riprap ranges between 150 pcf to 175 pcf according to USACE Engineering Manual EM 1110-2-1601 (USACE, 1994). A unit weight of 160 pcf is assumed for void filled and soil filled riprap.

(2) A lower density was assumed for the riprap to represent a material with higher soil content and lower compaction.

(3) Based on laboratory testing performed in USACE (2022), the unit weight of poorly graded sand sample in the outer bend at depth between 18 ft to 20 ft is 91.6 pcf. Soil excavated from the right bank of the Elbee Bend will be used and compacted to form the compacted fill. So, a unit weight of 110 pcf was used for compacted fill.

(4) Cohesion of rock toe, riprap, filter, and compacted fill is assumed to be zero which is a conservative assumption.

(5) Effective friction angle for rock toe and riprap is assumed to be 40 degrees based on average engineering properties of compacted inorganic soils (Samtani, N. C.; Nowatzki, E. A., 2006).

(6) Effective friction angle for filter and compacted fill is assumed to be 35 degrees based on average engineering properties of compacted inorganic soils (Samtani, N. C.; Nowatzki, E. A., 2006).

3.4 Results

Table 5 summarizes the slope stability analyses results of the SLOPE/W analyses for right bank for each case which included the minimum calculated FOS and the minimum required FOS. **Figures 14** through **19** show the stability analysis results and critical slip surfaces for all cases. Critical failure surfaces observed for all loading conditions were typically similar, with the critical slip surface passing primarily through the riprap and compacted fill on the upper part (above the bench) of the embankment slope.

The results show that the minimum calculated FOS meet the minimum required FOS criteria only for Case 1 and Case 6 with slope of 3.0H:1.0V and soil filled riprap (with unit weight of 160 pcf) extending along the slope to the crest embankment. Case 5 has the same configuration as Case 1 but with a steeper slope of 2.5H:1.0V. The minimum calculated FOS for Case 5 decreases from 1.4 to 1.0 in comparison with Case 1. For embankment configuration slope of 3.0H:1V, the minimum calculated FOS value was observed to be the lowest for Case 2 with the riprap extending only to the bench level. Case 6 was selected as the proposed configuration for the stabilized embankment because it meets the minimum required FOS of the embankment against slope stability failure and for constructability considerations.

The slope stability results described here are dependent on the characteristics of the constituent materials and the embankment construction procedures and might differ if different materials properties will be used.

Table 5 Summary Results of Stability Analyses – Right Bank of Elbee Bend

Case	Minimum Required FOS	Minimum Calculated FOS
1 (Figure 14)	1.4	1.4
2 (Figure 15)	1.4	0.9
3 (Figure 16)	1.4	1.3
4 (Figure 17)	1.4	1.3
5 (Figure 18)	1.4	1.1
6 (Figure 19)	1.4	1.4

Color	Name	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)
	Compacted fill	110	0	35
	Existing bank	100	0	30
	Foundation	110	0	35
	Granular bedding	160	0	40
	Soil Riprap	160	0	40
	Void filled riprap	160	0	40
	Void filled riprap (toe)	160	0	40

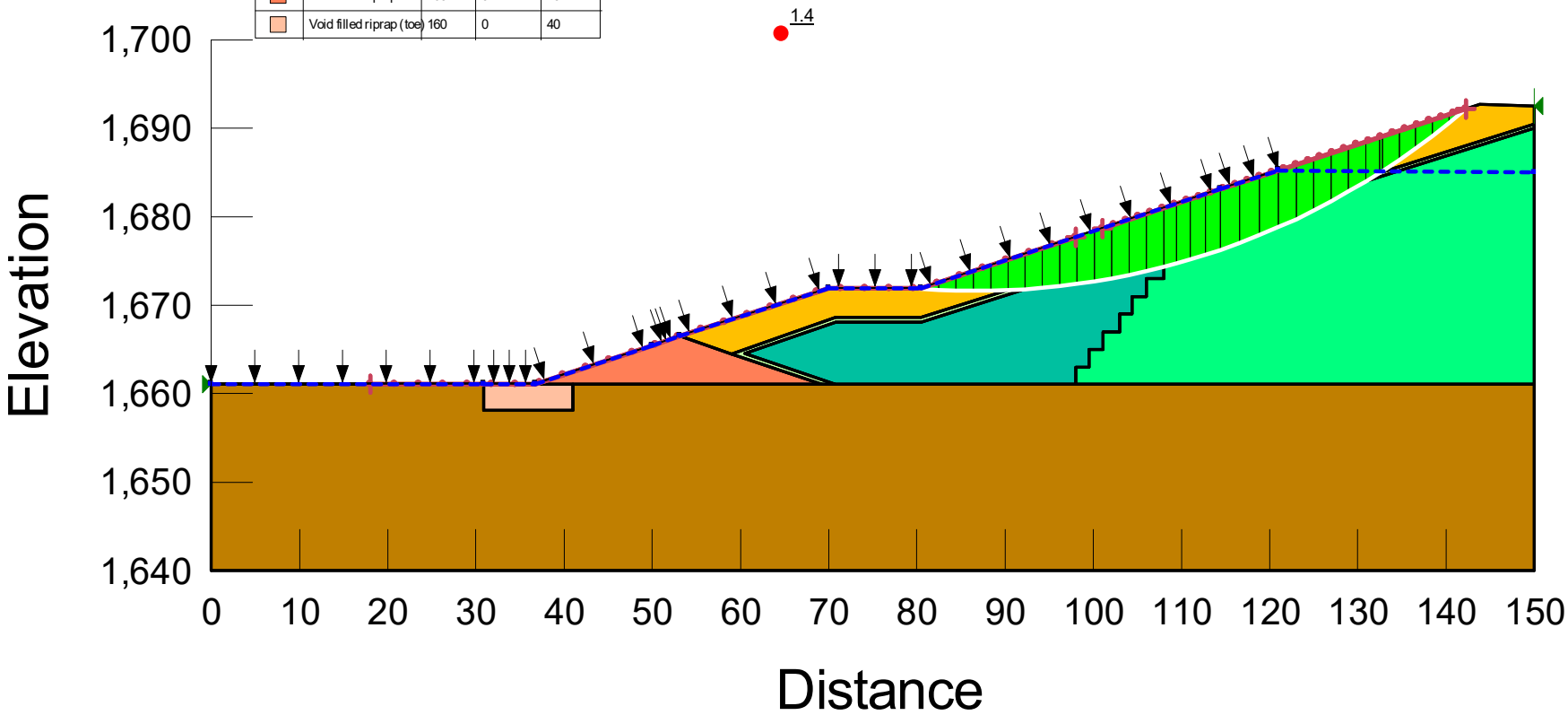


Figure 14 Stability analysis results and Slip Surface at the Right Bank of the Elbee Bend – Case 1

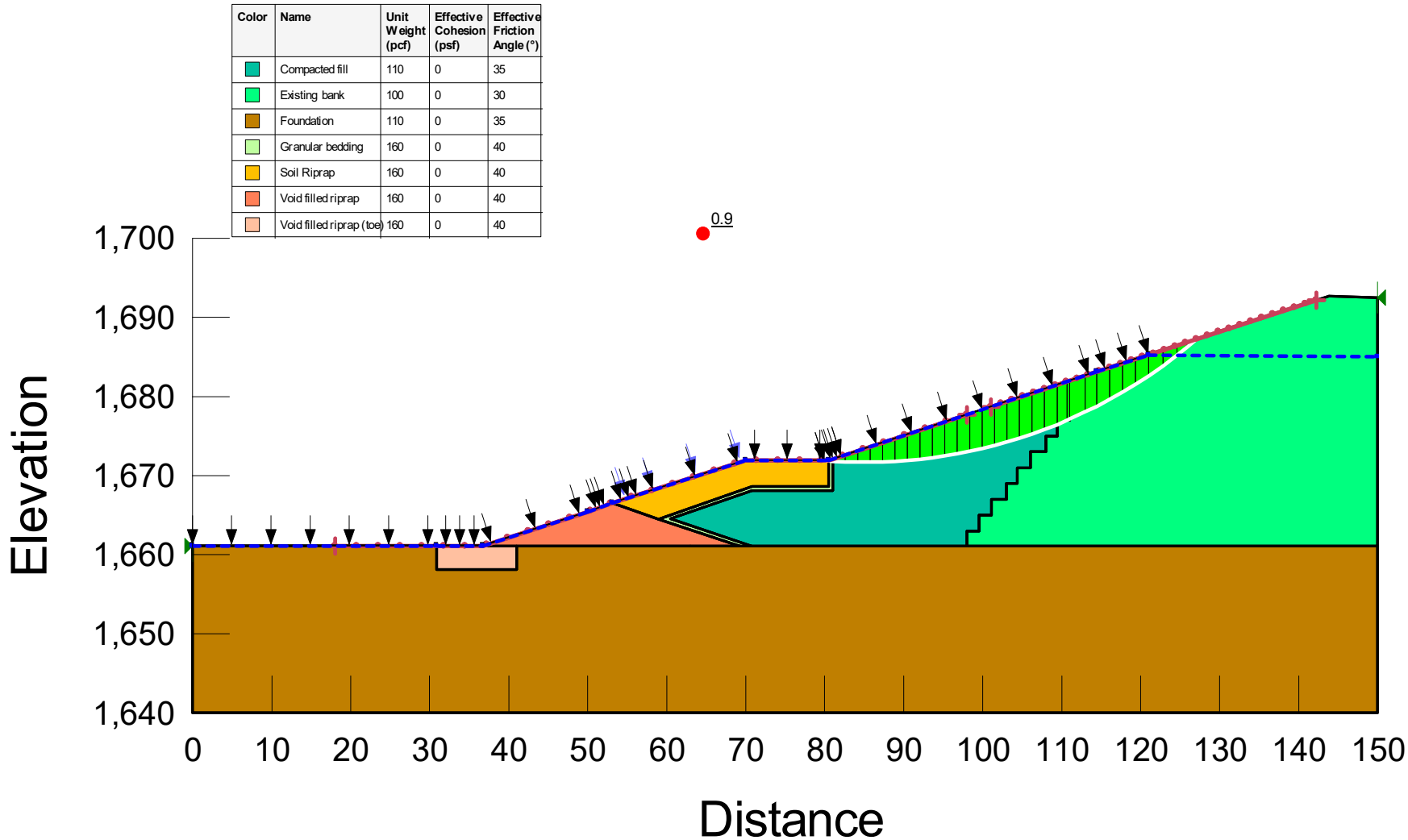


Figure 15 Stability analysis results and Slip Surface at the Right Bank of the Elbee Bend – Case 2

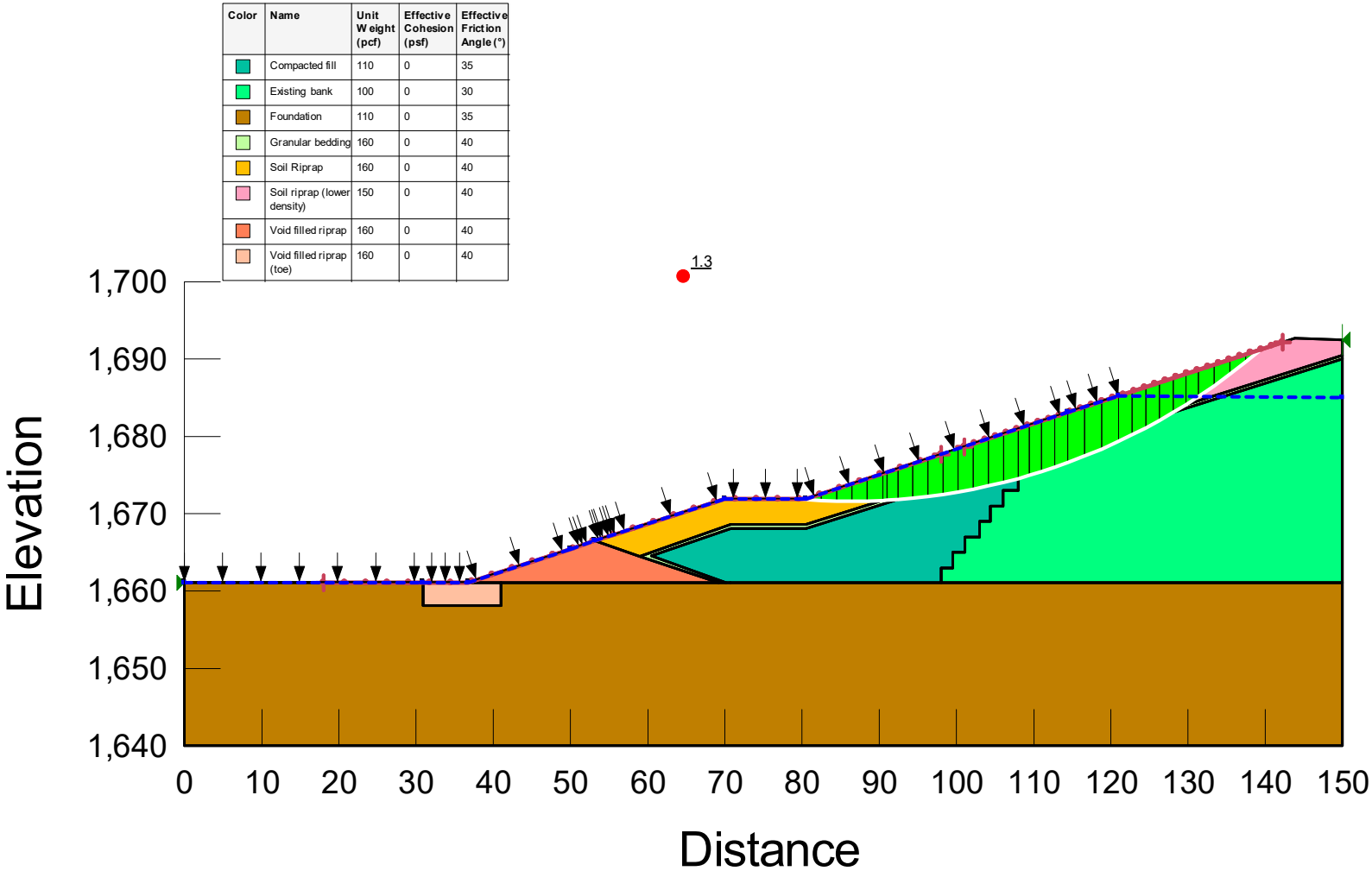


Figure 16 Stability analysis results and Slip Surface at the Right Bank of the Elbee Bend – Case 3

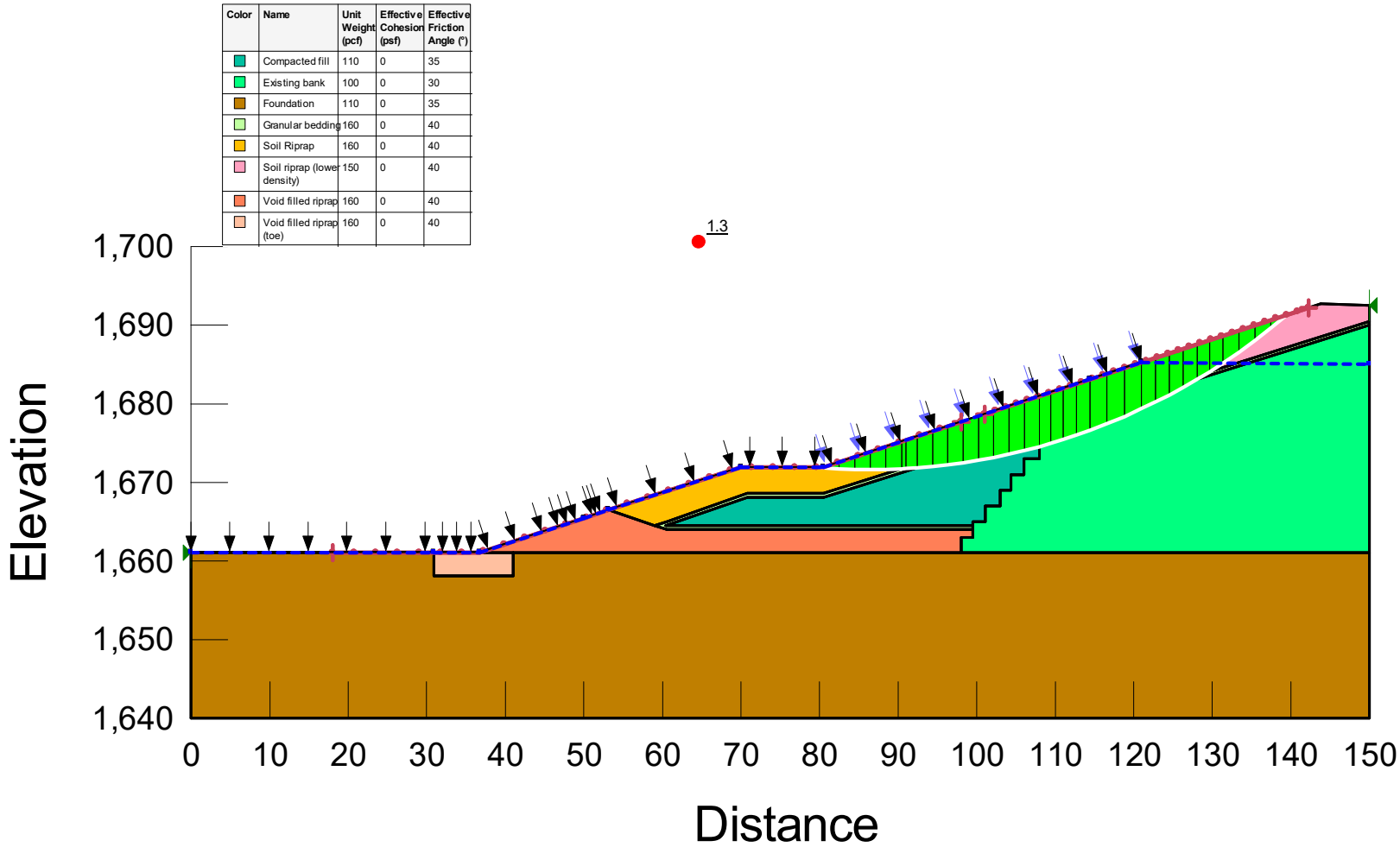


Figure 17 Stability analysis results and Slip Surface at the Right Bank of the Elbee Bend – Case 4

Color	Name	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)
	Compacted fill	110	0	35
	Existing bank	100	0	30
	Foundation	110	0	35
	Granular bedding	160	0	40
	Soil Riprap	160	0	40
	Void filled riprap	160	0	40
	Void filled riprap (toe)	160	0	40

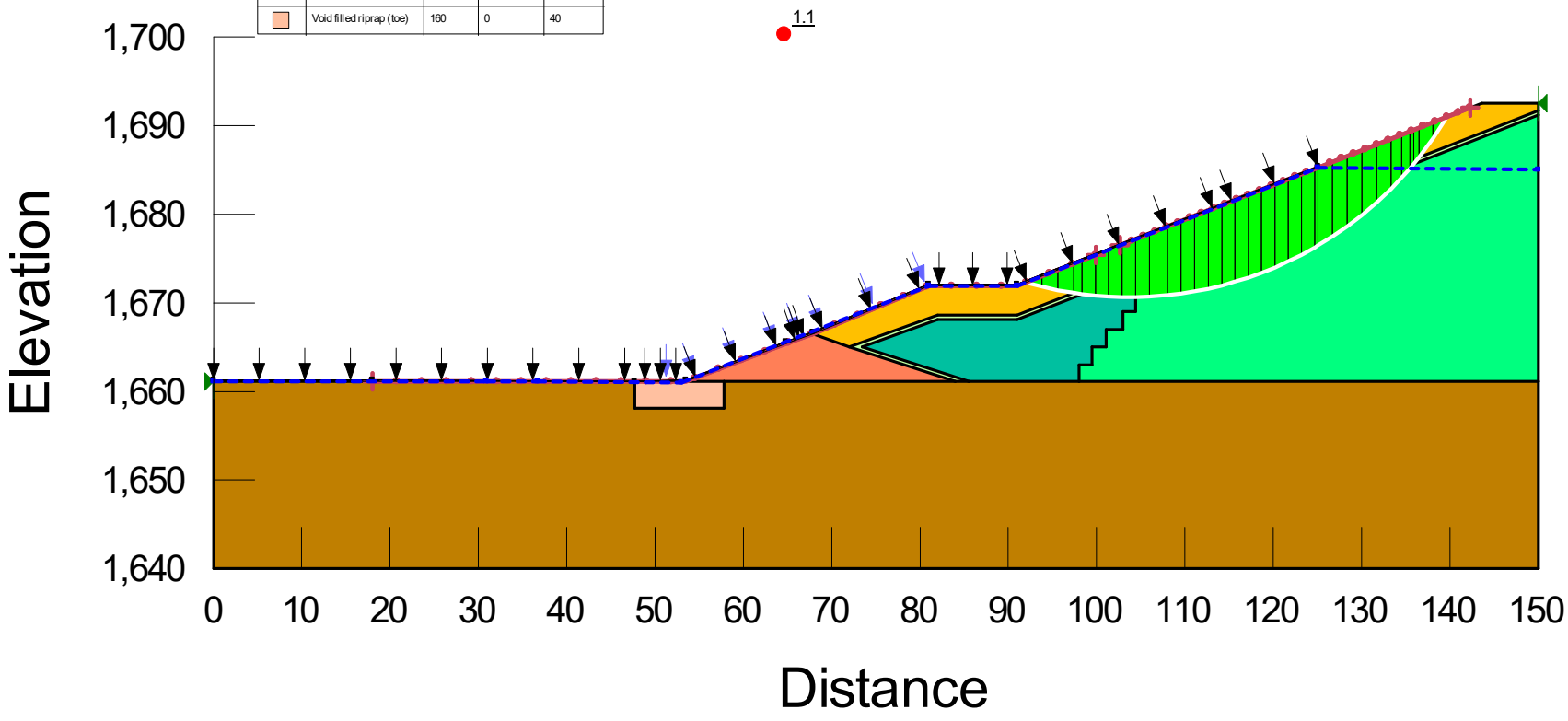
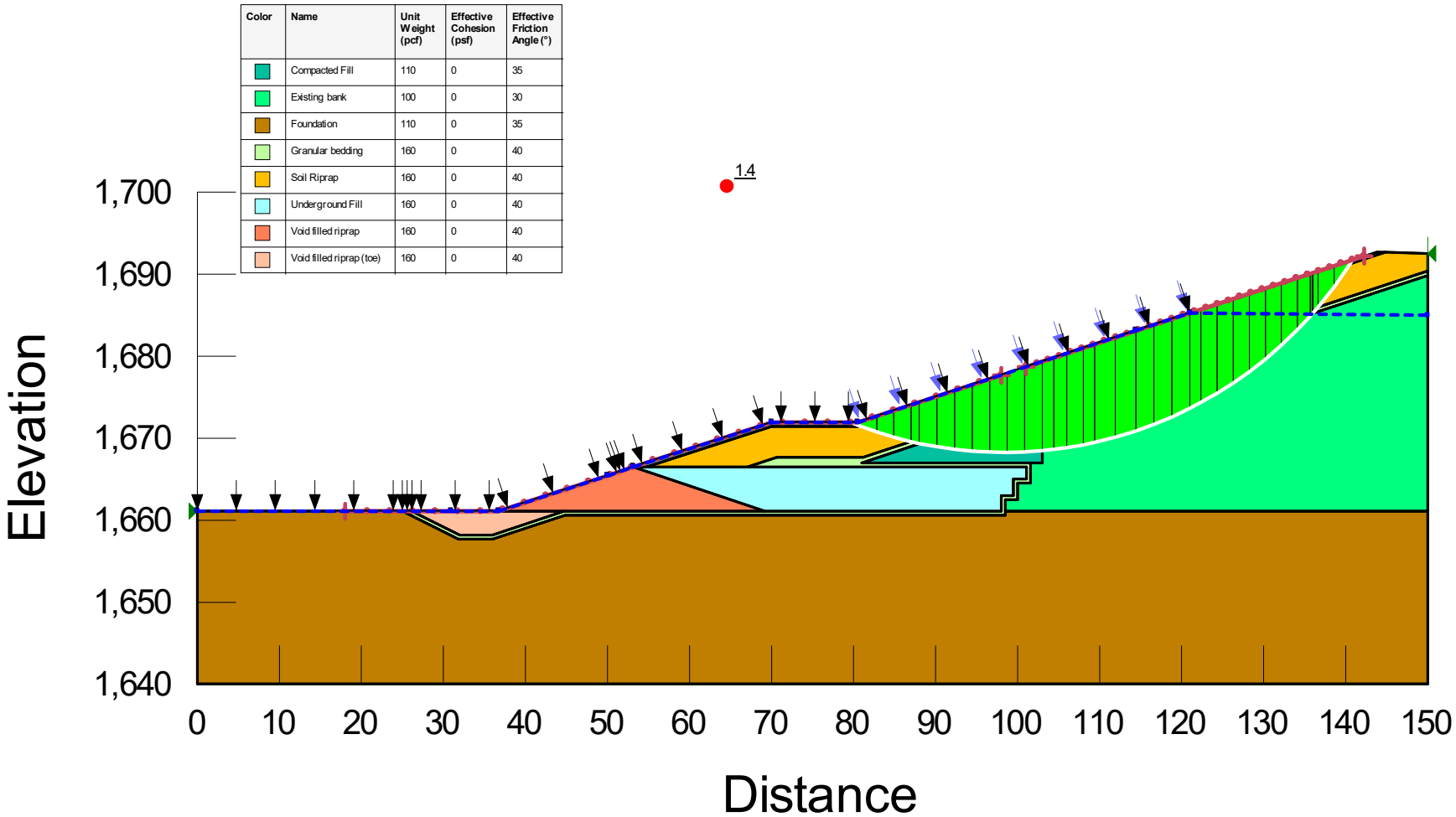


Figure 18 Stability analysis results and Slip Surface at the Right Bank of the Elbee Bend – Case 5



Color	Name	Unit Weight (pcf)	Effective Cohesion (psf)	Effective Friction Angle (°)
	Compacted Fill	110	0	35
	Existing bank	100	0	30
	Foundation	110	0	35
	Granular bedding	160	0	40
	Soil Riprap	160	0	40
	Underground Fill	160	0	40
	Void filled riprap	160	0	40
	Void filled riprap (toe)	160	0	40

Figure 19 Stability analysis results and Slip Surface at the Right Bank of the Elbee Bend – Case 6

4 Filter Design and Compatibility

4.1 Introduction

This section presents the filter design and compatibility calculations performed for the design of proposed embankment at the right bank of the Elbee Bend. The primary objective of this section is to evaluate the suitability of proposed filters with the embankment based on design material gradations of materials.

Filters are used to reduce the risk of particle migration from a finer material into the voids of an adjacent coarser material, and in some cases, to also provide drainage. In this section, the term base material refers to the finer material which is to be retained by the filter material. Filter compatibility calculations are used to evaluate the suitability of a given filter / base material pair.

The cross sections of different embankment configurations in **Figures 8** through **13** show the key material interfaces within the embankment. Although the flow direction within the embankment is expected to be inward, from the river through the embankment, once the river level rise, some occasions may exist when the river level drops where the flow is outward, from the embankment toward the river. Filter compatibility calculations were performed considering both conditions. Flow is primarily from inboard to outboard, with a downward component in the inboard shell and an upward component in the outboard shell. Filter/ granular bedding would be constructed between compacted fill and soil filled riprap, between compacted fill and void filled riprap, and between existing bank and void filled riprap, and between foundation and void filled riprap.

The following list summarizes the filter compatibility calculations that were performed as part of this assessment:

- Granular bedding (Filter) and compacted fill (Base). As soil type is expected to be similar for the compacted fill, existing slope, and foundation, this case includes the filter compatibility calculations between granular bedding and compacted fill, between granular bedding and foundation, and between granular bedding and existing slope.
- Void filled riprap (Filter) and granular bedding (Base)
- Soil filled riprap (Filter) and granular bedding (Base)

4.2 Material Description and Gradations

4.2.1 Void Filled Riprap

Void filled riprap will be placed at subsurface rock toe protection, longitudinal peak stone for toe protection, and underground fill to form the full revetment of the stabilized embankment. The material will be obtained from a commercial source, meeting North Dakota Department of Transportation (ND DOT) Grade II specifications (Sect. 256.03.C.1), placed in three (3) foot loose lifts and compacted with self-propelled vibratory compaction. Additionally, the material will be hard, durable and angular

and will be reasonably well graded with a maximum particle size of 28 inches. Details of the void filled riprap mixture are shown in **Table 6**.

Table 6 Void Filled Riprap Mixture

Approximate Proportions (loader buckets)	Material Type	Material Description
6	Riprap	Grade II (ND DOT Sect. 256.03.C.1)
2	Void-fill material	7-inch minus crushed rock surge (100% passing 7-inch sieve, 80-100% passing 6-inch sieve, 35-50% passing 3-inch sieve, 10-20% passing 1.5-inch sieve)
1	Void-fill material	Crushed rock (100% passing 4-inch sieve, 50-70% passing 3-inch sieve, 0-10% passing 2-inch sieve)
1	Void-fill material	4-inch minus pit run surge (round river rock and sand, well graded, 90-100% passing 4-in sieve, 70-80% passing 1.5-inch sieve, 40-60% passing 3/8-inch sieve, 10-30% passing #16 sieve)
1	Void-fill material	Class 3 Granular Bedding (ND DOT 816.02)
½ to 1	Void-fill material	Native soil

The compaction equipment, effort, and specifications will be dependent on the evaluation of the material obtained from the commercial source. Therefore, the void filled riprap mixture gradation (see **Table 7**) will be evaluated before the beginning of construction during initial commercial source selection.

Table 7 Void Filled Riprap Mixture Gradation

Size	Percent Lighter by Weight
In / Sieve #	%
28	100
22	65-90
16	60-75
10	50-53
6	47-51
4	42-46
3	33-39
2	24-30
1.5	19-26
3/4	15-22
3/8	13-18
#4	11-14
#10	10-12

Size	Percent Lighter by Weight
In / Sieve #	%
#16	9-11
#20	7-8
#40	5-8
#80	1-4
#200	0-3

The layer thickness as recommended in EM 1110-2-1601 is determined as the greater of two (2) times the D_{50} and one and a half (1.5) times the D_{100}. For the selected rock size, the minimum layer thickness following that guidance is 42 inches (3.5 feet). The D_{50} and D_{100} of a particle size distribution refer to the particle size corresponding to the cumulative frequency of 50% (median value) and 100%, respectively.

4.2.2 Soil Filled Riprap

Soil filled riprap will be placed above the longitudinal peak stone and along the slope. The material will be obtained from a commercial source, Grade II (ND DOT Sect. 256.03.C.1), placed in three (3) foot loose lifts and compacted with self-propelled vibratory compaction. The material will be hard, durable and angular and will be reasonably well graded with a maximum particle size of 28 in. The soil filled riprap mixture shall be a mixture of 65% riprap (Grade II) and 35% soil by volume.

The compaction equipment, effort, and specifications will be dependent on the evaluation of the material obtained from the commercial source. The soil filled riprap gradation will be evaluated before the beginning of construction during initial commercial source selection. The void filled riprap mixture gradation is shown in **Table 8**.

Table 8 Soil Filled Riprap Mixture Gradation

Size In / Sieve #	Percent Lighter by Weight %
28	100
22	77-94
16	74-84
10	68-69
6	65-68
4	62-65
3	56-60
2	54-58
1.5	48-52
3/4	44-49

Size	Percent Lighter by Weight
In / Sieve #	%
3/8	43-47
#4	41-44
#10	40-42
#16	39-41
#20	38-39
#40	26-39
#80	4-20
#200	1-14

The layer thickness as recommended in EM 1110-2-1601 is determined as the greater of two (2) times the D_{50} and one and a half (1.5) times the D_{100}. For the selected rock size, the minimum layer thickness following that guidance is 42 inches (3.5 feet).

4.2.3 Compacted Fill

The compacted fill will form the earthen embankment constructed behind the riprap, rockfill, and transition zone. The compacted fill will be obtained from the right bank of the Elbee Bend. Soil type of compacted fill is assumed to be the same as in the existing slope, and foundation. The material will have a maximum particle size of three-eighths (3/8) inch and a fines content of at least 15%. Compacted fill materials will be placed in maximum one (1) foot thick loose lifts with the moisture conditioned to between optimum and 2% above optimum moisture content (ASTM D698-12, 2021) and compacted with static sheepsfoot compactors to a minimum of 98% of the maximum Standard Proctor dry density (ASTM D698-12, 2021). Particle size distribution bands for the alluvium from right bank of Elbee Bend is included in **Table 9**.

Table 9 Compacted Fill Gradation

Sieve # or Size (in)	Sieve Size	Percent Passing (by Weight)	
	(mm)	Minimum	Maximum
3/8 in	9.5	100	
#4	4.75	98	100
#8	2.38	97	100
#16	1.18	93	100
#40	0.425	65	95
#50	0.3	7	81
#200	0.075	2	75

4.2.4 Granular Bedding

The purpose of granular bedding is to minimize the potential for migration of particles from compacted fill, existing compacted subgrade soils, and foundation to the various types of riprap. The granular bedding was evaluated for choke filter suitability according to the USACE - Engineering and Design EM 1110-2-2300 (USACE , 2004) as outlined in **Section 4.3**. Gradation for granular bedding shall conform with the gradation , presented in **Table 10**.

Table 10 Granular Bedding Gradation for Embankment (Choke Filter)

Sieve # or Size (in)	Sieve Size (mm)	Percent Passing (by Weight)	
		Minimum	Maximum
3/8 in	9.5	100	
#4	4.75	95	100
#16	1.18	45	58
#50	0.3	10	30
#100	0.15	2	10
#200	0.075	0	2

4.3 Choke Filter Compatibility

4.3.1 Assumptions

Filter compatibility calculations were performed according to the procedure defined by the USACE in Engineering and Design – General Design and Construction Considerations for Earth and Rock- Fill Dams (USACE , 2004). The procedure defines a multi-stage approach for evaluating filter-base compatibility, including criteria for particle retention, permeability, and segregation. Particle retention is the key criterion related to reducing the risk of internal erosion and therefore was the focus of these analyses. As mentioned in USACE (2004), it is essential that the individual particles in the embankment are held in place and do not move as a result of seepage forces between the fine and coarse zones. This is accomplished by ensuring that the zones of material meet “filter criteria” with respect to adjacent materials.

Filter was only considered to serve as a choke filter (USBR, 2011), which is defined as a filter whose only requirement is to support overlying fill (the base material) from moving into pervious or open work foundations. Choke filters are typically broadly graded and only have a requirement to stop particle movement and is not required to meet permeability or other requirements.

The following assumptions were considered for the current assessment:

- Design gradations for compacted fill are based on the existing gradation results of soil samples collected from the Right Bank of the Elbee Bend during the geotechnical

investigation performed in 2021 (USACE, 2022). Void filled riprap and soil filled riprap gradation are based on typical gradation as described in **Section 4.2.1** and **Section 4.2.2**. These calculations should be updated as more information becomes available.

- The fine limit of all base materials is used for these calculations. The finest measured base soil gradation provides conservative representation of the material, as finer-grained material is more susceptible to migration and requires a finer filter material (i.e., lower D_{15F}).
- Based on the USACE (2004), the key criterion for particle retention is D_{15}. The maximum required D_{15F} is calculated based on the d_{85} of the base material (d_{85}) or the percent passing the No. 200 (0.075 mm). The base soil is placed into a category according to the percentage of the material passing the No. 200 sieve (i.e., fines content), then the maximum D_{15} size for the filter is determined based on the category of the base soil.
- According to USACE (2004), the gradation should be adjusted of the base soils with particles larger than the No. 4 (4.75 mm) sieve. As compacted fill and granular bedding do not contain particles larger than the No. 4 sieve, no regrading is expected for the compacted fill or granular bedding. However, compacted fill and granular bedding should meet the following conditions:
    - Set filter maximum particle size of 3 in (75 mm) (D_{100max} = 3 in).
    - Set filter to a maximum passing No. 200 (0.075 mm) sieve at 5 percent (D_{5max}= 0.075 mm = 0.003 in).
    - The portion of the filter passing the No. 40 (0.425 mm) sieve must have plasticity index (PI) of zero when test in accordance with USACE (1986).
    - Filter should have a relatively uniform grain-size distribution curves and is not gap graded.
    - Sand filters with D_{90} less than about 20 mm generally do not need limitations on filter broadness to prevent segregation.
    - To ensure sufficient permeability, set the minimum D_{15} greater than or equal to 3 to 5 times the maximum d_{15} of the base soil before regrading, but no less than 0.1 mm (D_{15min} = 3 to 5 times the D_{15max}).

4.3.2 Granular Bedding (Filter) and Compacted Fill (Base)

Granular bedding was evaluated for compatibility with the compacted fill. Choke filter compatibility between granular bedding and compacted fill is shown in **Figure 20**. In this case, compacted fill is considered the base material and granular bedding is the choke filter. As compacted fill does not contain particles larger than the No. 4 (4.75 mm) sieve, regrading of compacted fill is not required. The compacted fill is expected to have between 2% to 36% fines considering the majority of alluvium gradation in the Right Bank of the Elbee Bend. So compacted fill corresponds to Category 3 base soil designation (USACE 2004) with 15 to 39% passing the No. 200 sieve. For Category 3 base soils, the required maximum $D_{15}F$ for particle retention is less or equal to $\frac{40-A}{40-15}$ where is the percent passing

the No. 200 (0.075 mm) sieve after any regrading (D_{15max} < 0.04 in). **Figure 20** displays this maximum D_{15F} for transition zone with measured compacted fill gradations.

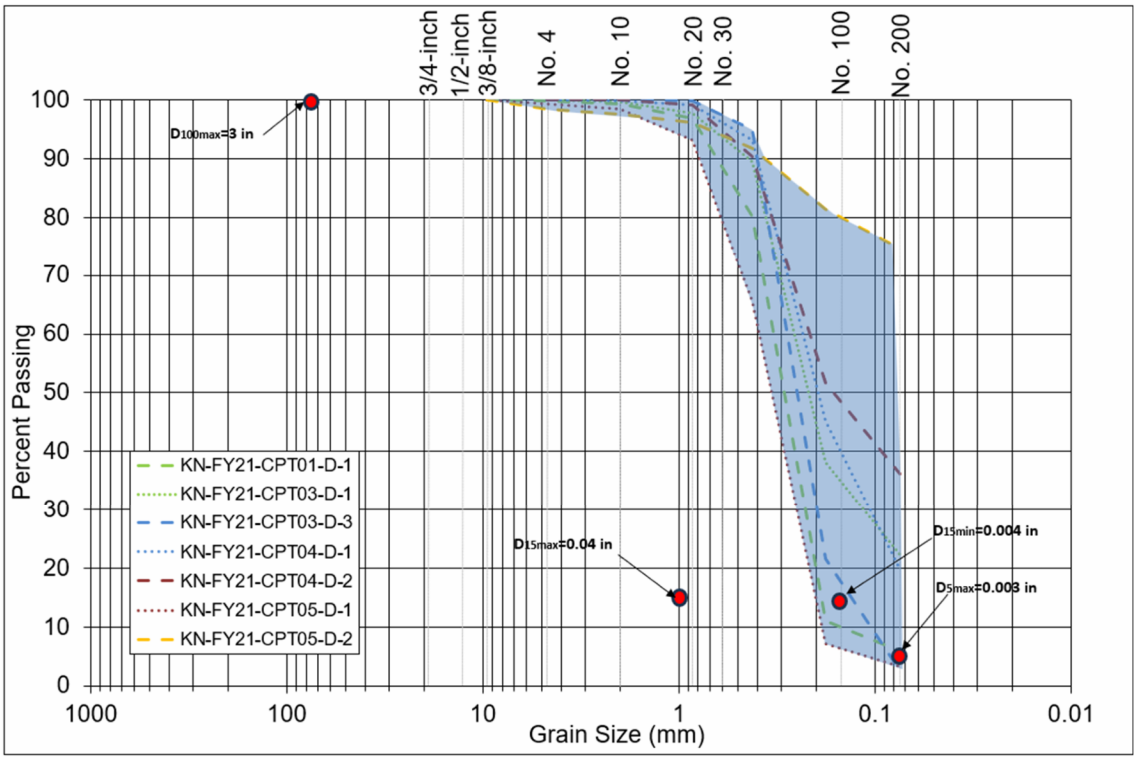


Figure 20 Transition zone (Choke Filter) Compatibility with the compacted fill (Base Material)

4.3.3 Void Filled Riprap (Filter) and Granular Bedding (Base)

Void filled riprap was evaluated for compatibility with the granular bedding zone. In this case, granular bedding is considered the base material and void filled riprap is the choke filter. As void filled riprap would consists of uniform mixture without voids, void filled riprap is assumed to reduce the potential for migration of particles from the granular bedding.

4.3.4 Soil Filled Riprap (Filter) and Granular Bedding (Base)

Soil filled riprap was evaluated for compatibility with the granular bedding zone. In this case, granular bedding is considered the base material and soil filled riprap is the choke filter. As soil filled riprap will consists of uniform mixture without voids, soil filled riprap is assumed to reduce the potential for migration of particles from the granular bedding.

4.4 Conclusions

This geotechnical report presented the data interpretation and analysis of the geological and geotechnical investigation at the Knife River – Elbee Bend Bank Stabilization Project (USACE, 2022). Preliminary geotechnical design parameters were derived and used in the static slope stability

analysis. The slope stability analysis was performed for the maximum section at the Elbee Bend considering different embankment configurations. Slope stability analysis results shows that the two configurations (Case 1 and Case 6) met the minimum FOS of the embankment against slope stability failure. These cases represent an embankment with 3.0H:1.0V slope and soil filled riprap (with unit weight of 160 pcf) extending along the slope to the crest embankment. Filter design and compatibility were performed between different embankment materials evaluate the suitability of proposed filters with the embankment based on design material gradations of materials. Filter compatibility analysis and calculation showed that filters gradations are suitable to reduce the risk of particle migration within the embankment.

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