Appendix F:

Geotechnical Design and Geology Report

Upper Mississippi River Basin
Lock and Dam 2 Upstream Island Project
Geotechnical Design and Geology

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B.1 INTRODUCTION

The St. Paul District, Army Corps of Engineers, (MVP District) operates and maintains lock and dam structures along the Upper Mississippi to maintain the Nine-Foot Navigation Channel and continually provide adequate water depth for commercial navigation passage. These structures were constructed in the 1930's and require continued maintenance to remain operational.

The scope of this project includes completion of design documentation along with plans and specs to construct an island upstream of the LD2 dam embankment that will provide erosion protection for the embankment along with environmental benefits. There was significant erosion that occurred on the upstream slope of the embankment during the 2001 high water which caused a significant loss of the embankment section.

Several studies called Problem Analysis Reports (PAR) have been completed by the St. Paul District since the early 2000's. These PAR's looked at the resiliency of the earthen embankments at LD2-10 which had not been significantly upgraded since their construction. Each embankment will overtop during a probable maximum flood and has experienced significant breakdown of the erosion protection that was initially placed in the 1930's era. The creation of pool upstream of the dam has also lead to erosion of upstream islands and increased fetch lengths which cause additional erosion on the LD 2-10 embankments. The PAR was finalized in early 2018 and identified several alternatives for improving the resiliency of the embankment which are being further developed as part of this project feasibility report.

The current proposed project at LD2 has the main objectives of improving the resiliency of the embankment while using material dredged from the 9' navigation channel. The project includes upstream island building.

This geotechnical analysis included site exploration, subsurface characterization, settlement modeling, and construction stability analysis for the upstream island.

All elevations referenced in the reference documents pertaining to the Lock and Dams project reference the mean sea-level of 1912 datum or the Memphis Datum while the current plans and specifications utilize the NAVD88 datum. All elevations in this report should be assumed to be in the NAVD88 vertical datum unless otherwise specified. The conversion between these datums is:

MSL 1912 – 0.45 feet = NAVD88
Memphis Datum – 8.175 feet = NAVD88

B.2 REGIONAL GEOLOGY

This section specifically addresses the physiography, topography, structure and hydrogeology near Lock and Dam 2.

B.2.1 General Regional Geology

Lock and Dam No. 2 is situated on the upper Mississippi River in a glacial valley, located in the Central Lowlands Physiographic Province. Minnesota has experienced several mountain building events, a crustal rift, and volcanism but in recent geologic time the Central Lowlands have undergone very little tectonic activity.

Regional topography in Dakota County is comprised of undulating till covered highlands with large outwash plains dissected by modern streams. The confluence with the St. Croix River, locally a major tributary, is approximately three river miles downstream of Lock and Dam 2. The upper Mississippi River is entrenched in a glacial valley with steep riverbanks that can reach upwards of a few hundred feet in height.

The upland areas on both banks of the river have a thin mantle of glacial soils overlying sedimentary rock. The bedrock is mostly alternating layers of limestone, siltstone, shale, and sandstone as shown in the figure below. Aquifers in the Jordan Sandstone provide water supply to the city of Hastings (population about 22,000).

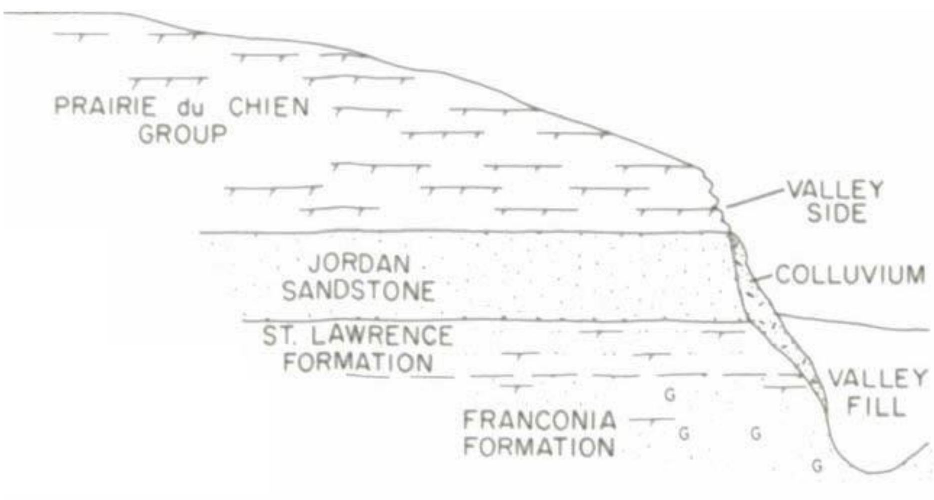


Figure 1: Typical Riverbank Stratigraphy near Lock and Dam No. 2

The Dakota County strata dips gently towards the Northwest due to a regional structural feature known as the Twin Cities Basin. The Twin Cities Basin developed in the Middle Ordovician (about 450 million years ago) over an older basin associated with the Proterozoic Midcontinent Rift System. The Twin Cities Basin is thought to be constrained by horst and grabben structures from the Proterozoic Midcontinent Rift System (1.1 billion years ago). A notable inactive fault in the area that formed in association with the Midcontinent Rift System is known as the Hastings fault and is located approximately 1.5 miles southeast of the site. Folding, faulting, and jointing in the project area can be attributed to flexural stresses from the Twin Cities Basin, faulting from the Midcontinent Rift System, and stress relief from valley incision.

B.2.2 Site Specific Geology

The lock, moveable dam, and embankment are founded primarily on alluvial and lacustrine deposits. The most recent sediments were deposited mainly by modern streams during episodes of flooding. The alluvial material consists of poorly graded sands, poorly graded sands and silt, and poorly graded gravels with sand. Lake Pepin formed in the early Holocene (about 10,000 years ago) as the Chippewa River Delta grew and began to impound the Mississippi River. Early Lake Pepin is thought to have existed as far North as the Robert Street Bridge in St. Paul, Minnesota which is upstream of the project.

During this impoundment large amounts of clays were deposited in the project area.
These deposits consisted of interbedded fat clays and silts up to 50 feet thick. This differentiates Lock and Dam No. 2 from the other Mississippi River locks in the St.
Paul District, and resulted in settlement and rotation of the original lock walls. The settlement issues are attributed to consolidation of the clay stratum.

Soil borings in the vicinity indicate that near surface soils consist of alluvial sands or lacustrine clays. The alluvial sands are typically loose at the surface but increase in density with depth. Underlying the alluvial and lacustrine deposits is the bedrock unit known as the Franconia Formation. This formation can be found at varying elevations across the valley from 500 to 600 feet. The Franconia Formation is Upper Cambrian in age (523 to 505
m.y. ago) and consists of very fine grained sandstone that can be glauconitic in part and with minor shale beds. The thickness of the Franconia Formation in this locality is approximately 60 to 80 feet. Below the Franconia Formation lies the Ironton and Galesville Sandstones which are composed primarily of fine to coarse grained quartzose sandstone with silt.

Few borings extend below an elevation of 600 feet (about 100 feet below the dam crest). This limits the information on the bedrock surface and the probable presence of basal gravel in the central portion of the valley.

B.2.3 Seismic Risk and Earthquake History

Lock and Dam 2 is located in the north central United States and is located in Seismic Zone 0 according to the Uniform Building Code Seismic Zone Map in Appendix C of USACE ER 1110-2-1806, Earthquake Design and Evaluation for Civil Works Projects.

There were no seismic considerations in the original design. The absence of major or catastrophic earthquakes, together with the infrequency of these earthquakes in general, implies a low risk level for seismic activity in the vicinity of Lock and Dam 2.

A Seismic Safety Review (SSR) or other special study has not been conducted for this project.

B.3 SUBSURFACE INVESTIGATION

B.3.1 Soil Borings

Pertinent borings for the Lock and Dam 2 non-structural embankment project are shown in the figure below.

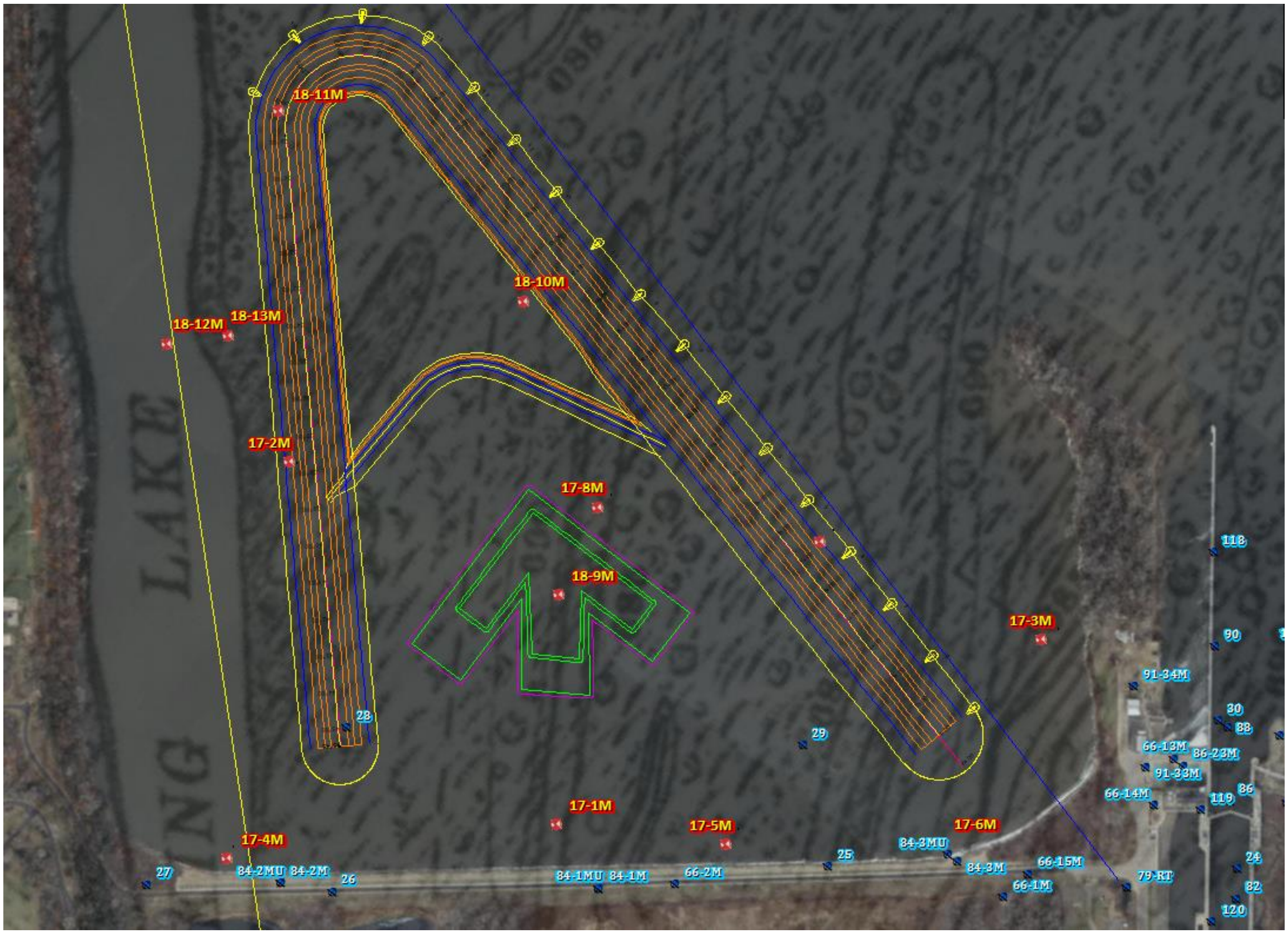


Figure 2: LD 2 Embankment Boring Locations (Facing Northwest with 2017 and 2018 borings accentuated; 1890's Topo map included to show topography before LD 2 Construction)

Fourteen borings (17-1M to 17-8M and 18-9M to 18-13M including 18-12MU) were completed upstream of the Lock and Dam 2 embankment to provide subsurface information near where potential features will be located. The borings completed in 2018 were located along the proposed alignment of the island at that time. Recent design changes have shifted the left leg of the island shown in the figure above closer to the lock and dam to avoid exceptionally deep soft clay deposits in a buried river channel. These borings were completed by Corps of Engineers personnel from the Corps' pontoon mounted drill rig. Borings were generally advanced through the upper fine grained layer and were terminated in the underlying sand strata. SPT tests were completed during this exploration and split spoon samples were collected some classification tests were completed on samples from the 2018 borings and a consolidation test was performed on the undisturbed sample obtained from boring 18-12MU.

Borings 84-1M, 84-2M, and 84-3M were completed near the centerline of the embankment in 1984. Additional borings were completed in the 1960's (66-1M, 66-2M, 66-3M, 66-15M, and 66-16M) and during the original design (25, 26, 27, 28, and 29) which were incorporated in to the stratigraphic model for island. These borings included the only stratigraphic information for layers at depth as the 2017 and 2018 borings in the upstream pool were not advanced once competent sand was reached.

B.3.2 Site Stratigraphy

Review of the project borings and the stratigraphic cross sections put together for Appendix B, Plate 2-9 of the 2004 Draft LD 2-10 Embankment Problem Analysis Report (Plate 1 in this report) led to the development of the deep stratigraphy used for the settlement analysis as there were no recent borings that extended more than 25 feet below the existing ground surface. Borings 28 and 29 were used to determine the top of the deeper lacustrine/organic clay layer. Both of these borings were completed upstream of the dam embankment and encountered what was described as a blue clay around elevation 635. The locations and boring logs for the original design borings are included in Plate 2. The overall thickness of this lacustrine/organic clay layer and the contact elevation with the lower sand unit was determined by averaging the depth of the clay unit shown in Plate 1 between borings 84-2M and 84-3M.

The upper lacustrine and alluvial clay layers were modelled based on the contacts encountered in the 2017 and 2018 borings across the project site. The upper lacustrine clay layer used in the settlement was assumed to transition to alluvial clay layers once the SPT hammer encountered significant resistance and recorded blows. This contact might not represent the actual contact with the alluvial clays that were in place before the dam was built and the area was inundated, but it is useful for differentiating the materials based on engineering properties. The upper lacustrine clay is also called the N=0 clay throughout this report. MVP geologists and geotechnical engineers reviewed the 2017 and 2018 borings to come up with the following table that differentiates the bottom of the zero blow clay and the bottom of the upper alluvial clays based on recent borings. The surficial clay thickness noted in the table below includes the N=0 (recent lacustrine) and upper alluvial clay layers.

The data from these borings was then put in to an ArcGIS dataset to depict the spatial variability of the N=0 (recent lacustrine) and upper alluvial clay layers. Contour maps of both the N=0 clay thickness and the surficial clay thickness (N=0 and upper alluvial) are shown in the figures below. This information is also shown in plates 3 and 4 at a larger scale. The layers thickness information was also used create a profile under the 2018 design alignment of the island shown in Figure 2.

The near surface stratigraphy used in each settlement analysis was obtained by averaging the N=0 clay thickness and upper alluvial clay thickness profiles throughout the design reach based on 2018 island alignment stationing. Profiles of the upper clay layers are shown in the figure below. A sample stratigraphy is also shown below.

Boring 18-9M was located in an area that will be dredged out to provide overwintering habitat and fine material for the project. The planned bottom of the cut is at elevation 678.1. The boring completed in the cut area showed that the bottom of the surficial clay layer was at elevation 671 and the clay thickness modeling showed at least 3 feet of blanket thickness in the entire overwintering area. This leads to the conclusion that dredging an overwintering area will not compromise the upstream clay blanket beneath the dam.

Table 1: N=0 and Upper Alluvial Clay Layers defined in 2017 and 2018 Borings

Boring #	Top of soil (ft, NAVD88)	Top elevation 0 blow clay (ft, NAVD88)	Bottom elevation 0 blow clay (ft, NAVD88)	Bottom elevation of surficial clay layers (ft, NAVD88)	Upper Surficial Clay Thickness (N=0 and alluvial) (ft.)	Upper soft clay (N=0) thickness
17-1M	680.5	680.5	677.6	677.6	2.9	2.9
17-2M	682.3	682.3	676.3	668.8	13.5	6
17-3M	684	680.1	678.1	670.3	13.3	2
17-4M	681.3	681.3	676.3	676.3	5	5
17-5M	681.3	681.3	679.8	673.6	7.7	1.5
17-6M	685.3	680.2	680.2	667.1	13.1	0
17-7M	681.1	681.1	678.3	675.6	5.5	2.8
17-8M	681.6	681.6	679.7	676	5.6	1.9
18-9M	681.5	681.5	675.2	671.3	10.2	6.3
18-10M	682.1	682.1	679.7	661.5	20.6	2.4
18-11M	681.6	681.6	672.5	664.7	16.9	9.1
18-12M	682.2	682.2	669.8	665.8	16.4	12.4
18-13M	682.2	682.2	676.6	666.5	15.7	5.6

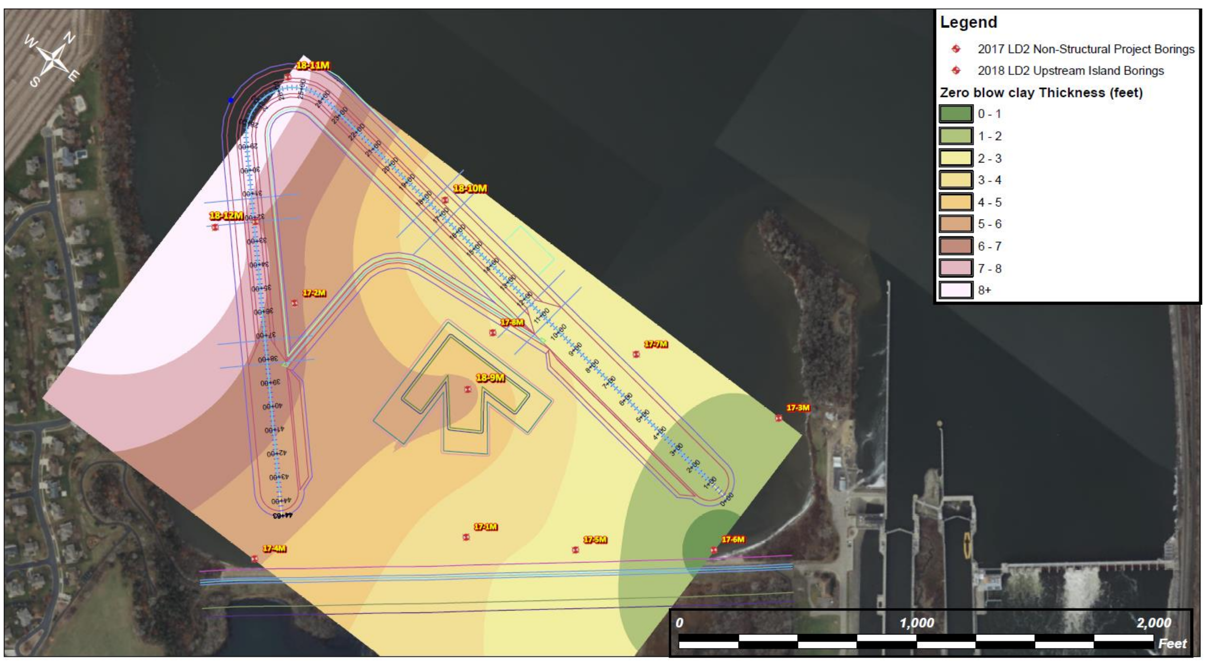


Figure 3: N=0 (Recent Lacustrine) Clay Thickness in Project Area (2018 Project Alignment Shown)

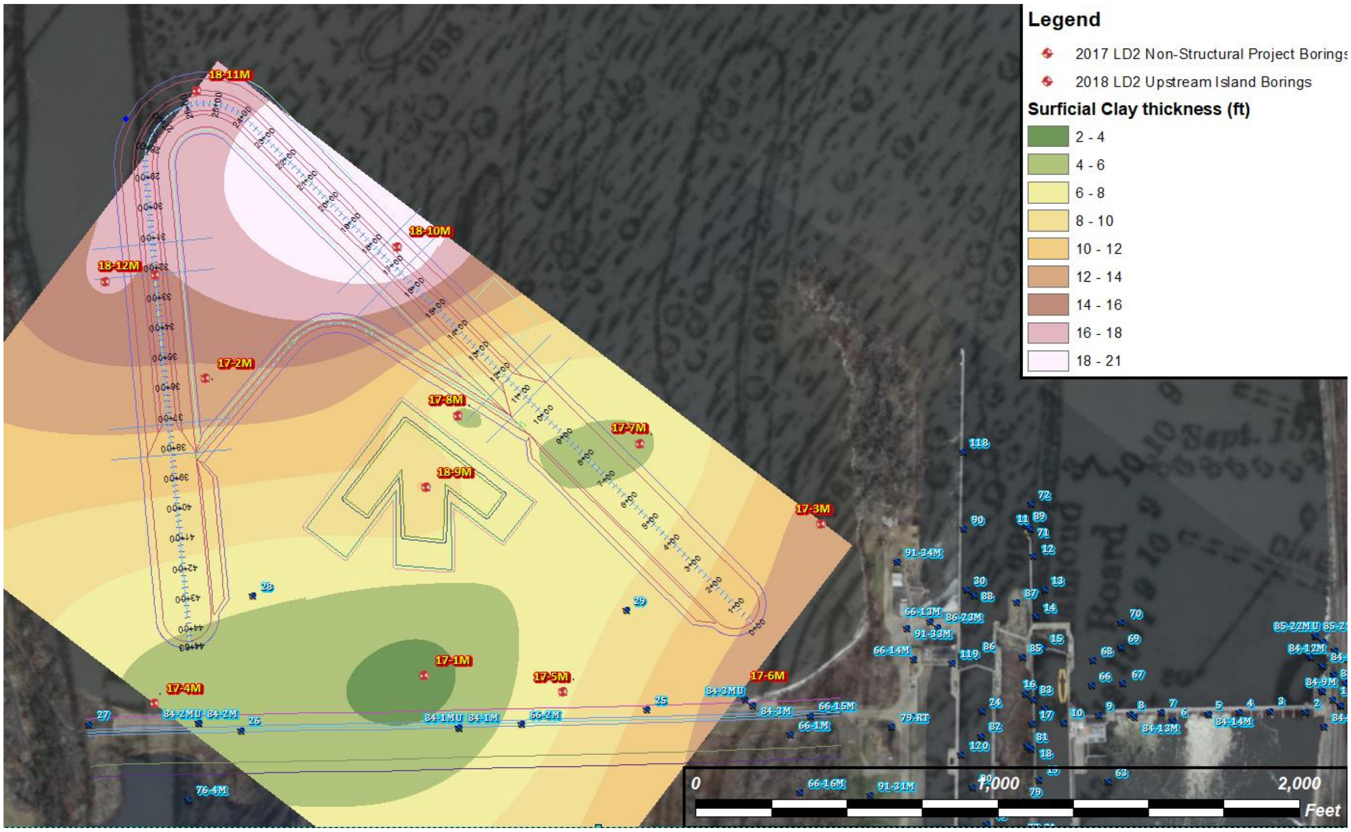


Figure 4: Surficial Clay Thickness in the Project Area (2018 Project alignment shown)

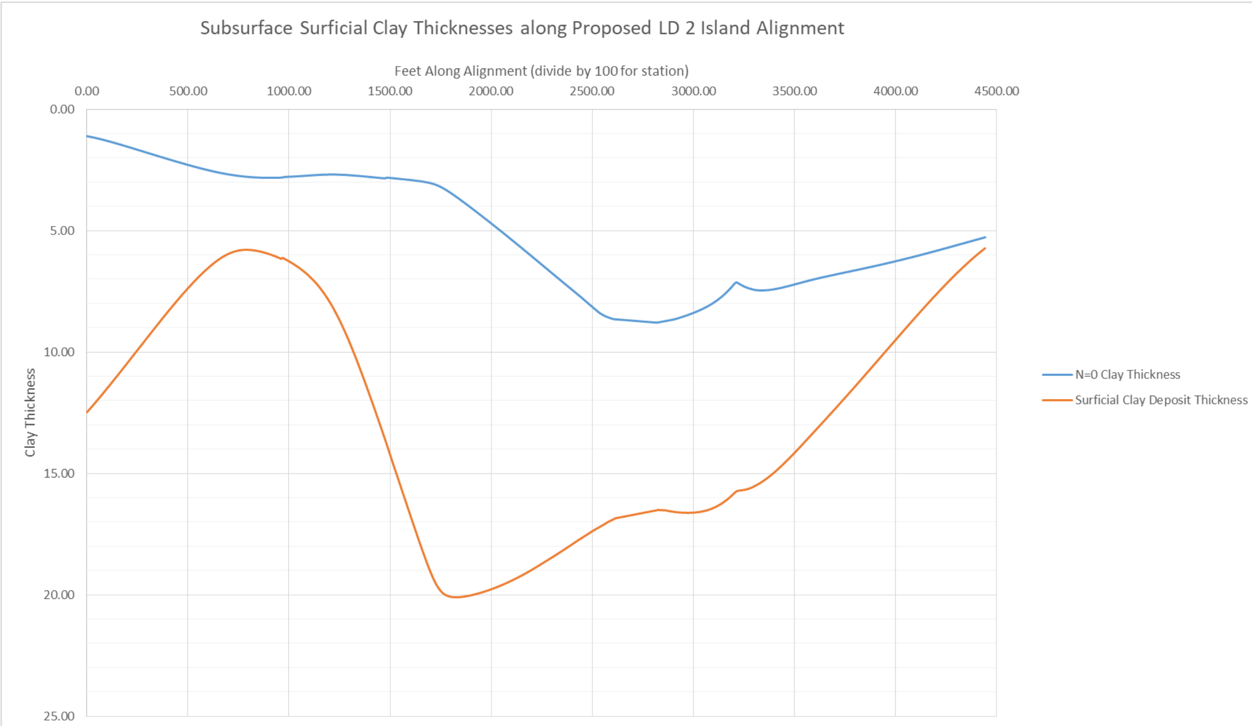
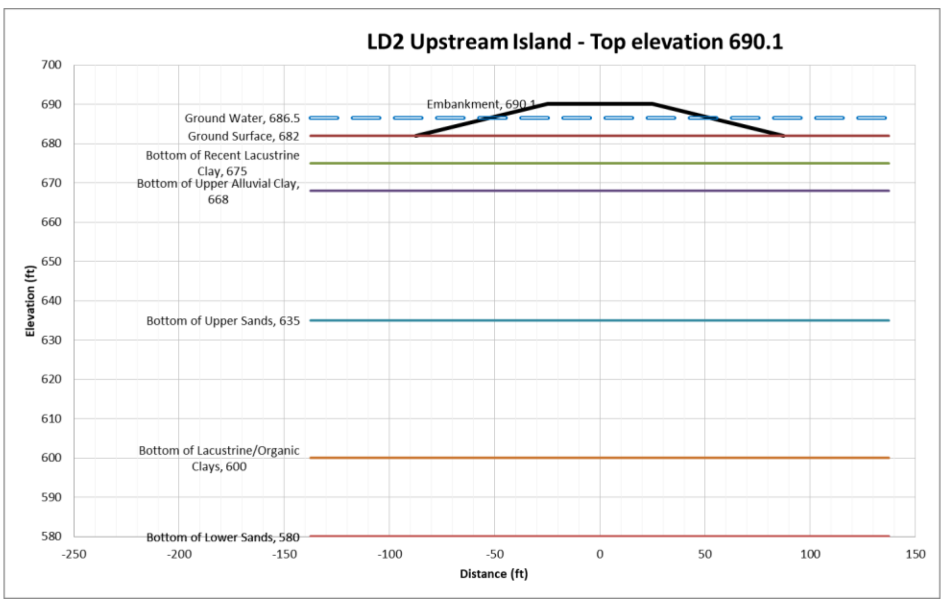


Figure 5: Surficial Clay Layer Profiles along 2018 Island Alignment



Stratigraphy Information						Material Properties - Mean					
Layer	Formation	Top Elevation		Bottom Elevation	Thickness	g_{sat} (pcf)	OCR	C_r	C_c	e_o	g'
1	Recent Lacustrine Clay	681.5	to	675.5	6	92	1	0.12	0.72	2.54	29.6
2	Upper Alluvial Clay	675.5	to	666	9.5	103	1	0.08	0.48	1.46	40.6
3	Upper Sands	666	to	635	31	128	1	0	0	0.3	65.6
4	Lacustrine/Organic Clays	635	to	600	35	100	1	0.13	0.84	1.69	37.6
5	Lower Sands	600	to	580	20	128	1	0	0	0.3	65.6

Figure 6: Typical Subsurface Stratigraphy below Island

B.3.3 Laboratory Testing

No geotechnical testing was completed on the 2017 borings obtained for the upstream island project. 2018 borings had classification tests run on select fine grained materials and one consolidation test was completed on material from boring 18-12MU.

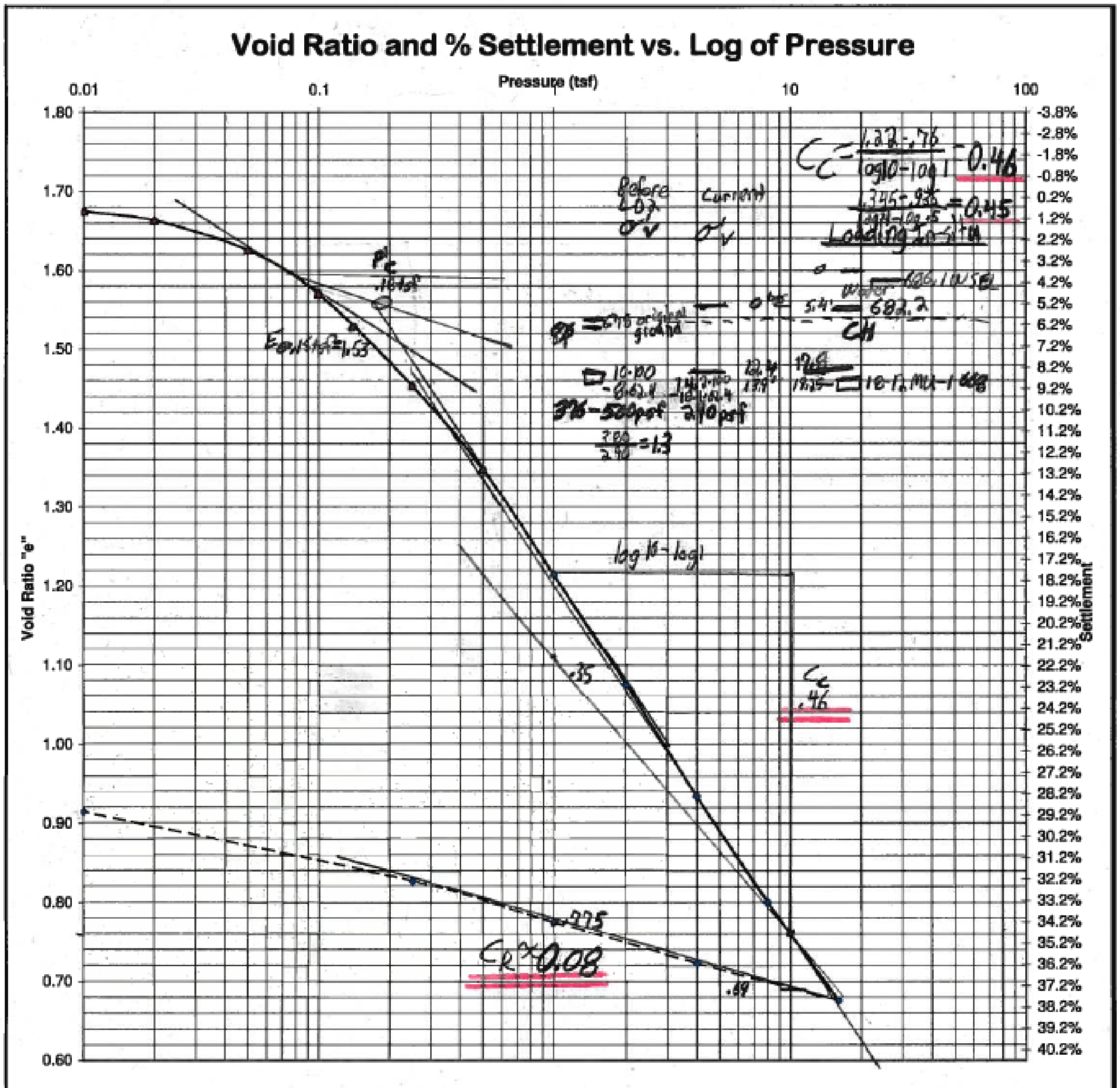
Environmental Samples were taken from borings 17-1M, 17-2M, and 17-3M. These samples were collected from the top 2.5 feet of surface sediments and didn't show any results above MPCA action levels.

Classification test results for the 2018 borings are shown in the table below.

Table 2: LD 2 Upstream Island Classification Test Results

Boring No.	Top of Boring Elevation [ft, NAVD88]	Sample No.	Sample Mid Elevation [ft, NAVD88]	Top of Sample Depth (ft)	Depth to bottom of Sample	Moisture %	Natural Dry Density [pcf]	Plasticity (atterberg limits) [PI = LL-PL] LL	PI	PL	Clay Layer
18-10M	687.70	2	679.10	8.0	9.2	40.2		37	17	20	Alluvial
18-10M	687.70	8	664.05	23.0	24.3	52.2		62	39	23	Alluvial
18-11M	687.50	6	666.75	20.0	21.5	46.8		63	42	21	Alluvial
18-12M	687.60	6	669.10	18.0	19.0	46.5		68	46	22	Alluvial
18-12MU	687.60	1	668.35	19.0	19.5	63.1	60.9				Alluvial
18-13M	687.60	3	669.10	18.0	19.0	59.1		74	46	28	Alluvial
18-11M	687.50	2	679.00	8.0	9.0	81.3		87	55	32	Lacustrine
18-12M	687.60	2	679.10	8.0	9.0	103.5		99	67	32	Lacustrine
18-9M	687.70	2	679.30	8.0	8.8	105.3		84	50	34	Lacustrine
18-9M	687.70	4	673.95	13.0	14.5	84.7		92	61	31	Lacustrine

Consolidation test data analyses for boring 18-12MU is included below.



Project: LD2 Non-Structural Embankment Modifications / USACE -Geotech. & Geology Section				Date:	9/25/18
Sample #: 1	Boring #: 18-12mu	Depth ft: 19-19.5		Job #:	11617
Soil Type: Fat Clay w/organic material (CH/OH)		From Adjacent Disturbed hole			
Initial W/C (%): 63.1	Dry Density (pcf): 60.9	LL: 68	PL: 22	PI: 46	Gs: 2.63 (Assumed)
Organic Content (%):	Initial Height (in.): 0.747	Diameter (in.): 2.503		e_o= 1.696	
Preconsolidation Pressure (Pc): 0.17 tsf		Compression Index (Cc): 0.35		Recompression Index (Cr):	≡ 0.08

Remarks: Testing performed in general accordance with ASTM:D2435

NDM Analysis

9530 James Avenue South — SOIL ENGINEERING TESTING, INC. — Bloomington, Minnesota 55431

Several consolidation tests were performed on undisturbed samples obtained for the construction of the new Lockhouse/Central Control Station in 1986-1988. Consolidation tests were performed on material from each clay layer that is present below the embankment as well as the control station. The generalized soil profile derived at the control station and associated test results are shown below.

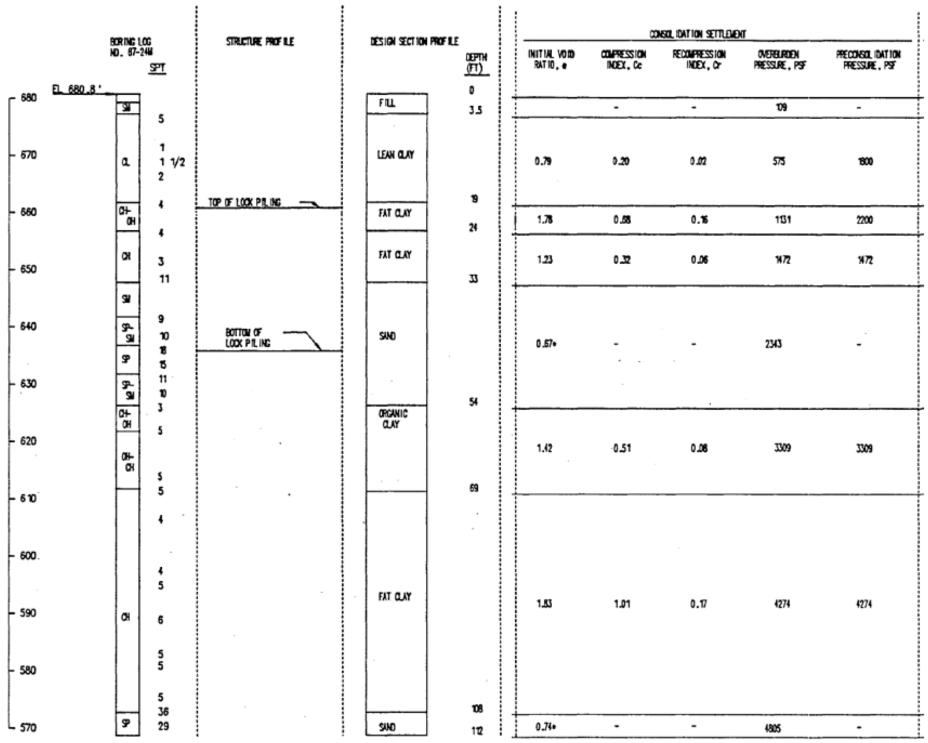


Figure 7: Clay Consolidation Parameters from Lockhouse Design

B.3.4 Design Parameters

B.3.4.1 Consolidation Parameters

The consolidation parameters used in this design for the deeper lacustrine layer were obtained from the consolidation testing performed for the construction of the new lockhouse. The lacustrine/organic layer consolidation properties were estimated by using a weighted average (based on layer thickness) of the organic and fat clay layers found deeper in the soil strata in Figure 7.

Consolidation parameters and unit weights for the upper soils were calculated based on the 1-D consolidation test performed on the alluvial clay layer from boring 18-12MU and on the index testing performed on the rest of the upper clay soils. The average material properties for the upper alluvial and recent lacustrine clays are shown in the table below. These average values were used along with parameter estimation relationships found in NAVFAC DM 7-1 and other widely known relationships between soil parameters for index/physical properties.

The OCR profile for the clays was determined by looking at the results of the consolidation test along with performing calculations for the existing and before lock and dam soil profiles. The consol test results alone weren't used exclusively because the sample was obtained from an old buried channel that had significantly more recent lacustrine material than others. The low pre-consolidation pressure in this sample would be exceeded for most other soil profiles. The condition of the soil immediately before construction of the lock and dam was assumed to be the maximum past pressure when looking at the soil profile based OCR. This assumption was made because the river channel appears to be gradually filling in after being scoured to bedrock during glacial periods. The inundation of alluvial soils would decrease the effective stress and slow deposition of materials may have led to increased effective stresses that reduce the OCR. The calculations included below look at the soil profile for the surficial clay layers at four foot increments and compare the effective stresses before and after inundation/deposition of recent lacustrine sediments to the current ground surface elevation. The pre-project ground water table was assumed from original design drawings for the LD2 project (Plate 2) which showed backwater swamp deposits and slough water surfaces just below the 685 MSL contour (below 677 NAVD88).

Table 3: Average Index Test Parameters and Consol Test Results for Upper Alluvial and Recent Lacustrine Clays

	Upper Alluvial	Recent Lacustrine (ooze/N=0)
Aver. LL	60.8	90.5
Aver. PI	38.0	58.3
Aver. PL	22.8	32.3
Aver. Wc,nat	51.3	93.7
Inorg. Cc (empirical)	0.46	0.72
Cc - 1D consol.	0.46	
Cr - 1D consol.	0.08	
Gs (tested/assumed)	2.7	2.7
E = Sat. WC*Gs (empirical)	1.39	2.53
E (1-D consol @ 0.15 TSF)	1.53	
ysat (empirical)	106.9	92.5
ysat (1-D Consol test)	101.6	

Table 4: NAVFAC DM 7-1 Cc Parameter Estimation

```
                              TABLE 3
          Estimates of Coefficient of Consolidation (C+c,)

+))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))))).
*                                                                          *
*   C+c, = 0.009 (LL - 10%) inorganic soils, with sensitivity less than 4  *
*                                                                          *
*   C+c, = 0.0115 w+n, organic soils, peat                                 *
*                                                                          *
*   C+c, = 1.15 (e+o, - 0.35) all clays                                    *
*                                                                          *
*   C+c, = (1 + e+o,)(0.1 + [w+n, - 25] 0.006) varved clays                *
*                                                                          *
*w+n, is natural moisture content, LL is water content at liquid limit and *
*e+o, is initial void ratio.                                               *
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Table 5: OCR Calculation for Surficial Clay Layers Upstream of LD 2

OCR Calcs				
	GSEL	GWSEL	ysat	
Before LD2	678	676	104	
Current Pool	682	686	100	*Assumed average total saturated unit weight of alluvial and lacustrine soil profile
Elevation	p'c	σ'v	OCR	
676	208	225.6	0.92	
672	374.4	376	1.00	
668	540.8	526.4	1.03	
664	707.2	676.8	1.04	
660	873.6	827.2	1.06	
		Average	1.01	
Assume OCR = 1.0				

Table 6: Consolidation Parameters Used in the Settlement Modeling for LD 2 Upstream Islands

Material	Sat. Unit Weight	OCR	C_r	C_c	e_o	Bottom Elevation NAVD88
N=0 (Recent Lacustrine) Clay	92.5	1	0.11	0.72	2.53	Varies
Upper Alluvial Clay	104.3	1	0.08	0.46	1.46	Varies
Upper Sands	128	1	0	0	0.3	635
Lacustrine/Organic Clays	100	1	0.13	0.84	1.69	600
Lower Sands	128	1	0	0	0.3	580

B.3.4.2 Undrained Shear Strength

No undrained shear strength tests were performed on the near surface soils under the proposed island because of poor sample recovery in the undisturbed samples. The difficulty in obtaining samples from the low blow count material does give some indication that the undrained shear strengths of the unconsolidated material is very low. A strength profile developed for use in the New Orleans FRM projects was used for this project. This New Orleans model was based on CPTU test data of very soft clays as outlined in (Duncan, Brandon, Wright, Vroman 2008). The strength profile for the surface clays with zero blowcounts was assumed to be zero at the surface and increase linearly with depth at a rate of 11 psf/foot. The undrained strength for the underlying clays was estimated based on SPT blow counts using the following equation from EM 1905. The alluvial clay layers were estimated to have an undrained strength of 200 psf based on average blow counts around 2.

(e) The undrained shear strength C_u in ksf may be estimated (Bowles 1988)

$$C_u \approx 0.12 N_{SPT} \tag{3-4}$$

B.4 GEOTECHNICAL DESIGN SUMMARY

B.4.1 Design Criteria and Methodology

The LD 2 upstream islands are not part of the damming surface so there were relaxed design criteria for the project that primarily dealt with constructability of the island, ensuring environmental benefits could be realized, and providing accurate quantity estimates. The main stability factor with the islands is the bearing capacity of the recent lacustrine (N=0) material at the surface and the likelihood that it will fail in shear during placement and cause a mud wave. Seepage is not an issue as there will be no differential head on the islands.

Settlement requirements were discussed with the project team and it was decided that the islands would not be overbuilt. There were a few reasons for this. There were large projected settlements for some of the embankment reaches that might have put the tops of islands close to the top of the dam embankment. Doing this could impact water surface elevations during flooding in the 10+ year span it would take for consolidation settlement to occur. Building taller islands would also decrease the time the island is inundated annually and would not allow for the target floodplain forest plant and tree species to thrive. Settlement of project embankments was still calculated to conceptualize mud wave that might occur and to help select where along the alignment to place the taller portions of the design embankment.

After discussion with Corps construction personnel and the Geotechnical RTS the following section was developed for the propagation of a mud wave (soft clays displaced bear a bearing capacity shear failure). There was not enough data available to calculate a reliable undrained strength profile for the recent lacustrine clay and it was thought that there might be a gradual transition between the clay layers where the recent lacustrine material might have some strength gain. Even though bearing capacity calcs would show the placed embankment would probably not have a bearing capacity factor of safety of 1 until the alluvial clays were reached the design team thought there was likely enough strength gain and consolidation of the recent lacustrine material that would occur such that only about 3 feet of the surficial clay might be displaced. This depth of displacement by sand fill was used in all settlement and quantity calculations.

The 3 feet level of material displacement was also when undrained slope stability analysis typically showed a FOS greater than 1 using the undrained strength profiles described above. The undrained slope stability analyses were run with increasing amounts of soft material replaced with sand immediately under the embankment. A FOS of 1 during construction was deemed to be acceptable based on the project constraints. These constraints were mainly to come up with accurate quantities of material required to build the island. The island will be expected to fail the upper soft clay layers during placement and come to a point where the strength gained during consolidation and replacement of material balances the loads being applied. This situation is how a FOS of 1 is defined. The embankment will continue to gain strength as the foundation consolidates and the increased pore pressures dissipate. The long term steady state factor of safety for the embankment at low control pool was found to be around 2. The table below and the plates at the end of the report summarize the stability analyses that were completed for each of the island heights. Lighter unit weights were used for the sand fill in the stability analysis than in the settlement analysis to provide conservative results. The overall unit weight of the sand placed could be variable based on the location in the island section.

Table 7: Stability Analysis Results for Upstream Island

Reach	Analysis Condition	Water Surface Condition	Initial Zero Blow Clay Thickness (feet)	Embankment Crest Elevation	Tailwater/Lower WSEL	Side Slopes	Min FOS	Required FOS
0+00-14+50	Undrained with 2 feet of Zero Blow Clay Replacement	LCP	3	692.1	686.1	5H and 4H:1V	1.09	1
0+00-14+50	Undrained with 3 feet of Zero Blow Clay Replacement	LCP	3	692.1	686.1	5H and 4H:1V	1.97	1
0+00-14+50	Long term steady State with 3 feet of Zero Blow Clay Replacement	LCP	3	692.1	686.1	5H and 4H:1V	1.97	1.3
14+50+26+50	Undrained with 2 feet of Zero Blow Clay Replacement	LCP	5	690.1	686.1	5H and 4H:1V	0.97	1
14+50+26+50	Undrained with 3 feet of Zero Blow Clay Replacement	LCP	5	690.1	686.1	5H and 4H:1V	1.06	1
14+50+26+50	Long term steady State with 3 feet of Zero Blow Clay Replacement	LCP	5	690.1	686.1	5H and 4H:1V	1.83	1.3
26+50-44+50	Undrained with 2 feet of Zero Blow Clay Replacement	LCP	7	692.1	686.1	5H and 4H:1V	0.92	1
26+50-44+50	Undrained with 3 feet of Zero Blow Clay Replacement	LCP	7	692.1	686.1	5H and 4H:1V	1.06	1
26+50-44+50	Long term steady State with 3 feet of Zero Blow Clay Replacement	LCP	7	692.1	686.1	5H and 4H:1V	1.72	1.3

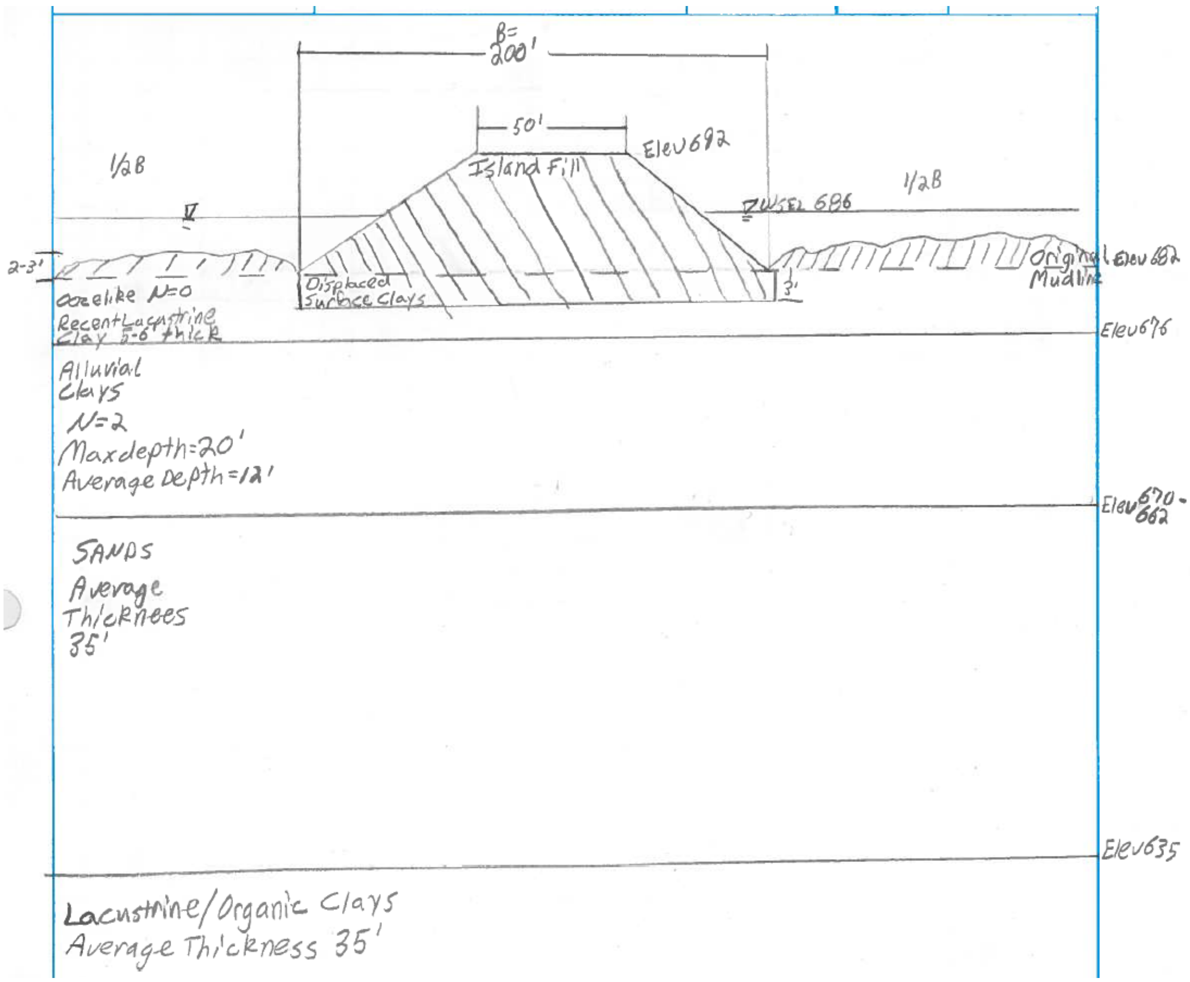


Figure 8: Conceptual Mud Wave Section

B.4.2 Settlement

Two different embankment profile (top elevations of 688.1, 690.1, and 692.1) along the proposed 2018 embankment alignment were evaluated for settlement in the different reaches to inform project design. The main points of the design were to locate the tallest portions of the embankment where the best foundations conditions were located to decrease overall settlement and mud wave action. The two different embankment profiles modeled are shown with the associated surficial clay stratigraphy in the profile below. All settlement reaches were modelled with the same bottom of sand and lacustrine/organic clay contacts shown in Table 6 above. The surficial clay layer thicknesses modeled in each reach were determined by averaging the thicknesses of each layer throughout the reach.

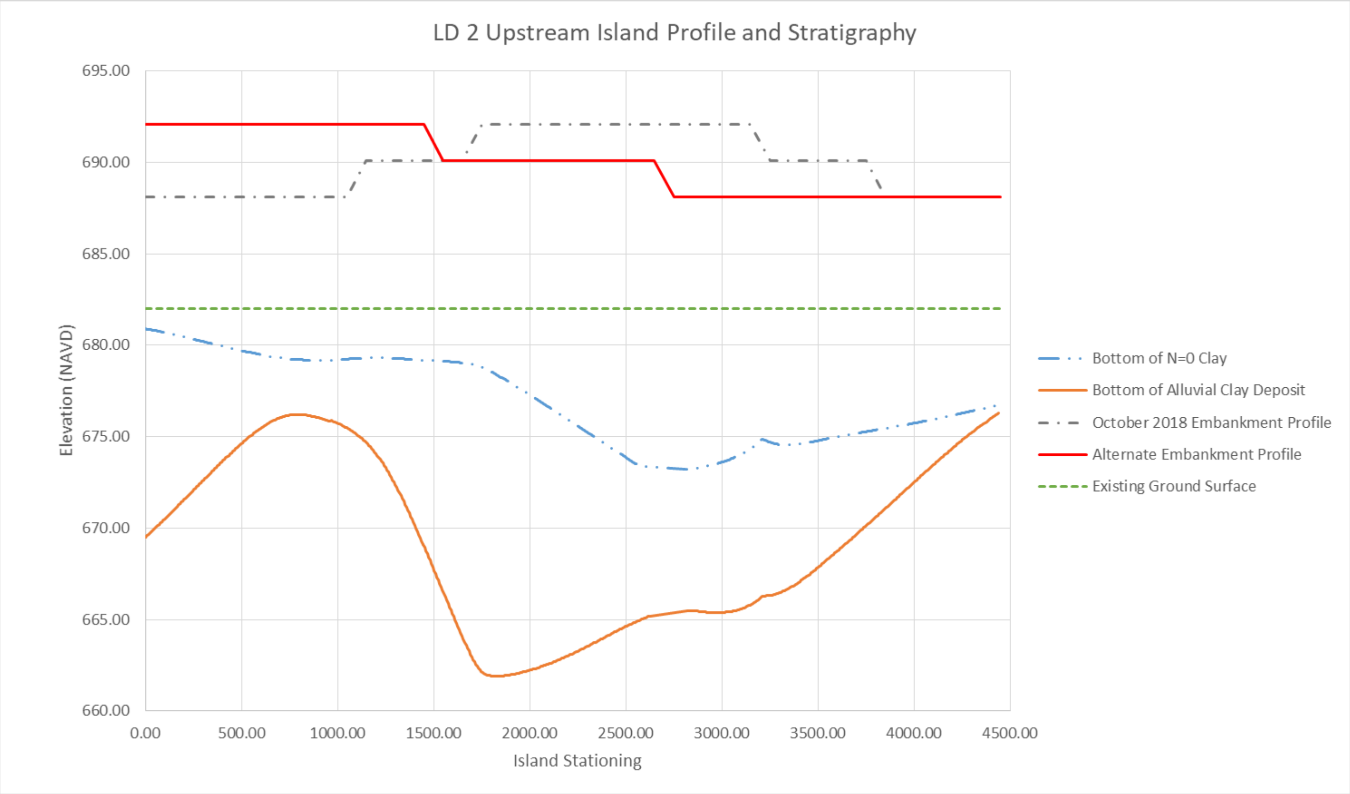


Figure 9: Embankment Profiles and Surficial Clay Stratigraphy Used in Settlement Modeling

Table 8: Modeled Stratigraphy for 2018 Island Profile Settlement Models

Station	October 2018 - Top of Island Elev.	Average Clay Thickness (ft)		Bottom elevation
0	688.1	N=0	2.20	679.80
1050	688.1	Alluvial	7.99	674.01
1150	690.1	N=0	2.79	679.21
1650	690.1	Alluvial	12.05	669.95
1750	692.1	N=0	6.67	675.33
3150	692.1	Alluvial	18.17	663.83
3250	690.1	N=0	7.17	674.83
3750	690.1	Alluvial	14.06	667.94
3850	688.1	N=0	5.94	676.06
4450	688.1	Alluvial	8.17	673.83

Table 9: Modeled Surficial Clay Stratigraphy for Alternate Island Profile Settlement Models

Station	May 2019 Proposed Top of Island Elev.	Average Clay Thickness		Bottom elevation
0	692.1	N=0	2.35	679.65
1450	692.1	Alluvial	8.29	673.71
1550	690.1	N=0	5.41	676.59
2650	690.1	Alluvial	18.66	663.34
2750	688.1	N=0	6.97	675.03
4450	688.1	Alluvial	12.40	669.60

The method used to determine stress increases was a spreadsheet developed by the St. Paul District which uses the Poulos and Davis elastic model to determine stress increases at different points below the loading. This model calculates stress increases due to the rectangular center loading beneath the island crest and the triangular loading imposed by the berm side slopes. Typical stress increase relationships due to a triangular and rectangular loading calculated using this method are shown in the figure below. The designed berms include benches around elevation 688 which were incorporated in to the side slopes used in the model.

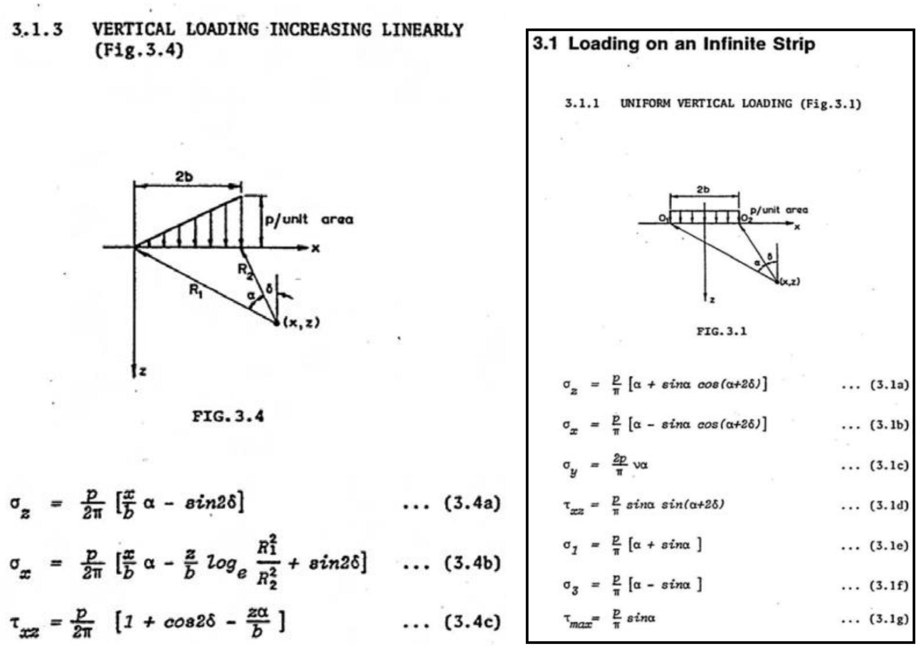

3.1.3 VERTICAL LOADING INCREASING LINEARLY (Fig.3.4)

FIG.3.4

$$\sigma_z = \frac{p}{2\pi}\left[\frac{x}{b}\alpha - \sin 2\delta\right] \quad \ldots (3.4a)$$

$$\sigma_x = \frac{p}{2\pi}\left[\frac{x}{b}\alpha - \frac{z}{b}\log_e\frac{R_1^2}{R_2^2} + \sin 2\delta\right] \quad \ldots (3.4b)$$

$$\tau_{xz} = \frac{p}{2\pi}\left[1 + \cos 2\delta - \frac{z\alpha}{b}\right] \quad \ldots (3.4c)$$

3.1 Loading on an Infinite Strip

3.1.1 UNIFORM VERTICAL LOADING (Fig.3.1)

FIG.3.1

$$\sigma_z = \frac{p}{\pi}[\alpha + \sin\alpha\cos(\alpha+2\delta)] \quad \ldots (3.1a)$$

$$\sigma_x = \frac{p}{\pi}[\alpha - \sin\alpha\cos(\alpha+2\delta)] \quad \ldots (3.1b)$$

$$\sigma_y = \frac{2p}{\pi}\nu\alpha \quad \ldots (3.1c)$$

$$\tau_{xz} = \frac{p}{\pi}\sin\alpha\sin(\alpha+2\delta) \quad \ldots (3.1d)$$

$$\sigma_1 = \frac{p}{\pi}[\alpha + \sin\alpha] \quad \ldots (3.1e)$$

$$\sigma_3 = \frac{p}{\pi}[\alpha - \sin\alpha] \quad \ldots (3.1f)$$

$$\tau_{max} = \frac{p}{\pi}\sin\alpha \quad \ldots (3.1g)$$

Figure 10: Poulos and Davis Stress Increase Method

A summary of the estimated consolidation settlement for each of the proposed alignment sections is shown below.

Table 10: Estimated Consolidation Settlement for LD2 Upstream Island Profiles

October 2018 Island Profile					Alternate Island Profile to Reduce Settlement			
Station Start	Station End	Top of Island Elevation	Estimated Consolidation Settlement at Centerline of Island (feet)		Station Start	Station End	Top of Island Elevation	Estimated Consolidation Settlement at Centerline of Island (feet)
0+00	10+50	688.1	1		0+00	14+50	692.1	1.5
11+50	16+50	690.1	1.5		15+50	26+50	690.1	2.25
17+50	31+50	692.1	2.5		27+50	44+50	688.1	1.5
32+50	37+50	690.1	1.75					
38+50	44+50	688.1	1					

* - Immediate Settlement was calculated to be less than 1/2" and was not included in total settlement calcs

*- Secondary Consolidation (Creep) was not analyzed as it would occur in a significant timeframe after the construction of the project and any overbuild required to account for the settlement would further impact existing upstream flood stages

* - time rate of primary consolidation was not calculated but was assumed to be in the range of years based on the clay layer thicknesses involved and much of the settlement coming from the clay layers at depth

*- These settlement estimates assume that the top three feet of soft clay material is displaced due to a mud wave effect during initial placement. This assumption reduces settlement reported here but needs to be accounted for in the project quantities for sand placement

* - Settlement values presented were rounded to the nearest quarter foot

The immediate settlement of the sand layers during embankment construction was estimated to be under 0.04 feet (or less than 1/2”). Stress increased at depth were taken from the Poulos and Davis model for every one foot section and were used to determine an elastic strain using a sand elastic modulus of 1,000,000 psf.

B.4.3 Design Recommendations

Geotechnical design recommendations include:

- Not overbuilding the embankments and allowing them to settle
- Shifting the alignment/profile of the island from the 2018 alignment. This would include moving the leg of the island between Sta 28+00 and 44+00 200 feet closer to the lock complex to avoid the large thicknesses of recent lacustrine clay in the inundated portions of Lake Rebecca/King Lake near the Minnesota bank of the river
- Construct island test sections as described below to monitor the performance of the embankment foundation prior to contract award.

The alignment of the island was revised for the final project design as shown in Figure 2. The profile of the island was also shifted to place the highest portion of the island (top elev. = 692.1) from Sta. 1+00-14+00 where surface conditions were found to be the best. Placing the tallest portion of the island in this location should help with constructability as discussed below. The redesigned island is shown in Plates 5-7.

An overwintering fish habitat area was also included with this project. The depth of the cuts were staged to minimize possible puncture of the clay blanket upstream of the dam. The overwintering habitat will be excavated to elevation 680.1 in the vicinity of borings 17-8M and 18-9M. The borings in this location show a bottom clay elevation of 675.6 and 670.5 respectively. The overwintering habitat increases in depth further to the west where the clay blanket was modeled to be thicker based on the boring data. Overall there should still be a greater than 2 foot thick blanket throughout the project site.

B.4.4 Constructability

The creation of a mud wave and potential shear failures of the embankment are the main constructability concerns. A secondary concern is developing an accurate estimate of the sand material needed for the project. The island location upstream of LD2 has a significantly higher thickness of soft clays in the foundation than has been encountered on any island constructed by the St. Paul District in recent memory. This fact led construction and Geotech personnel to suggest that several test embankment sections be constructed by M&R (USACE Maintenance and Repair) personnel prior to letting a final construction contract. It is also recommended that the placement method for the island be limited to mechanical methods to limit the mud wave. The test sections were not able to be constructed due to environmental permitting and crew availability.

Construction specifications should also include a requirement to place a mound of material approximately 4 feet above the finish elevation and the leading edge of the island construction. The berm should be left in place for a day or two to gain some benefits of pre-loading the area and forcing immediate deformation/settlement of the foundation. This mound will help to force the recent lacustrine material out from the immediate foundation and improve the bearing capacity of the island. The additional material mounded at the leading edge of the island could then be shaped in to the side berms of the island. The figure below depicts this construction concept.

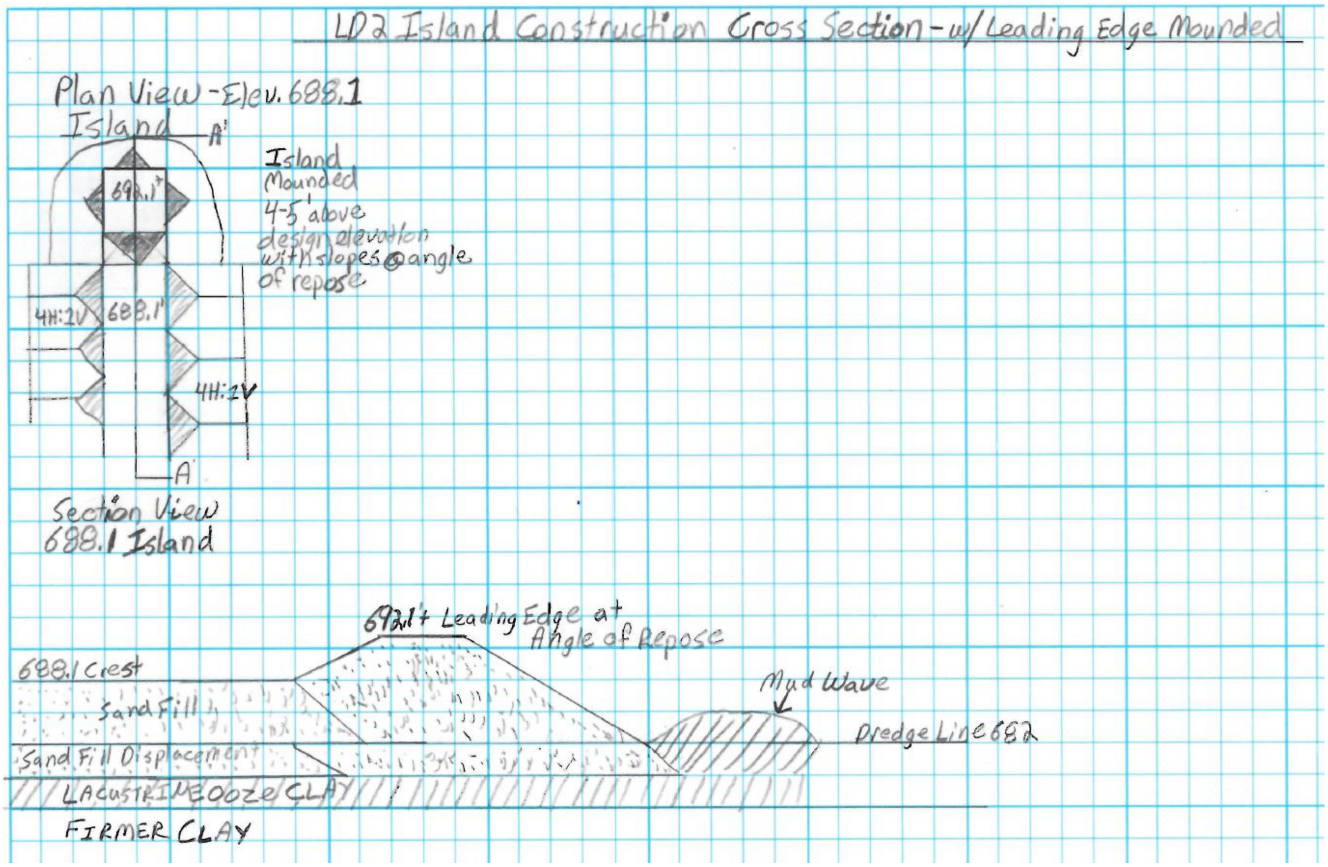


Figure 11: LD2 Leading Edge of Island Mounding Concept

REFERENCES

Duncan, J. Michael; Brandon, Thomas L.; Wright, Stephen G.; Vroman, Noah. (2008). “Stability of I-Walls in New Orleans during Hurricane Katrina”. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 134, No. 5,

Griffiths, D.V. (2001) Course Notes from “Finite Elements in Geotechnical Engineering”, Table 3 [Bowles (1988)].

Twin Cities Testing 1988. Twin Cities Testing Soil Report

U.S. Army Corps of Engineers 1929. Lock and Dam 2 Embankment As-Built drawings

U.S. Army Corps of Engineers 2003. Water Control Manual

U.S. Army Corps of Engineers 2004. Lock and Dam 2-10 Draft Embankment Problem Analysis Report

U.S. Army Corps of Engineers 2016. Lock and Dam 2 Periodic Assessment #01

U.S. Army Corps of Engineers 2017. Lock and Dam 2-10 Embankment Problem Analysis Report

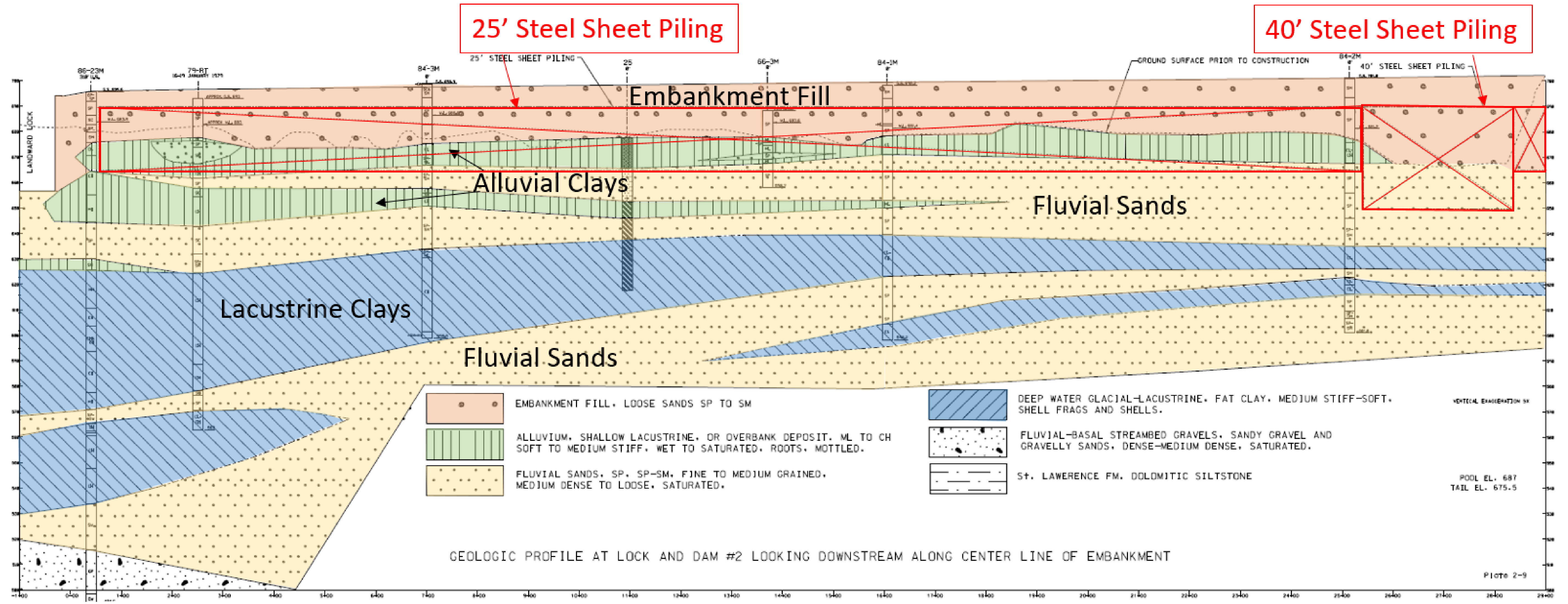


Plate 1: Lock and Dam 2 Embankment Foundation Stratigraphy

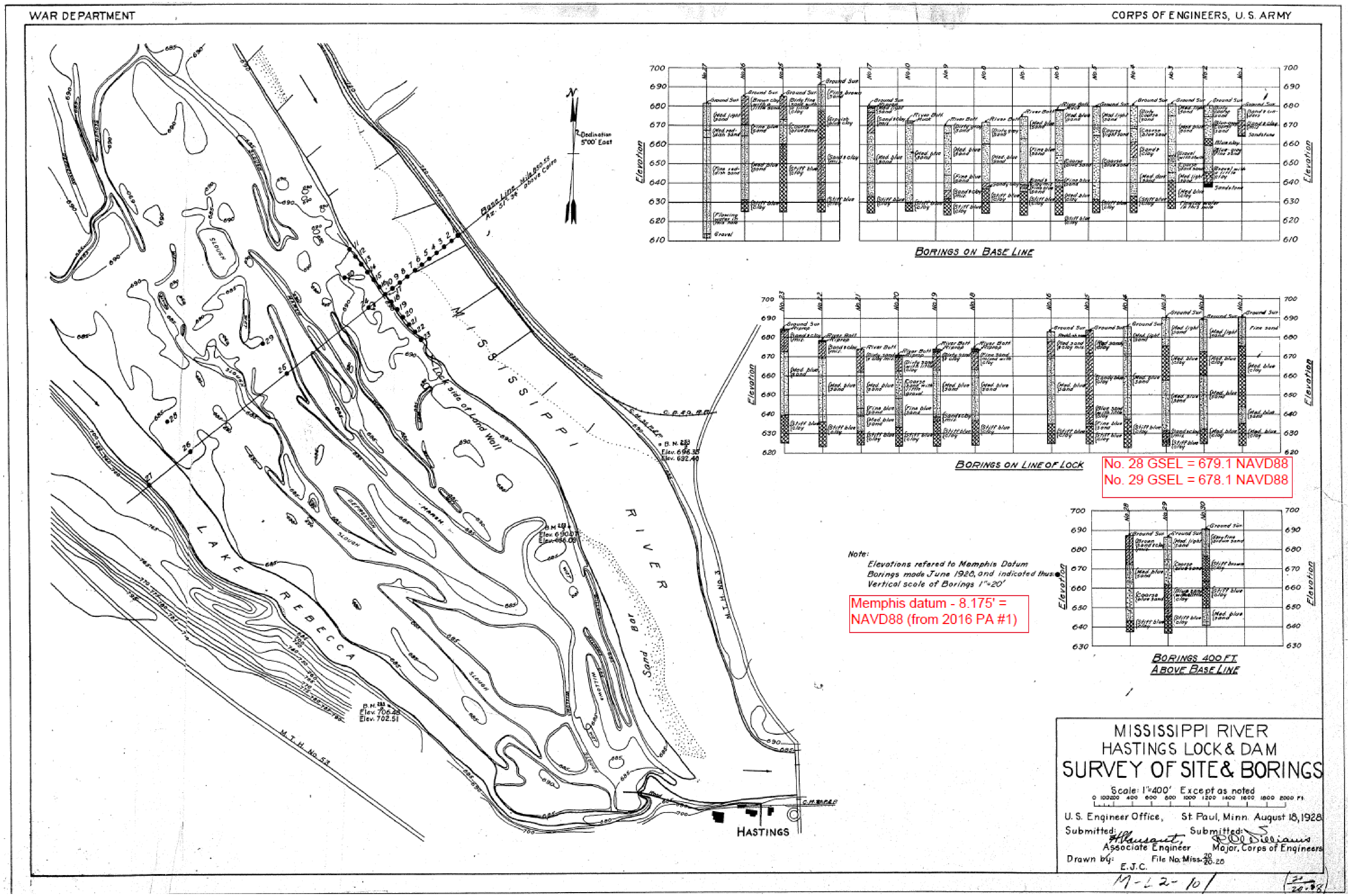
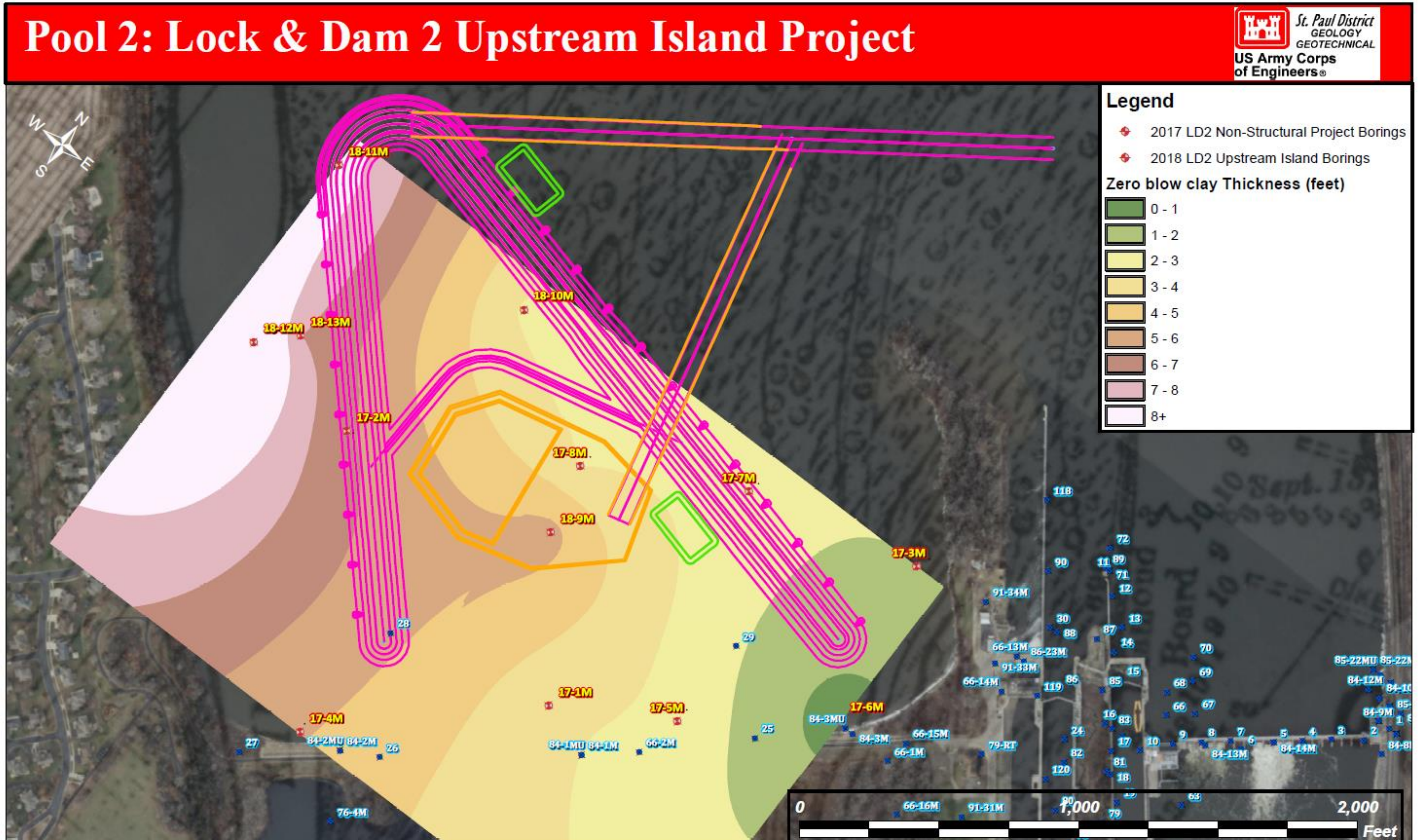
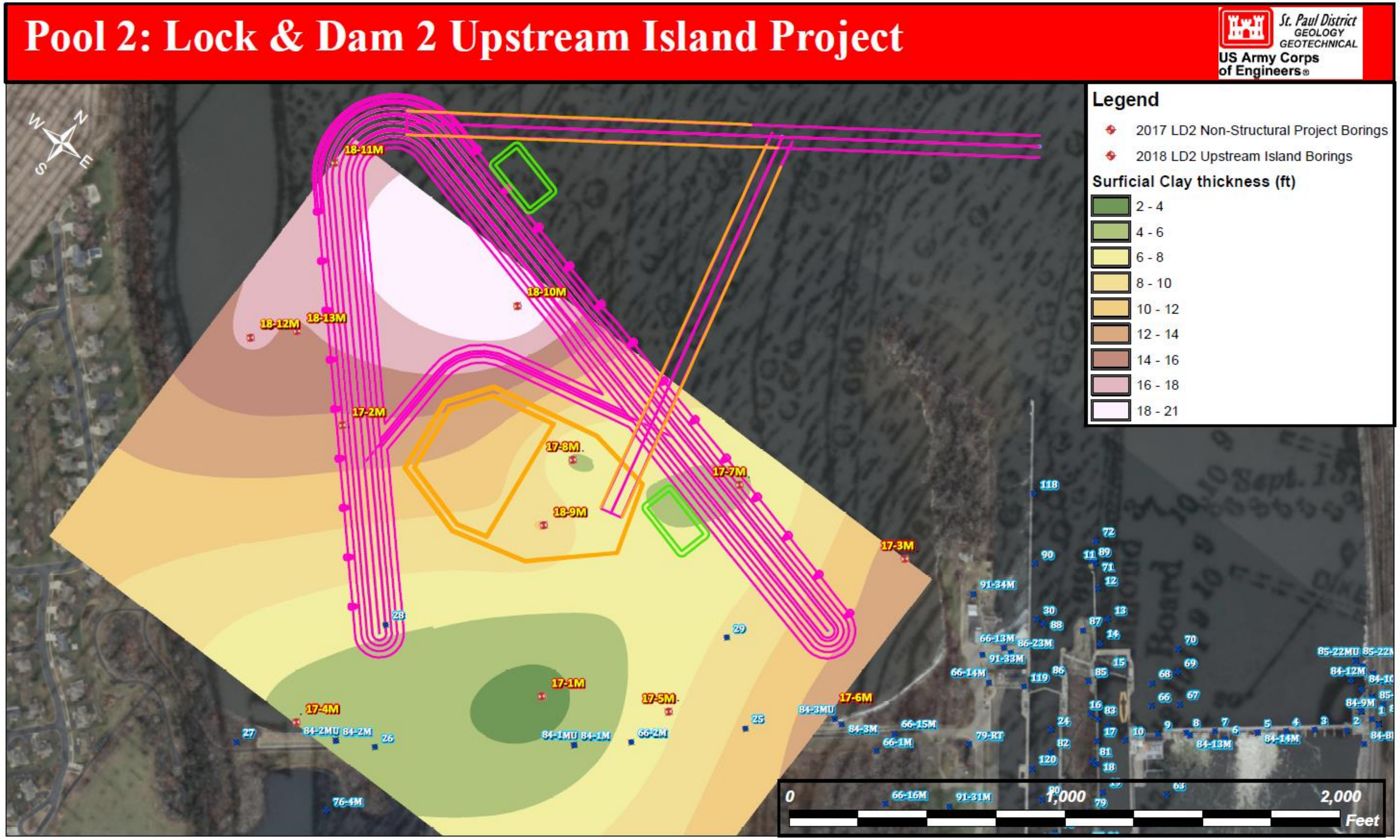


Plate 2: Original Lock and Dam Design Borings



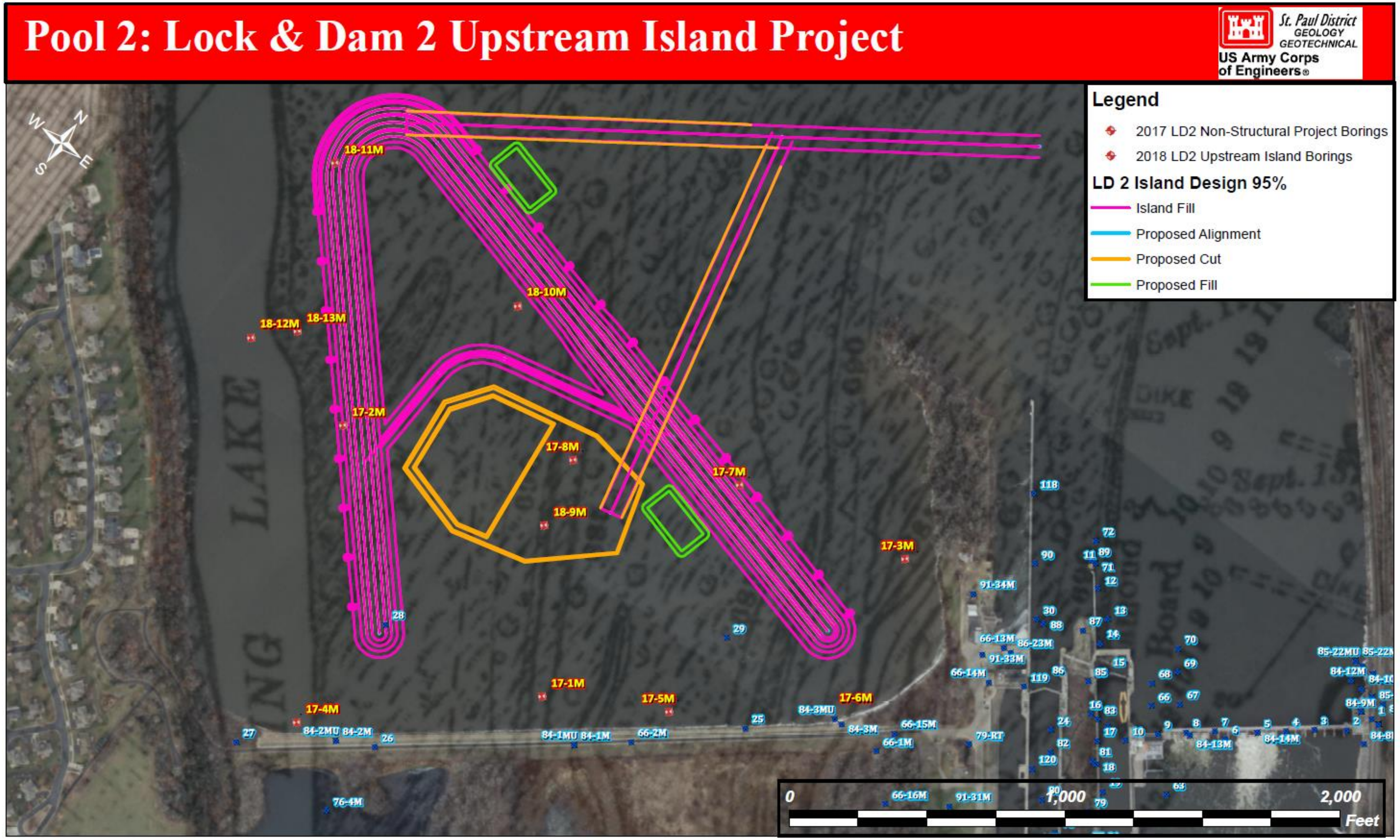
LD 2 Revised Island Geometry - September 2019 - Project Borings and 1890's Topo - Zero Blow Clay Thickness

Plate 3: LD 2 Revised Island Geometry – September 2019 - Zero Blow Count (recent lacustrine) Clay Thickness in Project Area



LD 2 Revised Island Geometry - September 2019 - Project Borings and 1890's Topo - Surficial Clay Thickness

Plate 4: LD 2 Revised Island Geometry - June 2018 - Surficial Clay Thickness in Project Area



LD 2 Revised Island Geometry - September 2019 - Project Borings and 1890's Topo

Plate 5: 2017 and 2018 Project Borings with Island Alignment at 95% Design

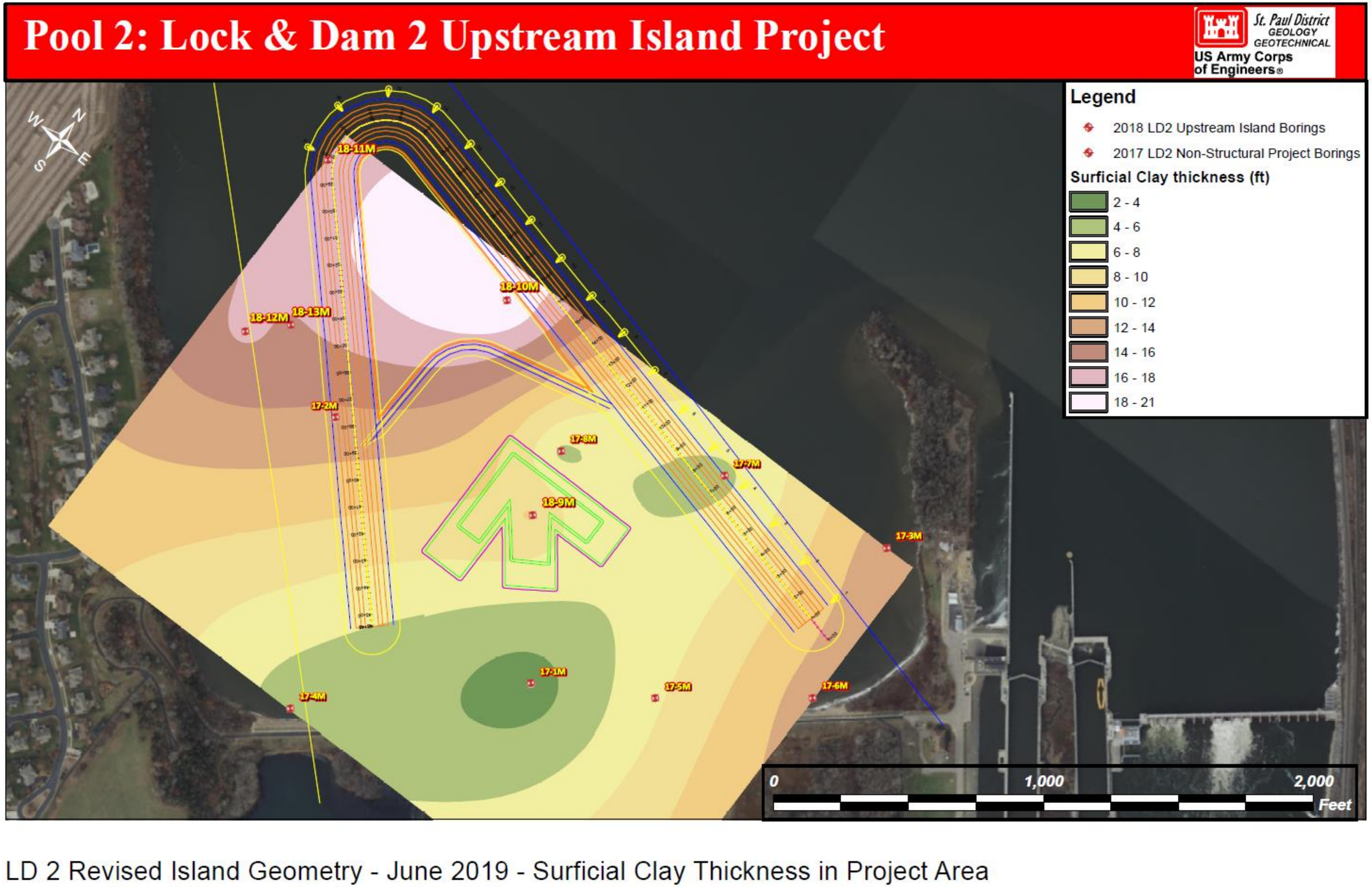
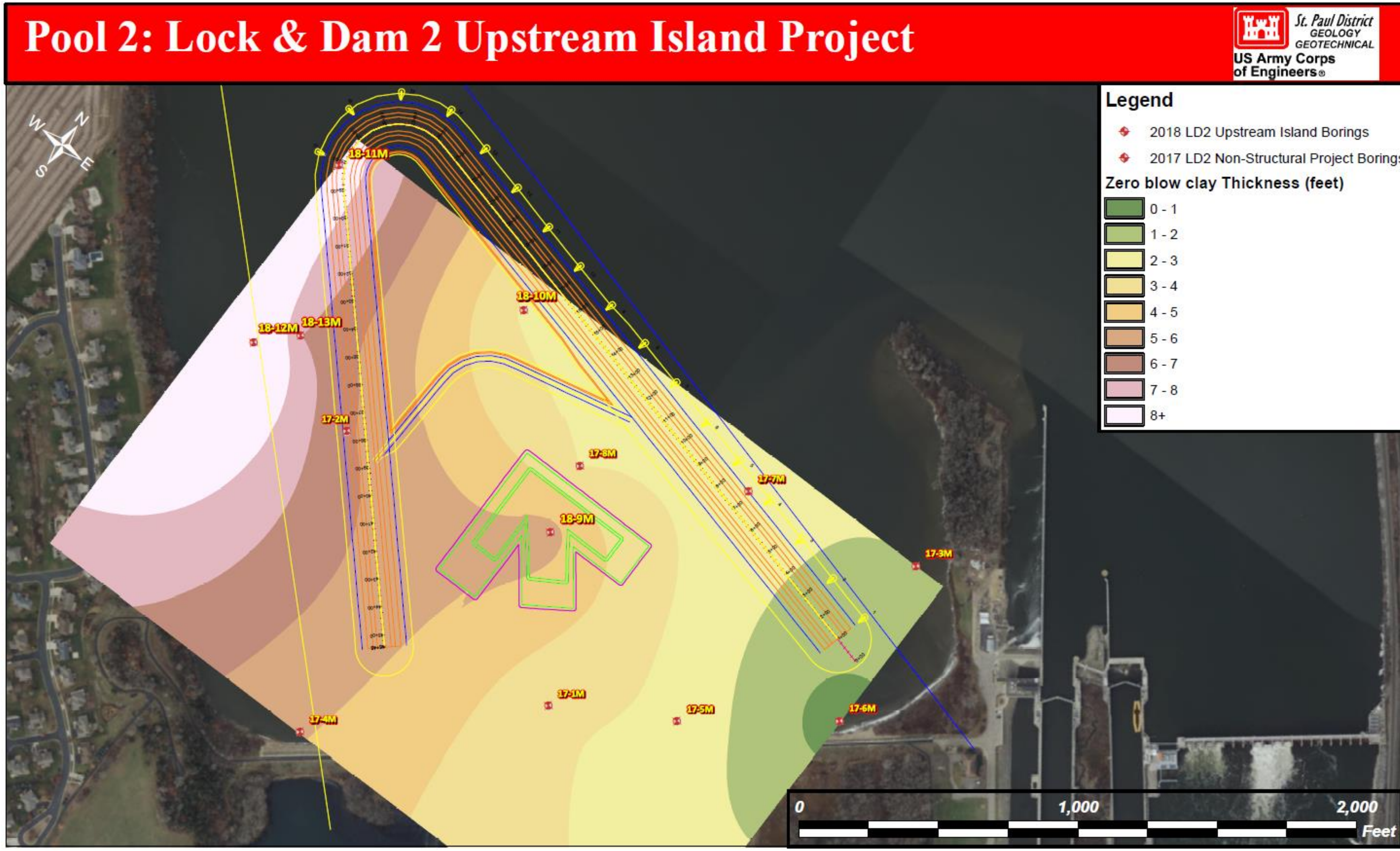


Plate 6: Surficial Clay Thickness with Island Alignment at 65% Design



LD 2 Revised Island Geometry - June 2019 - Zero Blow Count Clay Thickness in Project Area

Plate 7: Zero Blow Clay Thickness with Island Alignment at 65% Design

LD 2 Upstream Island - 692.1 Island Crest elevation
End of Construction Case - Island with 2 feet of Material Displacement
Stability Analysis using Spencer's Method
11 PSF/ft Cohesion increase in Recent Clay Deposits

Color	Name	Model	Unit Weight (pcf)	Cohesion (psf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	C-Top of Layer (psf)	C-Rate of Change ((lbf/ft²)/ft)	C-Maximum (psf)	Piezometric Line
	Recent Lacustrine Zero Blow Clay- Below 2ft	S=f(depth)	95					22	11	100	1
	Recent Lacustrine Zero Blow Clay- Upper	S=f(depth)	95					0	11	100	1
	Sands	Mohr-Coulomb	110		0	30	0				1
	Upper Alluvial Clay	Undrained (Phi=0)	105	200							1

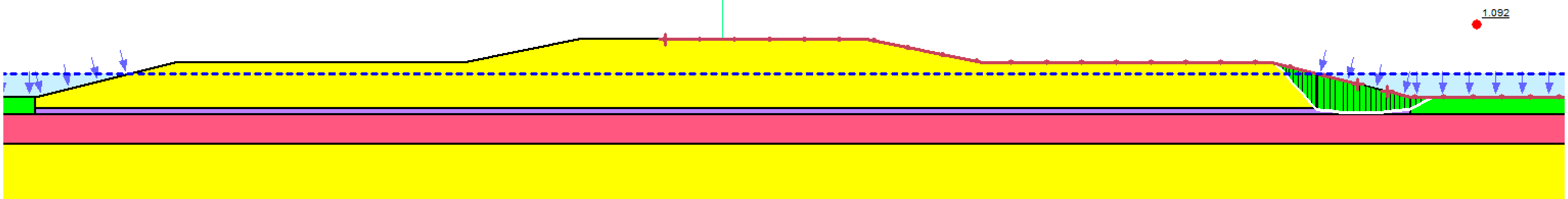


Plate 8: Undrained Slope Stability Analysis – Island Elevation 692.1 – 2 Feet of Material Displacement

LD 2 Upstream Island - 692.1 Island Crest Elevation
End of Construction Case - Island with 3 feet of Material Displacement
Stability Analysis using Spencer's Method
11 PSF/ft Cohesion Increase in Recent Clay Deposits

Color	Name	Model	Unit Weight (pcf)	Cohesion (psf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	C-Top of Layer (psf)	C-Rate of Change ((lbf/ft²)/ft)	C-Maximum (psf)	Piezometric Line
	Recent Lacustrine Zero Blow Clay - Upper	S=f(depth)	95					0	11	100	1
	Sands	Mohr-Coulomb	110		0	30	0				1
	Upper Alluvial Clay	Undrained (Phi=0)	105	200							1

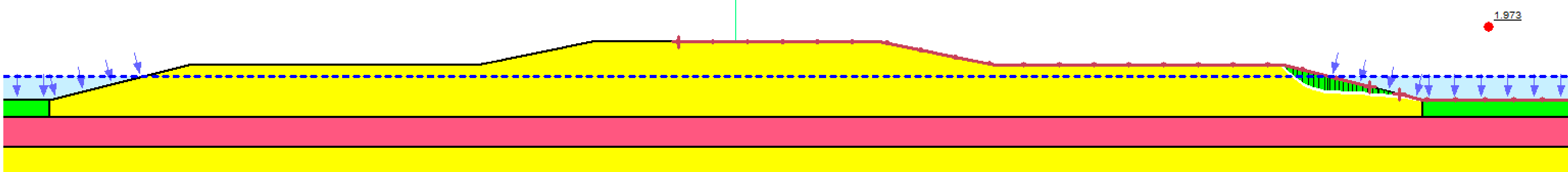
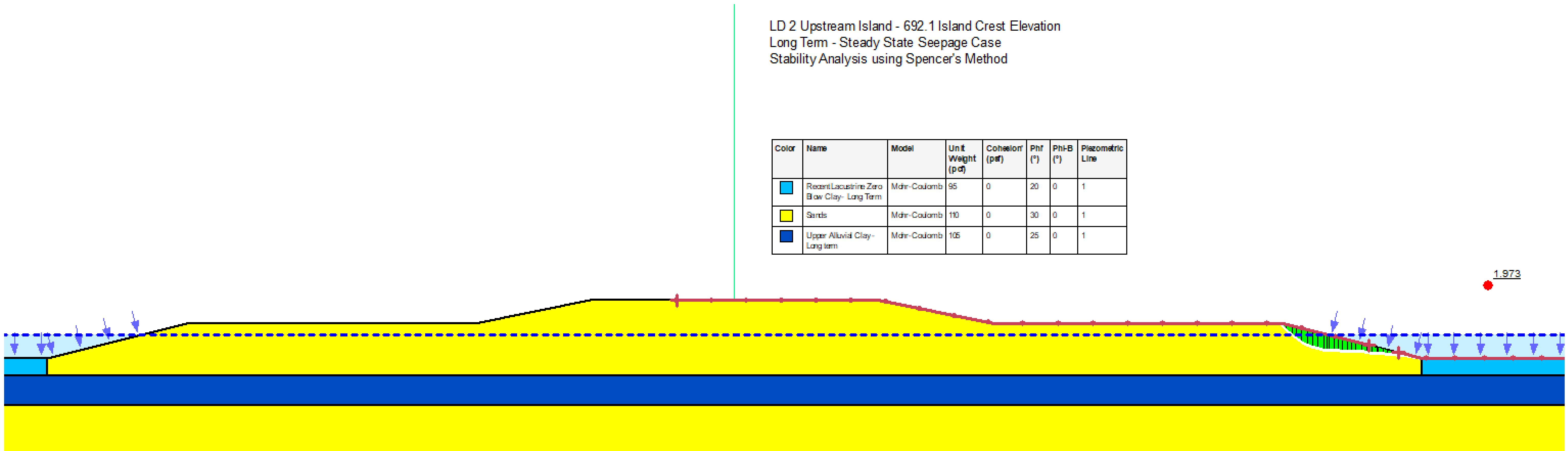


Plate 9: Undrained Slope Stability Analysis – Island Elevation 692.1 – 3 Feet of Material Displacement



Color	Name	Model	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	Piezometric Line
	Recent Lacustrine Zero Blow Clay- Long Term	Mohr-Coulomb	95	0	20	0	1
	Sands	Mohr-Coulomb	110	0	30	0	1
	Upper Alluvial Clay - Long term	Mohr-Coulomb	105	0	25	0	1

Plate 10: Drained Long Term Slope Stability Analysis – Island Elevation 692.1 – 3 Feet of Material Displacement

LD 2 Upstream Island - 690.1 Island Crest elevation
End of Construction Case - Island with 2 feet of Material Displacement
Stability Analysis using Spencer's Method
11 PSF/ft Cohesion increase in Recent Clay Deposits

Color	Name	Model	Unit Weight (pcf)	Cohesion (psf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	C-Top of Layer (psf)	C-Rate of Change ((lbf/ft²)/ft)	C-Maximum (psf)	Piezometric Line
	Recent Lacustrine Zero Blow Clay- Below 2 ft	S=f(depth)	95					22	11	100	1
	Recent Lacustrine Zero Blow Clay- Below 3 ft	S=f(depth)	95					33	11	100	1
	Sands	Mohr-Coulomb	110		0	30	0				1
	Upper Alluvial Clay	Undrained (Phi=0)	105	200							1

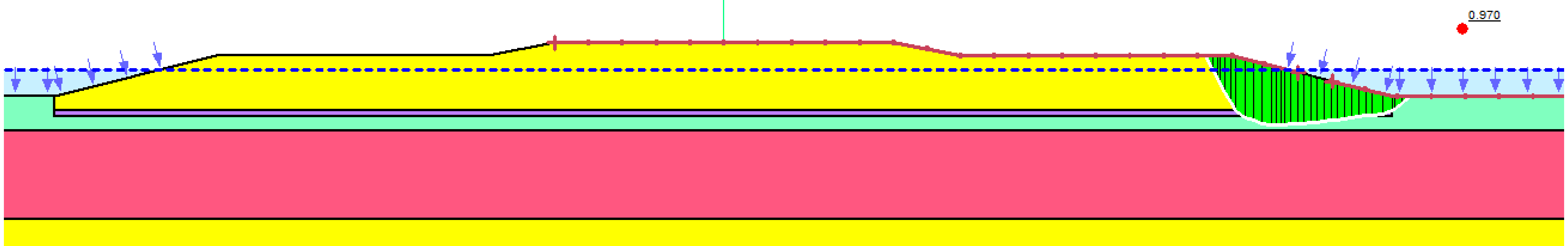


Plate 11: Undrained Slope Stability Analysis – Island Elevation 690.1 – 2 Feet of Material Displacement

LD 2 Upstream Island - 690.1 Island Crest Elevation
End of Construction Case - Island with 3 feet of Material Displacement
Stability Analysis using Spencer's Method
11 PSF/ft Cohesion Increase in Recent Clay Deposits

Color	Name	Model	Unit Weight (pcf)	Cohesion (psf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	C-Top of Layer (psf)	C-Rate of Change ((lbf/ft²)/ft)	C-Maximum (psf)	Piezometric Line
	Recent Lacustrine Zero Blow Clay- Below 3ft	S=f(depth)	95					33	11	100	1
	Recent Lacustrine Zero Blow Clay- Upper	S=f(depth)	95					0	11	100	1
	Sands	Mohr-Coulomb	110		0	30	0				1
	Upper Alluvial Clay	Undrained (Phi=0)	105	200							1

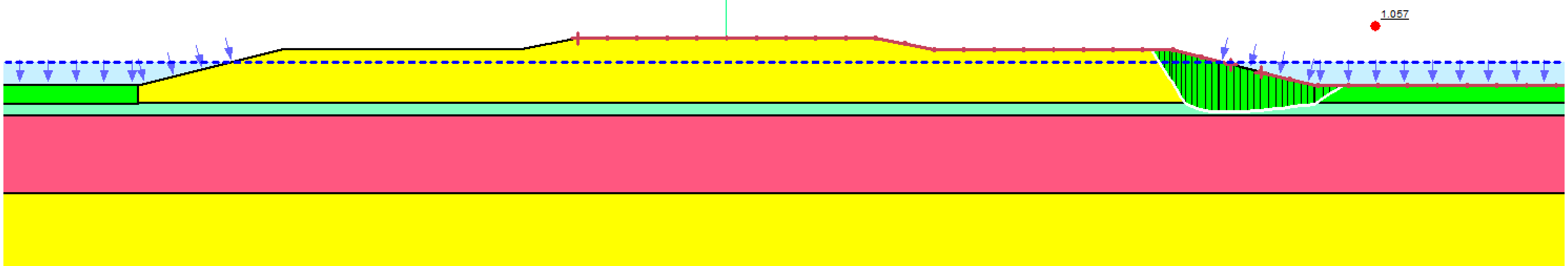
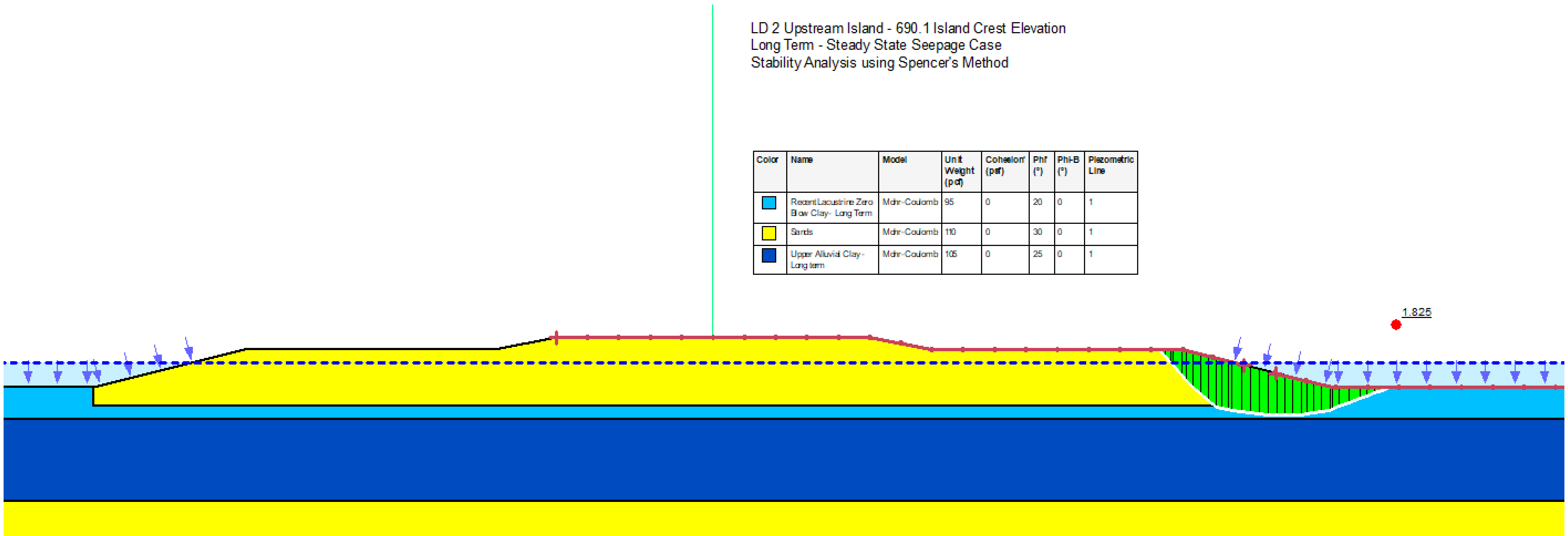


Plate 12: Undrained Slope Stability Analysis – Island Elevation 690.1 – 3 Feet of Material Displacement



Color	Name	Model	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	Piezometric Line
	Recent Lacustrine Zero Blow Clay- Long Term	Mohr-Coulomb	95	0	20	0	1
	Sands	Mohr-Coulomb	110	0	30	0	1
	Upper Alluvial Clay - Long term	Mohr-Coulomb	105	0	25	0	1

Plate 13: Drained Long Term Slope Stability Analysis – Island Elevation 690.1 – 3 Feet of Material Displacement

LD 2 Upstream Island - 688.1 Island Crest elevation
End of Construction Case - Island with 2 feet of Material Displacement
Stability Analysis using Spencer's Method
11 PSF/ft Cohesion increase in Recent Clay Deposits

Color	Name	Model	Unit Weight (pcf)	Cohesion (psf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	C-Top of Layer (psf)	C-Rate of Change ((lbf/ft²)/ft)	C-Maximum (psf)	Piezometric Line
	Recent Lacustrine Zero Blow Clay - Below 2 feet	S=f(depth)	95					22	11	100	1
	Recent Lacustrine Zero Blow Clay - Below 3 feet	S=f(depth)	95					33	11	100	1
	Recent Lacustrine Zero Blow Clay - Upper	S=f(depth)	95					0	11	100	1
	Sands	Mohr-Coulomb	110		0	30	0				1
	Upper Alluvial Clay	Undrained (Phi=0)	105	200							1

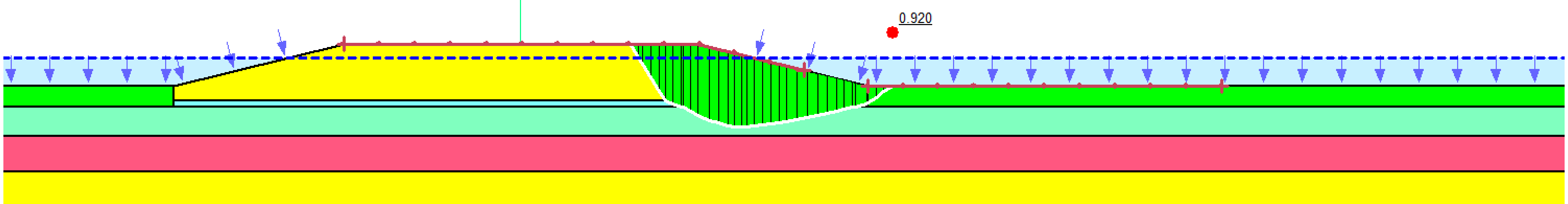


Plate 14: Undrained Slope Stability Analysis – Island Elevation 688.1 – 2 Feet of Material Displacement

LD 2 Upstream Island - 688.1 Island Crest elevation
End of Construction Case - Island with 3 feet of Material Displacement
Stability Analysis using Spencer's Method
11 PSF/ft Cohesion increase in Recent Clay Deposits

Color	Name	Model	Unit Weight (pcf)	Cohesion (psf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	C-Top of Layer (psf)	C-Rate of Change ((lbf/ft²)/ft)	C-Maximum (psf)	Piezometric Line
	Recent Lacustrine Zero Blow Clay - Below 3 feet	S=f(depth)	95					33	11	100	1
	Recent Lacustrine Zero Blow Clay - Upper	S=f(depth)	95					0	11	100	1
	Sands	Mohr-Coulomb	110		0	30	0				1
	Upper Alluvial Clay	Undrained (Phi=0)	105	200							1

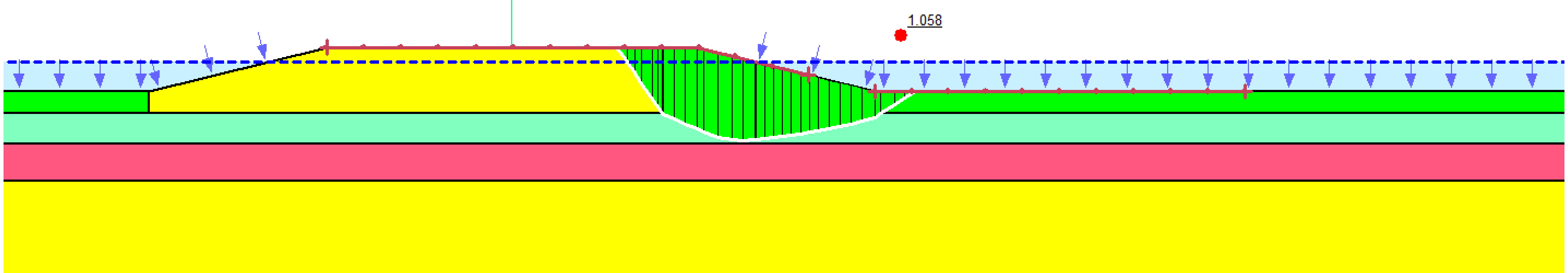


Plate 15: Undrained Slope Stability Analysis – Island Elevation 688.1 – 3 Feet of Material Displacement

LD 2 Upstream Island - 688.1 Island Crest elevation
Long-term Steady State Case - Island with 3 feet of Material Displacement
Stability Analysis using Spencer's Method

Color	Name	Model	Unit Weight (pcf)	Cohesion' (psf)	Phi' (°)	Phi-B (°)	Piezometric Line
	Recent Lacustrine Zero Blow Clay - Steady State	Mohr-Coulomb	95	0	20	0	1
	Sands	Mohr-Coulomb	110	0	30	0	1
	Upper Alluvial Clay - Steady State	Mohr-Coulomb	105	0	25	0	1

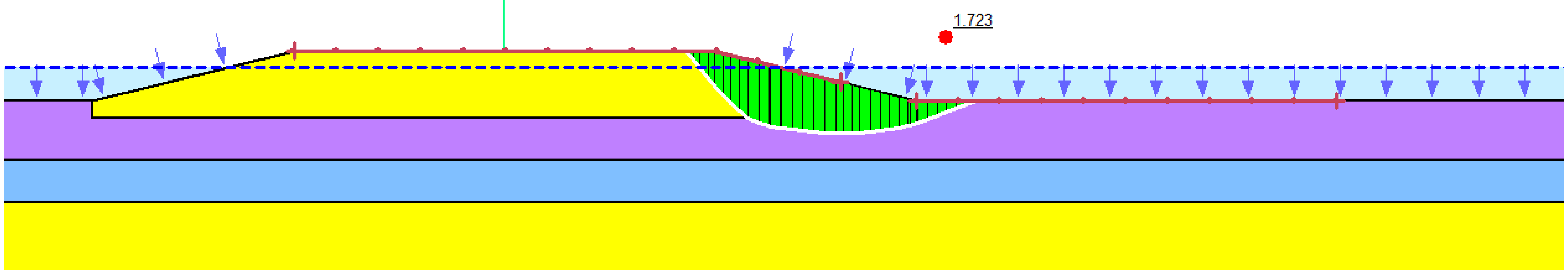
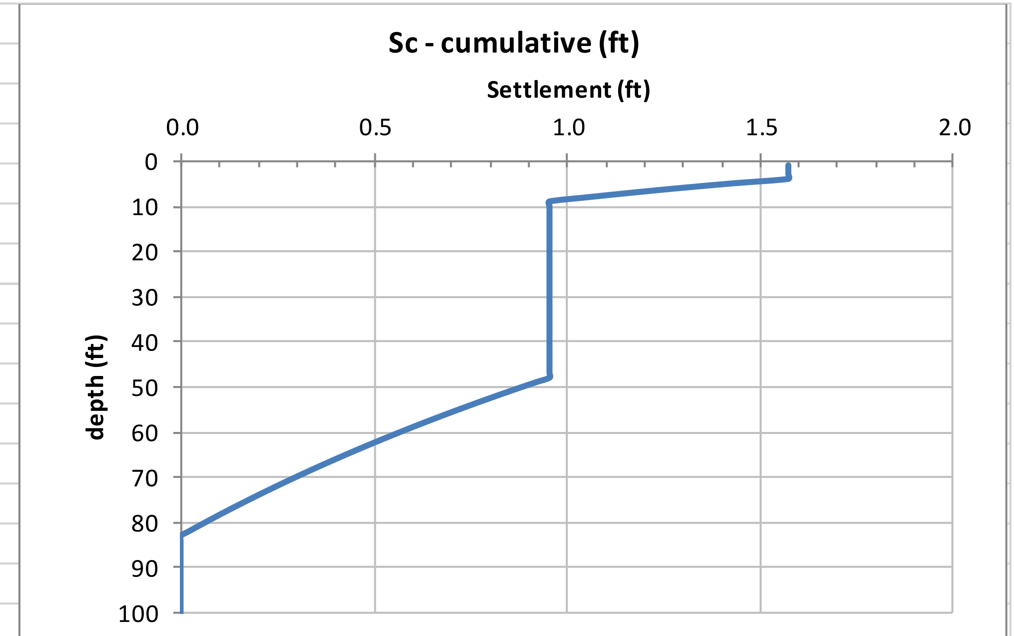


Plate 16: Drained Long-term Slope Stability Analysis – Island Elevation 688.1 – 3 Feet of Material Displacement

Project: Lock and Dam 2 Non-structural Embankment Improvements
Subject: Settlement Calculations for LD2 Upstream Island - Top elevation 692.1
nputed By: NDM   Reviewed By:
Date: 5/22/2019   Date:

Layer Thickness: 1 ft
Settlement Location: Centerline
Stress Calculations: Davis & Poulus



Results	(ft)	(in.)
Total Settlement	1.57	18.9

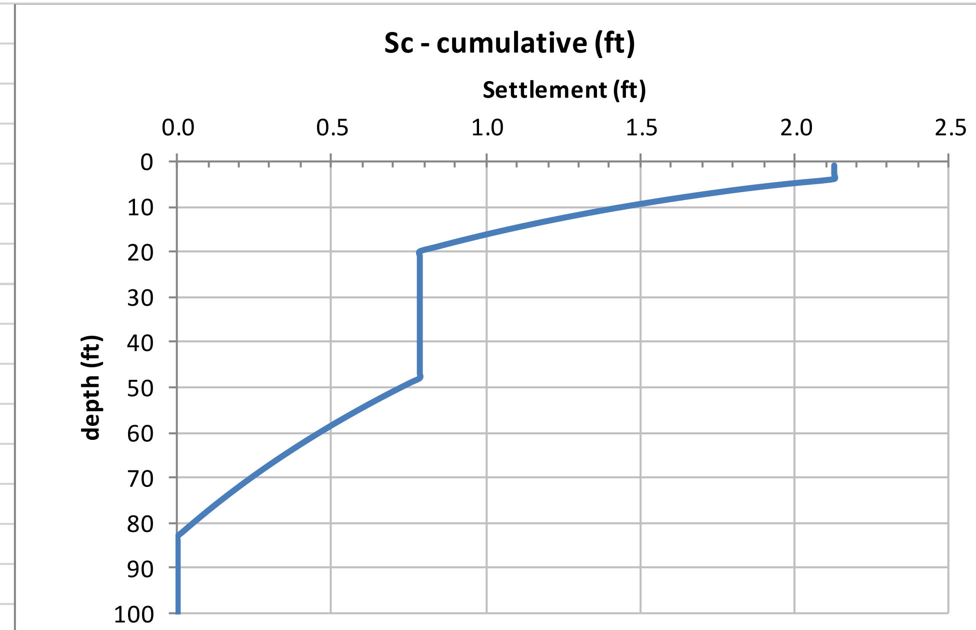
Depth (ft)	Elev. (ft)	Mid depth, z	GW depth (ft)	Formation	γ_{sat} (pcf)	σ_v (psf)	u (psf)	σ'_{vo} (psf)	$\Delta\sigma'_v$ (psf)	σ'_{vf} (psf)	OCR	σ'_{vc} (psf)	$C_{\varepsilon r}$	$C_{\varepsilon c}$	Recomp. ε (%)	Comp. ε (%)	S_c (ft)	ΣS_c (ft)	S_c - cumulative (ft)
1	682	0.5	5	nd fill Replacem	125	343.3	312	31.3	1023	1054.5	1	31.3	0.000	0.000	0.000	0.000	0.000	0.000	1.574
2	681	1.5	6	nd fill Replacem	125	468.3	374.4	93.9	1023	1117.1	1	93.9	0.000	0.000	0.000	0.000	0.000	0.000	1.574
3	680	2.5	7	nd fill Replacem	125	593.3	436.8	156.5	1023	1179.6	1	156.5	0.000	0.000	0.000	0.000	0.000	0.000	1.574
4	679	3.5	8	pper Alluvial Cl	104.3	707.95	499.2	208.75	1023	1231.8	1	208.8	0.033	0.187	0.000	0.144	0.144	0.144	1.574
5	678	4.5	9	pper Alluvial Cl	104.3	812.25	561.6	250.65	1023	1273.5	1	250.7	0.033	0.187	0.000	0.132	0.132	0.276	1.429
6	677	5.5	10	pper Alluvial Cl	104.3	916.55	624	292.55	1023	1315.1	1	292.6	0.033	0.187	0.000	0.122	0.122	0.398	1.297
7	676	6.5	11	pper Alluvial Cl	104.3	1020.85	686.4	334.45	1022	1356.5	1	334.5	0.033	0.187	0.000	0.114	0.114	0.512	1.175
8	675	7.5	12	pper Alluvial Cl	104.3	1125.15	748.8	376.35	1022	1397.9	1	376.4	0.033	0.187	0.000	0.107	0.107	0.618	1.062
9	674	8.5	13	Upper Sands	128	1241.3	811.2	430.1	1021	1450.9	1	430.1	0.000	0.000	0.000	0.000	0.000	0.618	0.955
10	673	9.5	14	Upper Sands	128	1369.3	873.6	495.7	1020	1515.6	1	495.7	0.000	0.000	0.000	0.000	0.000	0.618	0.955
11	672	10.5	15	Upper Sands	128	1497.3	936	561.3	1019	1580.1	1	561.3	0.000	0.000	0.000	0.000	0.000	0.618	0.955
12	671	11.5	16	Upper Sands	128	1625.3	998.4	626.9	1018	1644.5	1	626.9	0.000	0.000	0.000	0.000	0.000	0.618	0.955
13	670	12.5	17	Upper Sands	128	1753.3	1060.8	692.5	1016	1708.6	1	692.5	0.000	0.000	0.000	0.000	0.000	0.618	0.955
14	669	13.5	18	Upper Sands	128	1881.3	1123.2	758.1	1014	1772.5	1	758.1	0.000	0.000	0.000	0.000	0.000	0.618	0.955
15	668	14.5	19	Upper Sands	128	2009.3	1185.6	823.7	1013	1836.3	1	823.7	0.000	0.000	0.000	0.000	0.000	0.618	0.955
16	667	15.5	20	Upper Sands	128	2137.3	1248	889.3	1011	1899.9	1	889.3	0.000	0.000	0.000	0.000	0.000	0.618	0.955
17	666	16.5	21	Upper Sands	128	2265.3	1310.4	954.9	1008	1963.2	1	954.9	0.000	0.000	0.000	0.000	0.000	0.618	0.955
18	665	17.5	22	Upper Sands	128	2393.3	1372.8	1020.5	1006	2026.4	1	1020.5	0.000	0.000	0.000	0.000	0.000	0.618	0.955
19	664	18.5	23	Upper Sands	128	2521.3	1435.2	1086.1	1003	2089.4	1	1086.1	0.000	0.000	0.000	0.000	0.000	0.618	0.955

Plate 17: Settlement Calcs Island Elevation 692.1

Project: Lock and Dam 2 Non-structural Embankment Improvements
Subject: Settlement Calculations for LD2 Upstream Island - Top elevation 690.1
nputed By: NDM Reviewed By:
Date: 5/22/2019 Date:

Layer Thickness: 1 ft
Settlement Location: Centerline
Stress Calculations: Davis & Poulus

Results (ft) (in.)
Total Settlement 2.13 25.6



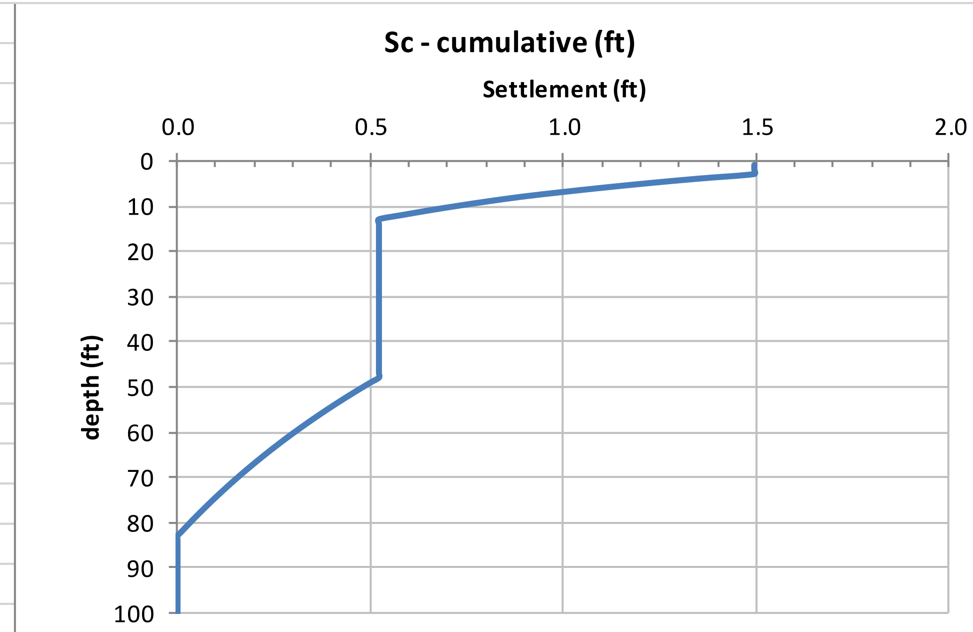
Depth (ft)	Elev. (ft)	Mid depth, z	GW depth (ft)	Formation	γ_{sat} (pcf)	σ_v (psf)	u (psf)	σ'_{vo} (psf)	$\Delta\sigma'_v$ (psf)	σ'_{vf} (psf)	OCR	σ'_{vc} (psf)	$C_{\varepsilon r}$	$C_{\varepsilon c}$	Recomp. ε (%)	Comp. ε (%)	S_c (ft)	ΣS_c (ft)	S_c - cumulative (ft)
1	682	0.5	5	nd fill Replacem	125	343.3	312	31.3	793	824.5	1	31.3	0.000	0.000	0.000	0.000	0.000	0.000	2.129
2	681	1.5	6	nd fill Replacem	125	468.3	374.4	93.9	793	887.1	1	93.9	0.000	0.000	0.000	0.000	0.000	0.000	2.129
3	680	2.5	7	nd fill Replacem	125	593.3	436.8	156.5	793	949.6	1	156.5	0.000	0.000	0.000	0.000	0.000	0.000	2.129
4	679	3.5	8	ent Lacustrine C	92.5	702.05	499.2	202.85	793	995.9	1	202.9	0.000	0.204	0.000	0.141	0.141	0.141	2.129
5	678	4.5	9	ent Lacustrine C	92.5	794.55	561.6	232.95	793	1025.8	1	233.0	0.000	0.204	0.000	0.131	0.131	0.272	1.988
6	677	5.5	10	pper Alluvial Cl	104.3	892.95	624	268.95	793	1061.5	1	269.0	0.033	0.187	0.000	0.111	0.111	0.384	1.857
7	676	6.5	11	pper Alluvial Cl	104.3	997.25	686.4	310.85	792	1103.0	1	310.9	0.033	0.187	0.000	0.103	0.103	0.487	1.746
8	675	7.5	12	pper Alluvial Cl	104.3	1101.55	748.8	352.75	792	1144.4	1	352.8	0.033	0.187	0.000	0.096	0.096	0.582	1.643
9	674	8.5	13	pper Alluvial Cl	104.3	1205.85	811.2	394.65	791	1185.6	1	394.7	0.033	0.187	0.000	0.089	0.089	0.672	1.547
10	673	9.5	14	pper Alluvial Cl	104.3	1310.15	873.6	436.55	790	1226.6	1	436.6	0.033	0.187	0.000	0.084	0.084	0.755	1.458
11	672	10.5	15	pper Alluvial Cl	104.3	1414.45	936	478.45	789	1267.5	1	478.5	0.033	0.187	0.000	0.079	0.079	0.835	1.374
12	671	11.5	16	pper Alluvial Cl	104.3	1518.75	998.4	520.35	788	1308.2	1	520.4	0.033	0.187	0.000	0.075	0.075	0.909	1.295
13	670	12.5	17	pper Alluvial Cl	104.3	1623.05	1060.8	562.25	787	1348.8	1	562.3	0.033	0.187	0.000	0.071	0.071	0.980	1.220
14	669	13.5	18	pper Alluvial Cl	104.3	1727.35	1123.2	604.15	785	1389.1	1	604.2	0.033	0.187	0.000	0.068	0.068	1.048	1.149
15	668	14.5	19	pper Alluvial Cl	104.3	1831.65	1185.6	646.05	783	1429.3	1	646.1	0.033	0.187	0.000	0.064	0.064	1.113	1.081
16	667	15.5	20	pper Alluvial Cl	104.3	1935.95	1248	687.95	781	1469.3	1	688.0	0.033	0.187	0.000	0.062	0.062	1.174	1.017
17	666	16.5	21	pper Alluvial Cl	104.3	2040.25	1310.4	729.85	779	1509.1	1	729.9	0.033	0.187	0.000	0.059	0.059	1.233	0.955
18	665	17.5	22	pper Alluvial Cl	104.3	2144.55	1372.8	771.75	777	1548.7	1	771.8	0.033	0.187	0.000	0.057	0.057	1.290	0.896
19	664	18.5	23	pper Alluvial Cl	104.3	2248.85	1435.2	813.65	775	1588.2	1	813.7	0.033	0.187	0.000	0.054	0.054	1.344	0.840

Plate 18: Settlement Calcs Island Elevation 690.1

Project: Lock and Dam 2 Non-structural Embankment Improvements
Subject: Settlement Calculations for LD2 Upstream Island - Top elevation 688.1
ıputed By: NDM | Reviewed By:
Date: 5/22/2019 | Date:

Layer Thickness: 1 ft
Settlement Location: Centerline
Stress Calculations: Davis & Poulus

Results	(ft)	(in.)
Total Settlement	1.50	18.0



Depth (ft)	Elev. (ft)	Mid depth, z	GW depth (ft)	Formation	γ_{sat} (pcf)	σ_v (psf)	u (psf)	σ'_{vo} (psf)	$\Delta\sigma'_v$ (psf)	σ'_{vf} (psf)	OCR	σ'_{vc} (psf)	$C_{\varepsilon r}$	$C_{\varepsilon c}$	Recomp. ε (%)	Comp. ε (%)	S_c (ft)	ΣS_c (ft)	S_c - cumulative (ft)
1	682	0.5	5	ıd fill Replacem	125	343.3	312	31.3	563	594.5	1	31.3	0.000	0.000	0.000	0.000	0.000	0.000	1.496
2	681	1.5	6	ıd fill Replacem	125	468.3	374.4	93.9	563	657.1	1	93.9	0.000	0.000	0.000	0.000	0.000	0.000	1.496
3	680	2.5	7	ent Lacustrine C	92.5	577.05	436.8	140.25	563	703.4	1	140.3	0.000	0.204	0.000	0.143	0.143	0.143	1.496
4	679	3.5	8	ent Lacustrine C	92.5	669.55	499.2	170.35	563	733.4	1	170.4	0.000	0.204	0.000	0.129	0.129	0.272	1.354
5	678	4.5	9	ent Lacustrine C	92.5	762.05	561.6	200.45	563	763.3	1	200.5	0.000	0.204	0.000	0.118	0.118	0.391	1.224
6	677	5.5	10	ent Lacustrine C	92.5	854.55	624	230.55	563	793.2	1	230.6	0.000	0.204	0.000	0.109	0.109	0.500	1.106
7	676	6.5	11	ent Lacustrine C	92.5	947.05	686.4	260.65	562	822.9	1	260.7	0.000	0.204	0.000	0.102	0.102	0.602	0.996
8	675	7.5	12	pper Alluvial Cla	104.3	1045.45	748.8	296.65	562	858.4	1	296.7	0.033	0.187	0.000	0.086	0.086	0.688	0.894
9	674	8.5	13	pper Alluvial Cla	104.3	1149.75	811.2	338.55	561	899.7	1	338.6	0.033	0.187	0.000	0.079	0.079	0.768	0.808
10	673	9.5	14	pper Alluvial Cla	104.3	1254.05	873.6	380.45	560	940.9	1	380.5	0.033	0.187	0.000	0.074	0.074	0.841	0.729
11	672	10.5	15	pper Alluvial Cla	104.3	1358.35	936	422.35	559	981.8	1	422.4	0.033	0.187	0.000	0.069	0.069	0.910	0.655
12	671	11.5	16	pper Alluvial Cla	104.3	1462.65	998.4	464.25	558	1022.7	1	464.3	0.033	0.187	0.000	0.064	0.064	0.974	0.587
13	670	12.5	17	Upper Sands	128	1578.8	1060.8	518	557	1075.2	1	518.0	0.000	0.000	0.000	0.000	0.000	0.974	0.523
14	669	13.5	18	Upper Sands	128	1706.8	1123.2	583.6	556	1139.4	1	583.6	0.000	0.000	0.000	0.000	0.000	0.974	0.523
15	668	14.5	19	Upper Sands	128	1834.8	1185.6	649.2	554	1203.5	1	649.2	0.000	0.000	0.000	0.000	0.000	0.974	0.523
16	667	15.5	20	Upper Sands	128	1962.8	1248	714.8	553	1267.4	1	714.8	0.000	0.000	0.000	0.000	0.000	0.974	0.523

Plate 19: Settlement Calcs Island Elevation 688.1