Three-Dimensional Effect on a Large Stockpile Slope Stability Analysis

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ABSTRACT
Wick drains were installed under a very large stockpile in Northern Ontario to increase the rate of consolidation and the strength gain of silty clay foundation deposits. Most of the wick drains penetrated the full thickness of the silty clay deposits, terminating in the sand till layer; however, at some localized areas the wick drains did not penetrate the full depth. Results from two-dimensional slope stability analysis based on the limit equilibrium method indicated that the slip surface extends through the clay under the shorter wick drains due to slower strength gain, indicating that the minimum required factor of safety was not satisfied. Further investigation suggested that the two-dimensional stability analysis did not accurately represent the three-dimensional condition of these areas, as the configuration of the wick drains, local geology, topography, and stockpile geometry were expected to provide a significant three-dimensional effect. Accordingly, the analysis was advanced to a three-dimensional limit equilibrium slope stability model. Results of the three-dimensional stability analysis indicated that the minimum required factor of safety was satisfied. Instruments installed at these areas indicate that no significant displacement has been observed to date, confirming the results of the three-dimensional slope stability analysis.

RÉSUMÉ
Des drains verticaux (wick drains) ont été installés sous une grande halde dans le nord de l'Ontario pour augmenter le taux de consolidation et la résistance du dépôt d'argile silteuse en fondation. La plupart des drains verticaux ont complètement pénétré la couche d'argile silteuse jusqu'à la couche de till sableux, sauf à certains endroits. Les résultats de l'analyse bidimensionnelle de stabilité des pentes basée sur la méthode de l'équilibre limite ont indiqué que la surface de glissement s'étendait à travers l'argile sous les drains verticaux les plus courts en raison d'un taux plus faible du gain de résistance, ce qui indique que le facteur de sécurité minimum requis n'a pas été respecté. Une investigation plus poussée a suggéré que l'analyse de stabilité bidimensionnelle ne représentait pas précisément la condition tridimensionnelle de ces zones, étant donné que la configuration des drains verticaux, la géologie locale, la topographie et la géométrie des empilements devraient avoir un effet tridimensionnel important. En conséquence, l'analyse a été poussée jusqu'à un modèle tridimensionnel de stabilité des pentes en équilibre limite. Les résultats de l'analyse de stabilité tridimensionnelle ont indiqué que le facteur de sécurité minimum requis était satisfait. Les instruments installés à ces endroits indiquent qu'aucun déplacement significatif n'a été observé à ce jour, ce qui confirme les résultats de l'analyse tridimensionnelle de stabilité des pentes.

1 INTRODUCTION

Construction of a large stockpile for waste overburden and waste rock was required at an operating mine in Northern Ontario, Canada. The stockpile foundation has up to 40 m thick of low to high plastic, slickensided, and lightly overconsolidated clay deposits. The stockpile required foundation ground improvement around its perimeter to support the planned ultimate height of up to 40 m, to be raised over 6 years. The ground improvement consists of a shear key, where the foundation silty clay thickness is between 3 m to 8 m and prefabricated vertical drains (wick drains), where the foundation silty clay thickness is more than 8 m. For locations where the silty clay thickness is less than 3 m, no ground improvement was required.

About 2,600,000 linear meters of wick drains were installed over the area of 772,000 m^2. Wick drains were installed beneath the stockpile perimeter slopes and crest, over a width varying from 138 m to 203 m. The outer boundary of the wick drain ground improvement area was inset 27 m inside the toe of the stockpile. The wick drains have a triangular pattern with a 2 m spacing. Overburden waste is placed in the interior of the stockpile and waste rockfill is placed at the exterior, buttressing the interior overburden fill. Only rockfill is placed above the wick drain zones.

During the installation of the wick drains, in some localized areas, the wick drains did not penetrate to the full required depth. In these areas, some or all of the wick drains terminated within the clay rather than penetrating into the underlying sand till. Where early wick drain termination occurs, there remains an underlying zone of unimproved silty clay. When this zone experiences elevated porewater pressures during subsequent stockpile raising, the porewater pressure dissipation will be much slower than that assumed in the design. As a result, the affected zone does not experience shear strength gain in the same timeframe as those areas with fully penetrated wick drains. If the early termination area is extensive, a potential slip surface may develop at depth, passing below the foundation zone improved by wick drains resulting in a low factor of safety (FoS).

Two areas of early wick drain refusal are considered here-in (Area A and Area B)

2 FOUNDATION CONDITIONS

The soil stratigraphy generally consists of (in order from ground surface downwards):

- Organic surficial layer;
- upper glaciolacustrine deposit;
- clay till;
- lower glaciolacustrine deposit;
- granular till; and
- bedrock.

The foundation conditions have been characterized based on geotechnical investigations, including boreholes, CPTs, test pits, bedrock probe holes, and Electrical Resistivity Imaging (ERI) geophysics survey. Sonic drilling was carried out to obtain continuous cores to log the overburden units, to collect samples, to determine the thicknesses of the deposits, and to check for the existence of pre-sheared (slickensided) layers. Mud rotary drilling was also carried out to collect high quality samples using a piston tube sampler and to carry out electrical vane shear tests. Index testing and advanced laboratory testing were carried out to measure the foundation clay deposits index parameters, total and effective stress shear strengths, and to determine the consolidation parameters.

The advanced laboratory tests carried out consisted of Consolidated Isotropic Undrained (CIU) triaxial compression, Consolidated Anisotropic Undrained (CAU) triaxial compression, consolidated constant volume Direct Simple Shear (DSS), oedometer, Constant Rate Strain (CRS), direct shear and ring shear tests.

Following the completion of wick drain installation, a better understanding of the overburden silty clay deposit thickness was obtained based on the installation depth, penetration rate with depth and crowd force data acquired.

The three cohesive soil units (i.e., the upper and lower glaciolacustrine units and the clay till) control the slope stability of the stockpile.

3 WICK DRAINS EARLY REFUSAL

Construction quality control (CQC) and construction quality assurance (CQA) programs were carried out as part of the construction monitoring during the wick drain installation. CQC data were provided by the wick drain contractor through their rig-mounted data acquisition systems, which included information on the rig ID, wick ID, installation location, depth, inclination, heading, penetration rate with depth and crowd force with depth.

Wick drain installation data were reviewed as a CQA measure to confirm that wick drain installation depth was consistent with the design requirements. Early refusal of a single wick drain is of little consequence; however, the effect on the wick drain performance may be substantial if the early refusal area is extensive. The review of the wick drain installation data indicated that wick drains may not be installed to the design depth in a few isolated areas.

A field investigation program was carried out to verify the CQA review observations and to investigate the source and the extent of this concern. The presence of a dense layer within the foundation or insufficient mandrel length were identified as causes of the wick drain early refusal in the affected areas.

The presence of a dense layer, consisting of dense sand, silty sand, or gravel, is believed to be related to the complicated surficial geology of the site resulting in an early refusal of the wick drain mandrel.

4 DESIGN CRITERIA

The stockpiles are designed to meet or exceed the following stability criteria based on the limit equilibrium analysis:

- FoS = 1.3 for static undrained condition using fully softened (i.e., post-peak, strain- weakened) shear strength condition.
- FoS = 1.1 for static slickensided condition using effective stress residual shear strength condition.
- FoS = 1.0 for pseudo-static condition.

5 GEOTECHNICAL DESIGN PARAMETERS

Geotechnical design parameters were selected based on a review of the results from field investigation, laboratory testing, and test fill observations. The details of the test fill program are provided in Etezad (2019). The geotechnical design parameters are summarized in Table 1. The laboratory test results indicate that the peak shear strength takes place at small shear strengths. Peak shear strength was used only for the areas of over-consolidated silty clay near the toe which are subject to limited stresses; otherwise fully softened shear strength was used. Residual shear strength was used to check for the slickensided condition.

A normally consolidated vertical coefficient of consolidation of 2 m^2/yr and a horizontal coefficient of consolidation of 10 m^2/yr were used for the silty clay layers based on extensive laboratory testing and the test fill program. Both radial drainage and natural (vertical) drainage were considered in the analyses. The pore water pressure calculation and the stability analysis were carried out for each year of the stockpile construction. Porewater pressure conditions, represented by B-Bar values, are summarized in Table 2. B-bar=1 was conservatively used for the area where the wick drains did not penetrate in the Area A two-dimensional stability analysis. Refined excess pore pressure generation (B-bar) calculations considering vertical drainage were used for the area where the wick drains did not penetrate in the Area B two-dimensional stability analysis. No excess pore water pressure dissipation (B-bar=1) was conservatively considered for the volume where the wick drains did not penetrate in the three-dimensional stability analyses.

Table 1: Geotechnical Design Parameters

Material	Unit Weight kN/m^3	Effective Strength Parameters		Undrained Shear Strength Parameters			
				Fully Softened		Peak	
		Friction Angle °	Cohesion kPa	S_u/σ'_v	S_{umin} kPa	S_u/σ'_v	S_{umin} kPa
Overburden Waste	18	n/a	n/a	n/a	40	n/a	n/a
Waste Rock	21.5	LS	0	n/a	n/a	n/a	n/a
UGU, Silt and Clay	19.5	22 (FS)	0	0.24	40	0.24	65
UGU, Silty Clay	19.5	12 (RS)	0	0.22	30	0.22	60
Clay Till	18.5	12 (RS)	0	0.22	30	0.22	60
LGU	18	15 (RS)	0	0.22	30	0.22	60
Sand Till	20	36	0	n/a	n/a	n/a	n/a
Bedrock	n/a	Impenetrable					

Notes:
UGU = upper glaciolacustrine unit; LGU = lower glaciolacustrine unit; FS = Fully softened (strain weakened) strength condition; RS = Residual strength condition; LS = Leps Strength Function (Leps 1970); n/a = not applicable

Table 2: B-Bar Design Parameters

Material	B-Bar[(a)]	
	Early Refusal Area	Wick Drain Zone
Overburden Waste	0	0
Waste Rock	0	0
UGU, Silt and Clay[(b)]		Year 1 – 0.16[(c)]
Clay Till		Year 2 – 0.08
LGU		Year 3 – 0.05
		Year 4 – 0.04
		Year 5 – 0.03
Sand Till	0	0

Notes:
(a) B-Bar excess pore water pressure due to loading added to static water level (assumed to be at original ground surface).
(b) B-Bar values for two-dimensional stability analyses for the wick drain early refusal area vary based on depth, fill height, clay thickness and dissipation time, and are presented on the Figures 1-6. A B-Bar of 1.0 was conservatively used for the wick drain early refusal areas for three-dimensional stability analysis to reduce complexity and add conservatism.
(c) B-Bar for Years 1 to 6 are applicable to UGU, Silt and Clay, Clay Till and LGU units.

6 STABILITY ASSESSMENT

The assessment utilized both two-dimensional and three-dimensional slope stability analyses for each of the construction years. As the minimum required factors of safety were not achieved using two-dimensional slope stability analyses, three-dimensional analyses were carried out to more accurately represent the complex geometry introduced by the early refusal wick drain installation depth in these areas.

Two-dimensional (plane strain) slope stability analysis assumes that the shear resistance mobilized along a potential slip surface in silty clay with the same dimension over long (infinite) areas. This is not representative of the actual ground condition and geometry that has finite dimensions. Where early refusal of wick drains occurs, a two-dimensional failure surface passes under the early refusal area (below the wick drain zone) and with the active wedge (entry slope) within the interior normally consolidated clay foundation, bypassing entirely or in-part the area of wick drains ground improvement. Two-dimensional analysis, therefore, is very conservative and likely not representative of the actual stability condition.

For slope instability to occur in three-dimensions, the side slopes of any failure surface must also shear through the wick drain ground improvement zone. The additional shear resistance mobilized with the side slopes of a three-dimensional failure surface passing through the wick drain zone can be significant at the scale of the early refusal areas considered, which are not accurately considered in a two-dimensional stability analysis.

The two-dimensional slope stability analysis was carried out using a combination of Geostudio 2020 Slope/W software version 10.2.1.1 and Slide2 software version 9.012, developed by Seequent and Rocscience Inc., respectively. The three-dimensional slope stability analysis was carried out using Slide3 software Version 3.010 developed by Rocscience Inc.

The stability analyses presented herein represents the end of the stockpile construction for those sections. Analyses were carried out for static undrained shear strength (total stress), slickensided (effective stress analysis) and pseudo-static conditions.

7 TWO-DIMENSIONAL SLOPE STABILITY ANALYSIS

7.1 Methodology

Two-dimensional slope stability analyses were carried out using the limit equilibrium method of slices. The Morgenstern-Price method was used where the inter-slice shear forces were represented with a half-sine function. The FoS, defined as the ratio of the forces resisting failure over the forces driving failure, was computed for numerous potential failure surfaces and the lowest FoS that causes a deep-seated failure was chosen as the minimum FoS. Following the U.S. Army Corps of Engineers (2003) recommendation, the failure was checked using different slip surface search methods.

7.2 Design Controlling Sections

The primary controlling stratigraphic factors that impact the stability of the stockpile are height, the foundation clay thickness, the sloping topography and the location and extent of the early refusal area. Sections were developed for Area A and B that represent a reasonable ‘worst-case’ geometry and soil profile and were used in the slope stability analysis.

7.3 Results

The results of the two-dimensional slope stability analysis for each wick drain early refusal area at the end of construction for Areas A and B are shown in Figures 1 to 6, and a summary of the minimum FoS determined at the end of construction are presented in Table 3. The results indicate that the design criteria (minimum FoS of 1.3 for undrained condition, 1.1 for slickensided condition and 1.0 for pseudo-static condition) are not obtained.

Table 3: Two-Dimensional Slope Stability Analysis Results

Stability Area	Factor of Safety		
	Static Undrained	Slickensided	Pseudo-Static
A	1.1	1.0	1.0
B	0.5	0.7	0.6

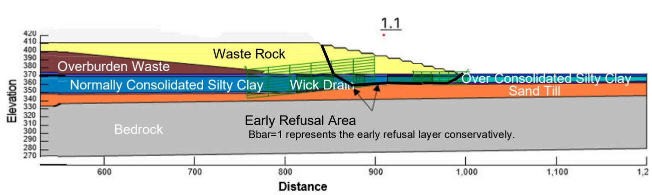

Figure 1. Area A Two-Dimensional Slope Stability Analysis – Undrained Condition

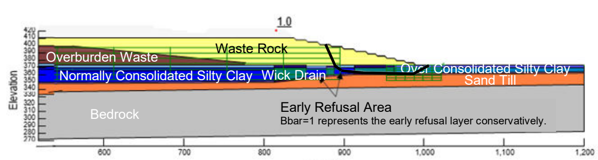

Figure 2. Area A Slope Two-Dimensional Stability Analysis – Slickensided Condition

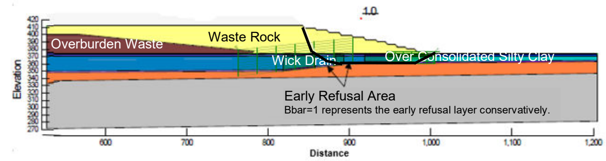

Figure 3. Area A Slope Two-Dimensional Stability Analysis – Pseudo-static Condition

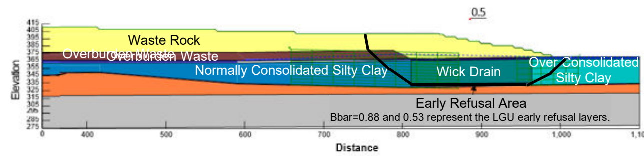

Figure 4. Area B Slope Two-Dimensional Stability Analysis – Undrained Condition

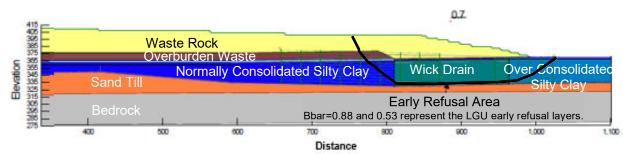

Figure 5. Area B Two-Dimensional Slope Stability Analysis – Undrained Condition

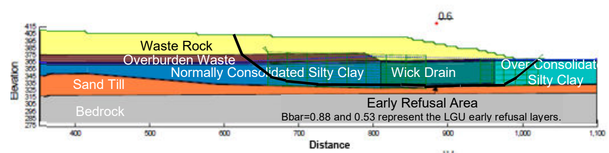

Figure 6. Area B Two-Dimensional Slope Stability Analysis – Undrained Condition

8 THREE-DIMENSIONAL SLOPE STABILITY ANALYSIS

8.1 Methodology

Three-dimensional slope stability analyses were carried out using the limit equilibrium method. The Morgenstern-Price method was used, in which the inter-column shear forces were represented with a half-sine function. Like two-dimensional analysis, the FoS, defined as the ratio of the forces resisting failure over the forces driving failure, was computed for numerous potential failure surfaces and the lowest FoS passing through the wick drain early refusal area was chosen as the minimum FoS.
Potential failure surfaces were identified using the Particle Swarm Search method and verified with the Cuckoo Search method. Ellipsoid failure surfaces were considered allowing block failure modes along the base of the foundation clay. Surface altering optimization was completed on slip surface having the lowest initial FoS.

8.2 Geometry

The three-dimensional model was developed first by uniformly extending the two-dimensional design controlling section horizontally into the third dimension. The lateral extent of the wick drain early refusal area was then trimmed to match the actual dimensions. This simplified approach provides a conservative representation of the three-dimensional geometry, as the worse-case topography and foundation clay thickness are considered along the third dimension. This simplified approach was used for Areas A. For Area B, this simplified approach demonstrated a minimum FoS marginally below the design criteria requirement. Accordingly, a more complex and representative three-dimensional geometry was generated.

For the latter case, the triangular irregular network (TIN) surfaces in Autodesk Civil3D 2021 CAD modeling software were used and the modelling was carried out based on the as-built wick drain and stockpile information, the original ground topography, the interpreted clay thickness from geotechnical investigation and wick drain installations, and the ultimate stockpile design. Modeled three-dimensional surfaces included:

- the ultimate stockpile;
- the internal overburden stockpile;
- the original ground surface;
- the base of combined clay foundation units (UGU, Clay Till, and LGU);
- the limits of wick drain installation; and
- the early refusal area.

The three-dimensional surfaces were then imported into Rocscience Slide3 software. The foundation soil clay units (UGU, Clay Till and LGU) were combined to reduce model complexity, with material properties of Clay Till conservatively applied to the full foundation clay volume. Furthermore, no strength gain was assumed in the early refusal areas, conservatively.

The design phreatic surface was generally taken to be at the original ground surface. For Area B an elevated phreatic surface was used due to the ponding water at the stockpile toe.

8.3 Results

The results of the three-dimensional slope stability analysis for each wick drain early refusal area are shown in Figures 7 to 14. A summary of the minimum FoS determined for each of the areas is presented in Table 4. The results of the three-dimensional stability analysis indicate that the minimum FoS of 1.3 for undrained condition, 1.1 for slickensided condition and 1.0 for pseudo-static condition are satisfied for the early refusal areas.

Table 4: Three-Dimensional Slope Stability Analysis Results

Stability Area	Factor of Safety		
	Static Undrained	Slickensided	Pseudo-Static
Area A	1.5	1.1	1.4
Area B	1.3	1.2	1.2

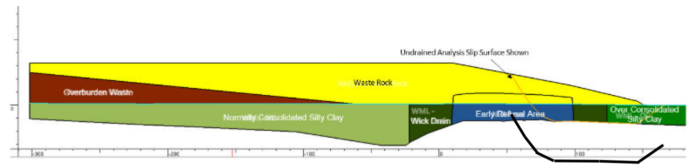

Figure 7. Area A Cross Section Through Three-Dimensional Analysis Slip Surface

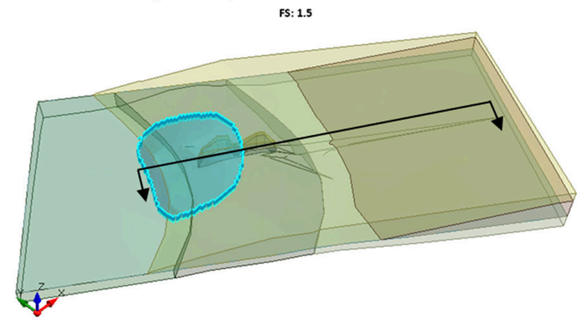

Figure 8. Area A Three-Dimensional Slope Stability Analysis – Undrained Condition

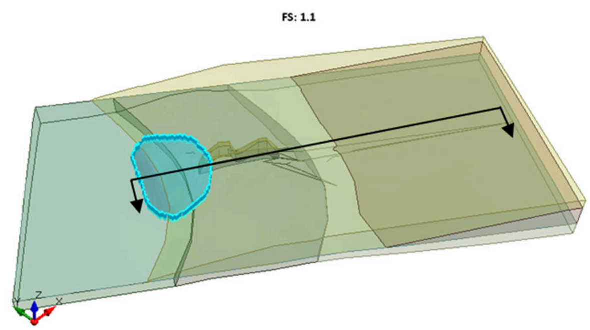

Figure 9. Area A Three-Dimensional Slope Stability Analysis – Slickensided Condition

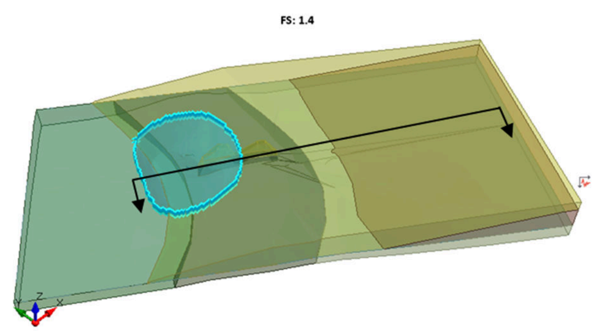

Figure 10. Area A Three-Dimensional Slope Stability Analysis – Pseudo-Static Condition

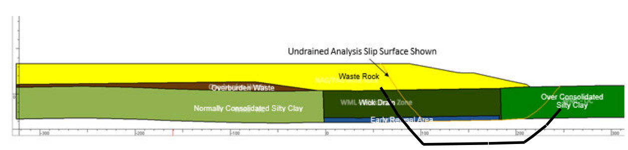

Figure 11. Area B Cross Section Through Three-Dimensional Analysis Slip Surface

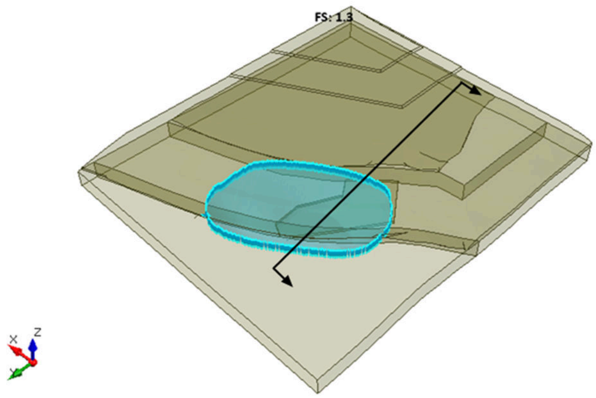

Figure 12. Area B Three-Dimensional Slope Stability Analysis – Undrained Condition

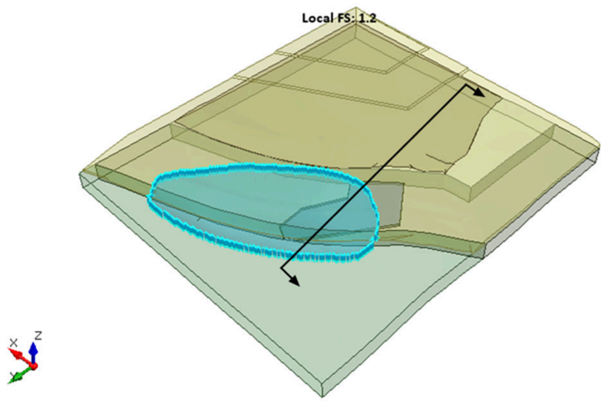

Figure 13. Area B Three-Dimensional Slope Stability Analysis – Slickensided Condition

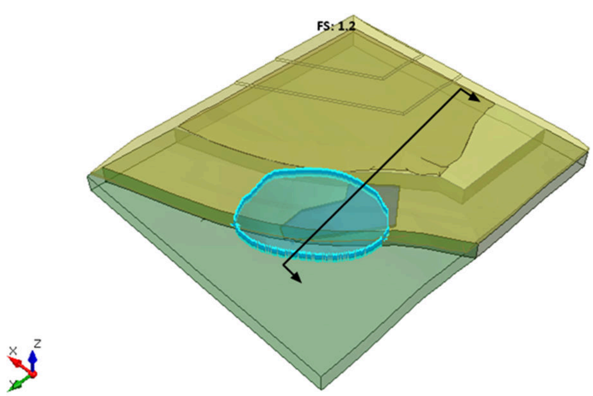

Figure 14. Area B Three-Dimensional Slope Stability Analysis – Pseudo-Static Condition

A sensitivity analysis was carried out for Area B, where the two-dimensional model was extended far enough in the third dimension so that the three-dimensional model approximates the two-dimensional model plane strain condition. As shown in Figure 15, as the the non-conformance length is extended to more than 950 m, the three-dimensional FoS is approaching the two-dimensional FoS. Assuming all wick drains were installed to the design depth, the results from the three-dimensional analysis extension of the two-dimensional analysis indicates about 20% increase of the FoS, which is within the range expected for similar conditions reported in the literature. For the sensitivity analysis, the maximum thickness of clay observed within Area B was used, which is more conservative than the design section analyzed. In reality, the maximum observed clay is within a limited concave shape and not representing the actual site condition. For the case of actual foundation geometry (i.e. non-uniform combined clay thickness), the three-dimensional FoS of 1.3 noted in Table 4 increases to 1.5.

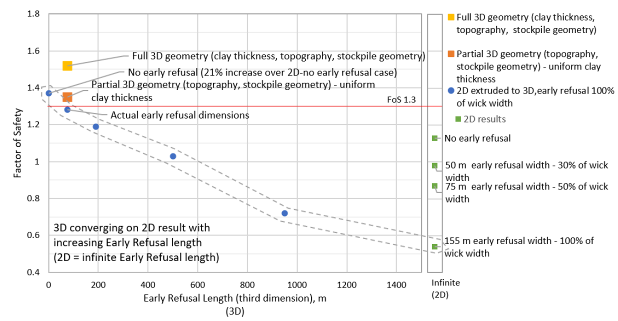

Figure 15. Area B Sensitivity Analysis

9 INSTRUMENTATION

Instrumentation was installed to monitor the geotechnical performance of the foundation clay at the critical locations, where the wick drains did not penetrate to the design depth. The installed instrumentation consists of:

- Vibrating Wire Piezometers (VWPs)
- Settlement Plates (SPs)
- Slope Inclinometers (SIs)

VWPs were installed to measure the excess pore water pressure following loading. SPs were installed to measure the consolidation settlement of the clay and SIs were installed to measure the lateral ground movement and to identify the development of a shear layer within the foundation clay.

Figure 16 presents the data observed for an SI installed at Area B, where the wick drains had early refusals. As shown, the observed displacements are minimal and within the acceptable ranges. The data obtained from the instruments agree with the results of the three-dimensional slope stability analysis.

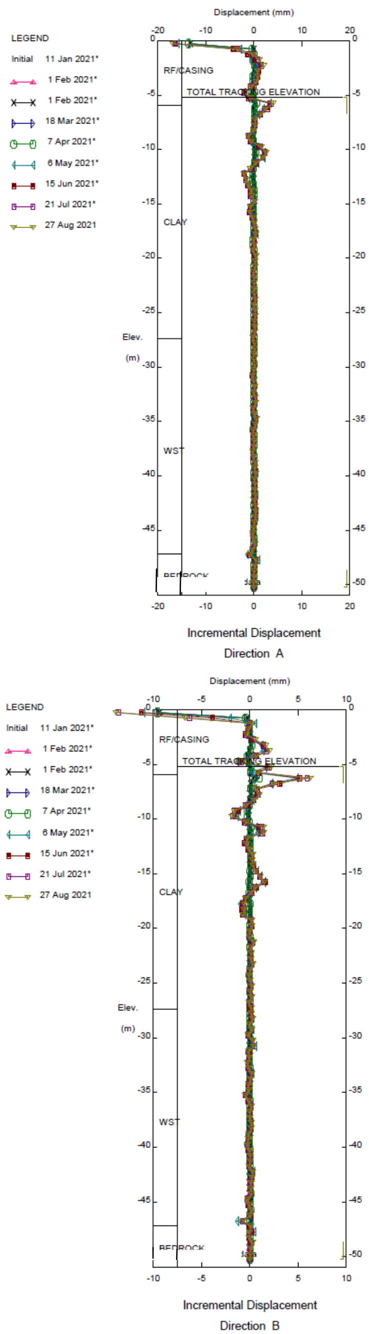

Figure 16. Slope Inclinometer results

10 CONCLUSIONS

The two-dimensional analyses results indicate that the minimum required FoS is not satisfied for the wick drain early refusal areas. Significant reduction in the stockpile capacity would be required to satisfy the two-dimensional FoS for these areas. However, based on the results of the three-dimensional stability analyses, no design changes are required. This is due to the fact that the partially installed wicks drains provide sufficient strength gain during loading of stockpile construction at the two ends of the three-dimensional slide surface, resulting in achieving the minimum required FoS. This three-dimensional effect cannot be adequately modeled in the two-dimensional stability analysis.

Monitoring and instrumentation indicate that the performance of the stockpile is acceptable, and the foundation displacements are within the tolerable ranges.

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