INTEGRATED APPROACH TO RAPIDLY ITERATE THROUGH LEA STABILITY ANALYSES FOR DESIGN OF STAGED CONSTRUCTION OVER SILTY CLAY SOILS

AUTHORS
Amy L. Adams, Ph.D., P.Eng., P.E, Senior Engineer, Knight Piésold Ltd., North Bay, Ontario, Canada
Jessica Breault, P.Eng., .ing, Senior Engineer, Knight Piésold Ltd., North Bay, Ontario, Canada
Reagan McIsaac, Ph.D., P.Eng., Specialist Engineer, Knight Piésold Ltd, North Bay, Ontario, Canada
Gabriel Ploudre, Mill Manager, Orezone Québec Inc., Casa Berardi Mine, La Sarre, Québec, Canada
Dominic Girard, Tailings Facility Coordinator, Orezone Québec Inc., Casa Berardi Mine, La Sarre, Québec, Canada

ABSTRACT

Staged construction of large embankments over silty clay soils requires a detailed understanding of the variation in strength with effective stress as well as careful prediction and monitoring of changes in pore pressure which affect effective stress. The pore pressure, effective stress, and strength of silty clay foundation soils can vary laterally, vertically, and with time. Staged construction requires even more careful planning and monitoring if pore pressures from previous stages do not have time to fully dissipate before the next stage of construction and the pore pressure profile becomes highly variable in space and time.

This paper describes an integrated methodology that has been developed to rapidly iterate through design of a staged embankment over silty clay soils using Limit Equilibrium Analysis (LEA). The approach uses a single soil strength model to evaluate strength ranging from drained (frictional) at low effective stress to undrained (strength ratio) at higher effective stress, eliminating the need to divide the foundation into different behavioural zones and addressing several common errors in slope stability analyses as summarized by Brown and Gillani (2016). Effective use of the integrated method is illustrated via a case history for a large mining embankment that was raised over silty clay foundations over the last four years. The integrated method was used to develop the initial design, develop Factor of Safety (FoS) based trigger levels, and respond quickly to proposed changes in the construction schedule that would impact overall stability.

RÉSUMÉ

La construction par étapes de grands remblais sur des sols d'argile silteuse exige une compréhension détaillée de la variation de la résistance en fonction de la contrainte effective, ainsi qu'une prévision et un suivi rigoureux des variations de la pression interstitielle, lesquelles influencent cette contrainte effective. La pression interstitielle, la contrainte effective et la résistance des sols de fondation en argile silteuse peuvent varier latéralement, verticalement et avec le temps. Une construction par étapes nécessite une planification et un suivi encore plus minutieux si les pressions interstitielles générées lors des étapes précédentes n'ont pas eu le temps de se dissiper complètement avant la prochaine étape de construction, et le profil des pressions interstitielles devient hautement variable dans l'espace et dans le temps.

Cet article décrit une méthodologie intégrée élaborée afin de procéder à des itérations rapides lors de la conception d'un remblai construit en étapes sur des sols d'argile silteuse, à l'aide de l'analyse d'équilibre limite (AEL). Cette approche fait appel à un modèle unique de résistance du sol pour évaluer la résistance, allant d'un comportement drainé (frottement) à de faibles contraintes effectives, à un comportement non drainé (rapport de résistance) à des contraintes effectives plus élevées. Cela élimine la nécessité de diviser

la fondation en différentes zones de comportement et permet de corriger plusieurs erreurs courantes dans les analyses de stabilité des pentes, comme résumé par Brown et Gillani (2016). L'utilisation efficace de cette méthode intégrée est illustrée par une étude de cas portant sur un remblai minier grand, lequel a été surélevé sur des fondations d'argile silteuse au cours des quatre dernières années. La méthode intégrée a été utilisée pour élaborer la conception initiale, définir des seuils de déclenchement basés sur le facteur de sécurité, et réagir rapidement aux modifications proposées à l'échéancier de construction qui auraient eu une incidence sur la stabilité globale.

1 INTRODUCTION

Staged construction of large embankments such as water or tailings dams, mine waste piles, or civil engineering infrastructure, over silty clay foundation soils requires a detailed understanding of the variation in strength with effective stress as well as careful prediction and monitoring of changes in pore pressure which affect effective stress. The pore pressure, effective stress, and strength of silty clay foundation soils can vary laterally (both along the structure, and perpendicular to the structure), vertically, and with time. Staged construction requires even more careful planning and monitoring if pore pressures from previous stages do not have time to fully dissipate before the next stage of construction. In this case, the pore pressure profile can become highly variable in space and time. Changes in the construction schedule can significantly impact performance and stability and must be carefully (and sometimes quickly) evaluated. For these reasons, the critical time for stability of embankments constructed over silty clay foundation soils is often during construction.

This paper describes an integrated methodology that has been developed to rapidly iterate through design of a staged embankment over silty clay foundation soils using Limit Equilibrium Analysis (LEA). The approach uses a single soil strength model for a lightly overconsolidated silty clay foundation soil to evaluate strength ranging from drained (frictional) at low effective stress to undrained (strength ratio) at higher effective stress. The use of a single soil strength model eliminates the need to divide the foundation into different behavioural zones, streamlining design iterations by focusing on varying the geometry (and thus applied load) of the embankment, and addresses common errors in slope stability analyses related to embankments constructed over silty clay foundations as summarized by Brown and Gillani (2016). Construction induced pore pressures are estimated and integrated into the stability analyses as B-Bars that are estimated via separate simplified consolidation models during the design phase, and measured values during construction. The integrated methodology described herein is applicable to the design of any type of embankment over a silty clay foundation soil, including tailings dams, water dams, mine waste storage piles, or civil engineering infrastructure.

Effective use of the integrated method is illustrated with the case history of a large mining embankment that was raised over silty clay foundations over the last four years. The definition of the soil strength model based on site investigation results and development of the B-Bar model are summarized. Two soil strength models were developed to incorporate stress-strain concepts and to meet regulatory design criteria: one for peak strengths; and one for residual (softened) strengths. The soil strength models allowed for more rapid evaluation of the Factor of Safety (FoS) for different slip surfaces (circular, block) and different configurations to efficiently define a final design geometry and the required construction sequence. The integrated method was also useful to verify stability with monitoring data during construction, update the construction sequence in response to changing conditions, as well as to develop Factor of Safety (FOS) based trigger levels for Vibrating Wire Piezometer (VWP) readings.

2 BACKGROUND

2.1 Strength and Behaviour of Silty Clay Soils under Loading Conditions

The strength and behaviour of silty clay soils are variable depending on the effective stress, stress history, and strain rate. This subject is discussed in detail by many authors including but not limited to Terzaghi et al. (1996), Ladd and Foott (1974), Ladd and DeGroot (2003), and EM 1110-2-1902 (USACE, 2003), and more recently summarized by Brown and Gillani (2016) and Shewbridge (2019). In general, silty clay soils behave in a drained and frictional manner at very low strain rates, and low effective stresses generally two to four times (Shewbridge et al, 2019) lower than the maximum past pressure. The transition to undrained behaviour occurs as the strain rate increases and/or the effective stress increases. Normally consolidated

silty clays, where the current effective stress is the highest ever experienced by the soil structure, generally behave in an undrained manner at the strain rates applied by most civil engineering structures.

The strength and behaviour of silty clay soils under loading conditions, such as in the foundation of a large embankment can be measured and evaluated in different ways depending on the consolidation and drainage conditions as follows:

- Unconsolidated, Undrained (UU) Analysis: This approach uses a fixed value of undrained strength as illustrated in Figure 1(a) and is generally representative of rapid, short term loading at potentially high strain rates. The undrained shear strength value incorporates both load induced and shear induced pore pressures. This approach is based on the Q test as summarized by EM 1110-2-1902 (USACE, 2003).
- Consolidated, Undrained (CU) Analysis: This approach varies the undrained strength with effective stress as illustrated in Figure 1(b) and is generally representative of moderate to long term loading at moderate to high strain rates. The undrained shear strength incorporates shear induced pore pressures. This approach is based on the R test as summarized by EM 1110-2-1902 (USACE, 2003).
- Consolidated, Drained (CD) Analysis: This approach varies the drained strength with effective stress (often effective normal stress by means of a friction angle) as illustrated in Figure 1(c) and is generally representative of long term loading at low strain rates. The strength does not incorporate pore pressures. This approach is based on the S test as summarized by EM 1110-2-1902 (USACE, 2003).

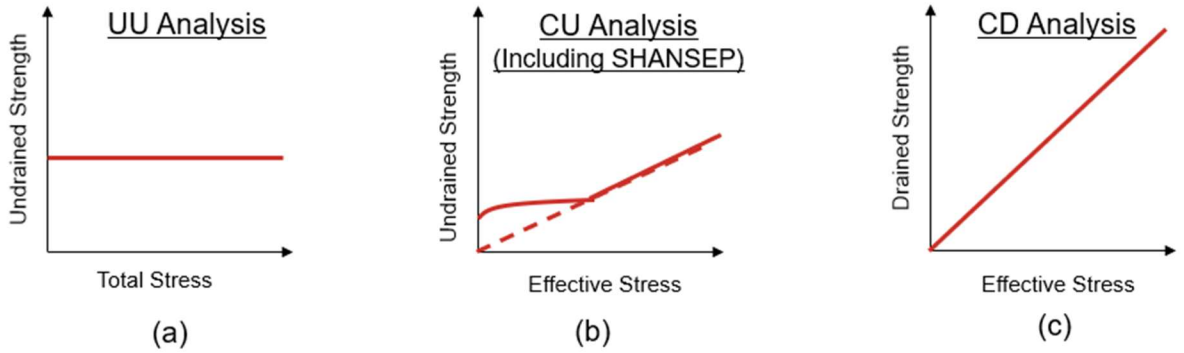

Figure 1: Soil models and analysis types for silty clay soils (a) Unconsolidated, Undrained (UU) Analysis, (b) Consolidated, Undrained (CU) Analysis, (c) Consolidated, Drained (CD) Analysis.

The Stress History and Normalized Soil Engineering Properties (SHANSEP) method developed by Ladd and Foott (1974) is a type of Consolidated Undrained Analysis that uses an undrained strength ratio that varies as a function of the stress history (overconsolidation ratio) to estimate the undrained strength for different effective stresses and is illustrated by the solid line on Figure 1(b).

In addition to varying with effective stress, degree of consolidation, and drainage conditions, the strength of silty clay soils also vary with the mode of shear. Shear modes may vary from compression shear where the soil is being compressed, such as near the top of a slope, through extension shear where the soil is in tension, such as at the toe of a slope as illustrated on Figure 2. Simple shear occurs near the middle of the slip surface where the forces are primarily horizontal. In general, silty clays are strongest in compression shear mode and weakest in extension shear mode, with simple shear mode representing an average between compression and extension shear mode (Ladd and DeGroot, 2003).

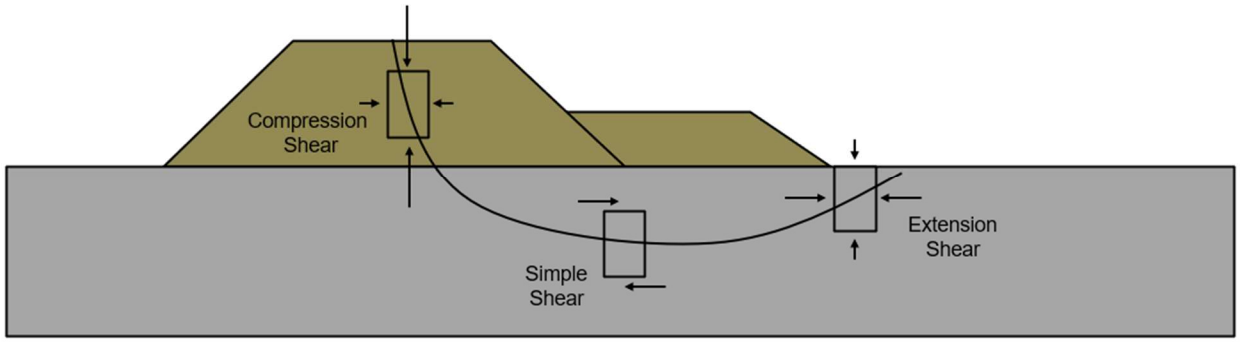

Figure 2: Types of shear in embankment loading (after Terzaghi et al, 1996; Ladd and DeGroot, 2003)

Finally, the undrained strength ratio of silty clay soils also varies (increases) with increasing plasticity index, especially for simple shear and extension shear modes (Ladd and DeGroot, 2003).

2.2 Common Method and Errors in Slope Stability Analyses

To evaluate the stability of a large embankment, the engineer must first consider the range of strength and behaviour in the materials, especially silty clay foundations, over the life cycle. The strength and behaviour of the materials prior to construction, as measured during initial site investigations, is often not representative of the strength and behaviour during or following construction of the embankment. The key difference between these time periods, before and after construction, is related to the long term change in effective stress and the short term change in pore pressures that occurs as a result of construction of the embankment.

Brown and Gillani (2016) provide a general overview of different critical aspects that should be considered as part of a stability evaluation, including shear strength envelopes, pore pressure estimation, and methods of analyses. Based on this, they highlight several common errors in slope stability analyses related to embankments constructed over silty clay foundations, including the following:

1. Ignoring construction induced pore pressures, shear induced pore pressures, or both in stability analyses
2. Adopting an undrained strength that is higher than the drained strength
3. Ignoring changes in behaviour from overconsolidated to normally consolidated states with increasing effective stress (loading from the embankment)
4. Defining strength based on site investigation measurements evaluated using hydrostatic pore pressure profiles, especially in materials that are actively consolidating with excess pore pressures

These four common errors in slope stability analyses are linked by a single commonality – pore pressure. The pore pressure controls the effective stress, which in turn controls strength. It is thus paramount that the engineer develops a clear understanding of the variation in pore pressure over space and time and accurately incorporates this into the stability modelling.

3 CHALLENGES WITH EXISTING SOIL STRENGTH MODELS

The challenge of relying upon a single soil model, such as the UU, CU, or CD analysis method illustrated on Figure 1, is that the soil model will overestimate the strength over a specific range of effective stress, resulting in an overestimated FoS. This is especially true for the effective stress CU and CD analysis methods, illustrated on Figure 3, which account for changes in effective stress with loading.

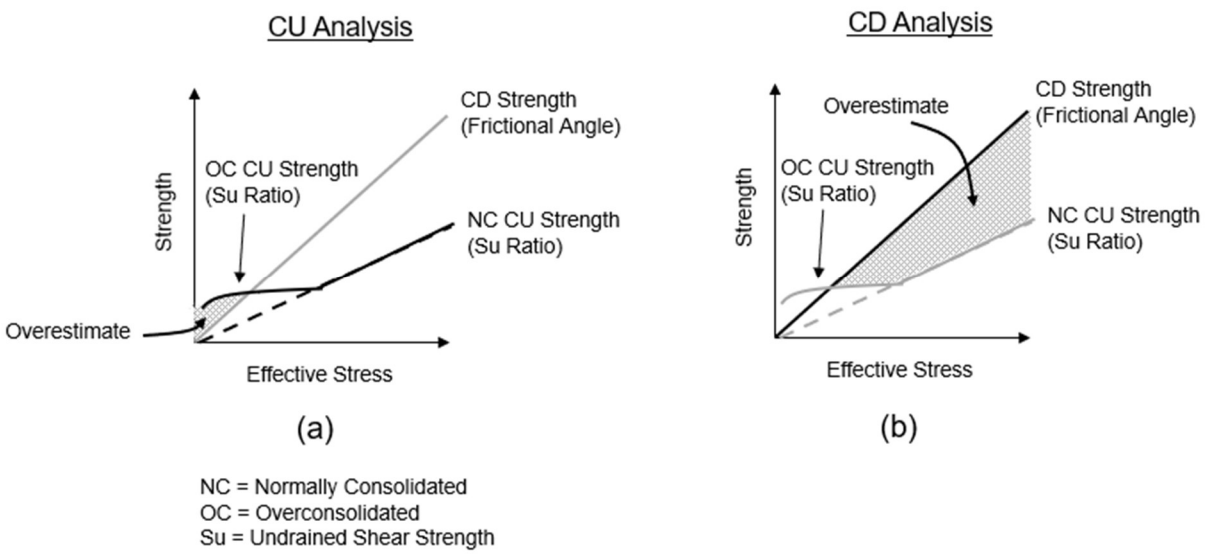

Figure 3: Overestimate of shear strength using (a) CU and (b) CD effective stress analysis methods

As shown on Figure 3, the CU Analysis represents the lowest strength at moderate and high effective stress but over estimates the strength at low effective stress which is characteristic of the toe of the slope. The over estimate of strength at low effective strength is further compounded as the shear mode at the toe of a slope is extension shear (Figure 2), which generally has a lower undrained shear strength than simple shear or compression shear modes representative of the remainder of the slope. This over estimate is the same as common error No. 2 summarized above (Brown and Gillani, 2016) which relates to adopting an undrained strength that is higher than the drained strength.

Conversely, the CD analysis represents the highest strength at moderate to high effective stress, largely due to the fact that the influence of shearing induced pore pressures is not included in the strength. The CD analysis could be made to give the same result as the CU analysis at moderate to high effective stress if the shear induced pore pressures were included in the Effective Stress term, however this is challenging to incorporate and is rarely attempted.

Historically, the challenges summarized above were accounted for by doing both a CU and a CD analysis, as summarized by Shewbridge (2019). This approach of calculating the FoS using two different methods was computationally straight forward and is unfortunately still common today. The magnitude of the error associated with this approach will vary for every analysis depending on the range of effective stress along the slip surface.

Another approach that is sometimes used is to sub-divide the foundation into different zones as illustrated on Figure 4, with each zone representative of a range of effective stress to which an appropriate analysis method is applied. The zones may be sub-divided horizontally, as shown in Figure 4, vertically, or both horizontally and vertically.

In the example shown in Figure 4, the toe of the slope is assigned a CD strength model using a friction angle to model the strength at low effective stress and in extension shear mode, while areas under higher embankment loading are assigned CU strength models with varying values of undrained shear strength ratios. This approach can be straight forward to evaluate the stability of an existing embankment configuration, especially when site investigations can be undertaken to evaluate the lateral and vertical variation in strength that can be directly input into the stability model. Subdividing the foundation becomes

complex and time consuming when used for design where the sub-divisions need to be adjusted for each geometry iteration to account for changing effective stress. The challenge associated with sub-dividing the foundation while varying the embankment geometry is illustrated by comparing Figure 4 (a) and Figure 4 (b).

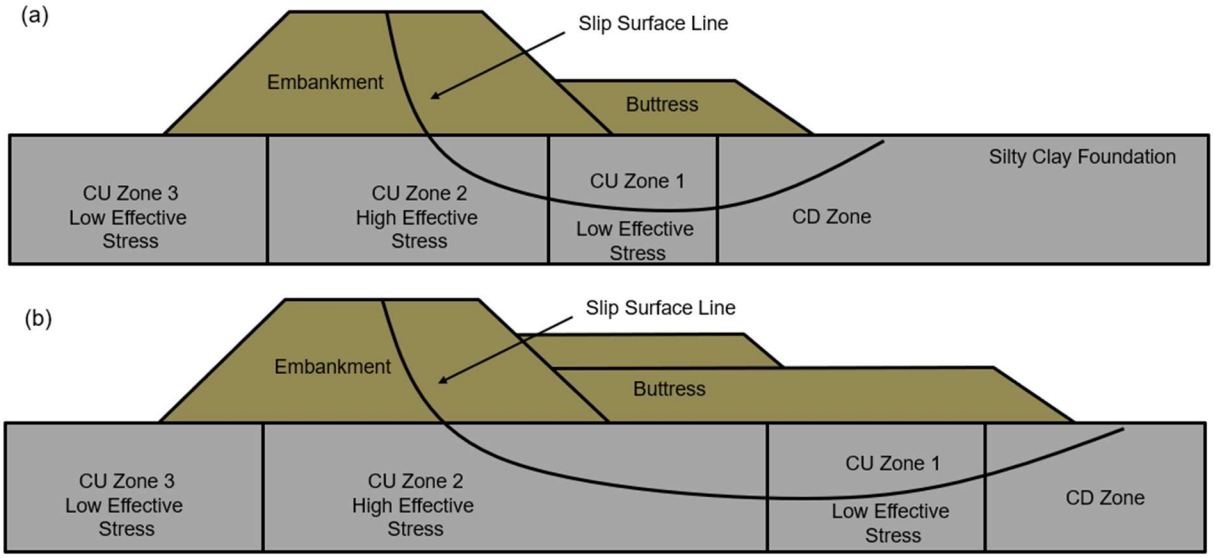

Figure 4: Analysis approach involving sub-dividing the foundation into different zones to which different strength models (analysis methods) (a) initial iteration with small buttress; and (b) second iteration with a larger buttress

4 INTEGRATED APPROACH

4.1 General

An integrated approach has been developed to simplify stability analyses for design of large embankments over silty clay foundations while improving accuracy of the analysis and computed FoS. The integrated approach uses two key components as follows:

1. A combined soil model, which relates strength and effective stress over a range of effective stresses and incorporates both drained and undrained strength models for the silty clay foundation soil.
2. A construction-induced pore pressure model, which addresses the temporal and spatial variance of the load induced pore pressure.

These components are further described in the following sub sections.

3.2 Combined Soil Model

The combined soil model incorporates both CU and CD soil strength models into a single model that can be input as a custom function of strength vs. effective stress as illustrated on Figure 5. The combined soil model uses the concept illustrated by Shewbridge (2019) as part of an overlay of SHANSEP, fully softened, and critical state concepts with the USACE design envelopes (Q, R, S). Herein the combined soil model is defined on axis of strength vs. vertical effective stress which is most correct for the CU portions of the model. It is recognized that there will be a slight error associated with use of vertical effective stress for the CD portion of the model which is usually defined with a friction angle and varies with normal effective stress. This error is small compared to other approaches as summarized above. Commercial slope stability

analysis programs such as Slope/W (Bentley, 2026) allow for user input strength vs. effective stress functions (SHANSEP - Function).

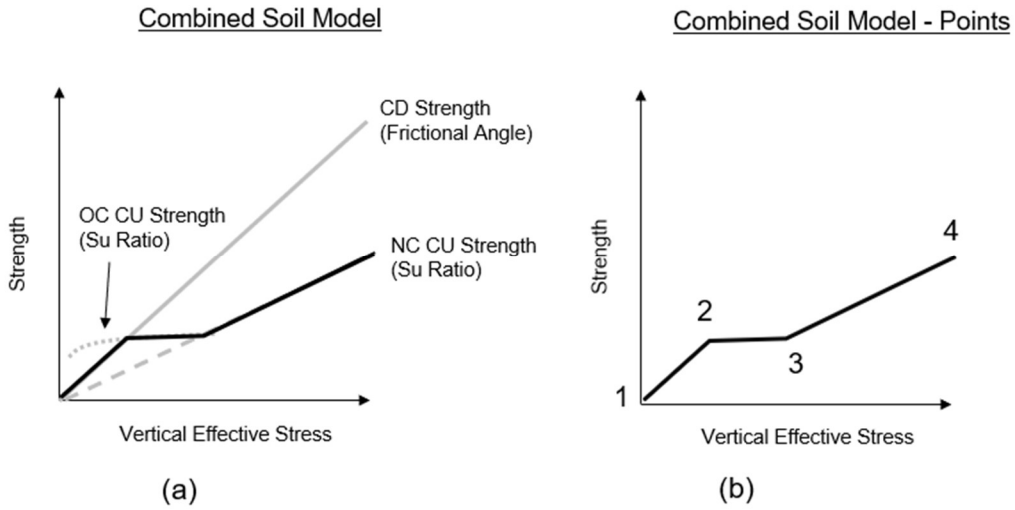

Figure 5: Combined Soil Model – Strength vs. Effective Stress

The combined soil model can be defined in different ways; the approach used by the authors for ranges of effective stress between about 0 and 1,000 kPa is to define it based on four points and the following soil parameters which are easily obtainable from site investigations:

- Effective Friction Angle (φ'): Estimated from typical correlations with index properties or material type (i.e. Carter and Bentley, 2016), measured directly using drained (CD) or undrained (CU) triaxial tests, or interpreted from Cone Penetration Tests (CPTs).
- Minimum Undrained Shear Strength (Su min): Measured with in situ field vane measurements that are run fast enough to maintain undrained conditions. Alternatively, the Su min could be estimated by testing intact specimens in the UU triaxial cell in the laboratory under appropriate confining pressures representative of the in situ condition. Sample disturbance will affect the UU triaxial result and this should be considered in the analysis.
- Normally consolidated undrained shear strength ratio (Su/σ'_{vo}): Estimated from typical correlations with plasticity index and index properties (Ladd and DeGroot, 2003) or measured in the laboratory using CU triaxial tests or Direct Simple Shear (DSS) tests. DSS tests are preferred by the authors for most projects as the dominate shear mode in silty clay foundations below large embankments is typically simple shear. Caution is recommended in interpreting the Su/σ'_{vo} based on field vane or cone penetration test (CPTs) as these tests are representative of the in situ condition at the time of testing and often do not reflect changes in soil strength and behaviour with increased effective stress due to loading.

The X (vertical effective stress) and Y (strength) coordinates for each point of the combined soil model illustrated on Figure 5(b) are summarized in Table 1 based on the key input parameters.

Table 1: X,Y coordinates for the combined soil model points based on the key input parameters

Point	X Vertical Effective Stress	Y Strength
1	0	0
2	Su min / tan (φ')	Su min
3	Su min / Su/σ'_{vo}	Su min
4	High # *	High # x Su/σ'_{vo}

* High # should represent an effective stress that is larger than the highest effective stress being modelled; typically 1,000 kPa or more.

Based on the above, the authors apply a naming scheme to the combined soil models used. A combined soil model based on a friction angle of 32 degrees, a minimum undrained shear strength of 20 kPa, and a normally consolidated undrained shear strength ratio of 0.22 is referred to as a 32-20-0.22 soil model. This helps identify the different material models, especially when multiple models are used for a stability analysis, such as to represent different strain conditions (i.e. peak strength or residual strength) or different silty clay foundation layers.

4.2 Construction Induced Pore Pressure Model

The combined soil model is defined based on vertical effective stress and incorporates both CU and CD methods. Shear induced pore pressures are implicit in the CU strengths but load induced pore pressures are not and must be carefully defined in order to calculate the correct vertical effective stress. The load induced pore pressures will vary with time and the construction schedule (number of stages, timing of each stage). The load induced pore pressures are most important for the end of construction stability analysis where the embankment loads are applied and cause a rapid increase in pore pressure followed by gradual dissipation of pore pressure as shown on Figure 6. Decrease in pore pressure is accompanied by increase in effective stress and strength gain following the combined soil model (Figure 5).

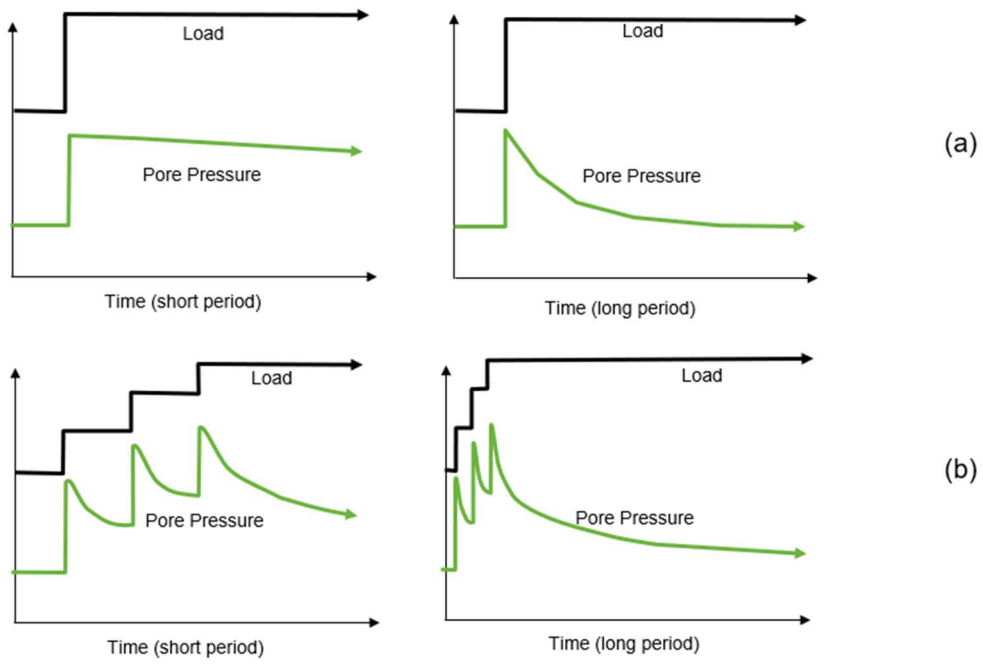

Figure 6: Conceptual variation in pore pressure over time following construction (a) single stage and (b) multi-stage construction

There are different approaches to evaluate construction induced pore pressure and the best approach will vary by project. A detailed explanation of these calculations is not within the scope of this paper. Realistic estimates can be obtained using one dimensional consolidation theory (e.g. Terzaghi et al, 1996). Increases in pore pressure can be readily incorporated into slope stability programs such as Slope/W (Bentley, 2026) using the B-Bar functionality which increases the pore pressure as a percentage (B-Bar) of the applied load (Add Weight). It is recommended that the pore pressure be computed in real units (i.e. kPa) and that it be converted to equivalent B-Bars based on the add weight that will be applied in the model such that the product of the B-Bar and Add Weight equal the desired pore pressure.

4 CASE HISTORY

4.1 Project Overview

Use of the integrated approach is illustrated via a case history for the design of a large rockfill embankment that was constructed over thick silty clay foundations to raise the Tailings Facility Cell 7 at the Casa Berardi Mine located in Western Quebec.

A typical section of the Cell 7 embankment is illustrated on Figure 7, showing the historic embankment portion and the raised embankment design.

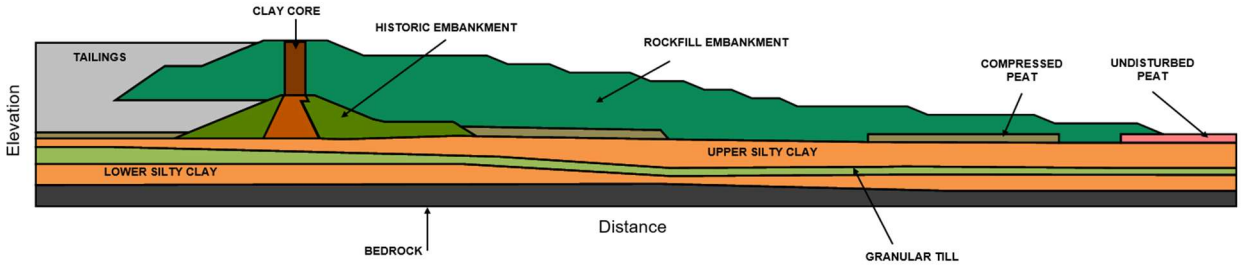

Figure 7: Typical section of the South Embankment at the Tailings Facility Cell 7, Casa Berardi Mine.

The Cell 7 embankment is a centerline embankment of compacted rockfill with a clay core. The historic embankment was constructed to crest El. 5,011.5 m (local mine elevation datum) and is being incrementally raised by 12.5 m to a final crest El. 5,024.0 over approximately 6 years (i.e. approximately 2 m/year rate of rise). The foundations comprise a thick layer (approximately 2 to 10 m thick) of lightly overconsolidated to normally consolidated soft silty clay (referred to as the Upper Silty Clay) overlying a dense Granular Till, a very dense Lower Silty Clay, and bedrock. The focus of this work is on the South Embankment that is being constructed on virgin (i.e. previously undisturbed) silty clay foundations. The final embankment geometry includes wide buttresses with overall slope angles (from downstream crest to downstream toe of the buttress) that range from approximately 8H:1V to 10H:1V along the length of the embankment depending on the varying foundation conditions. The design is governed by the end of construction stability analysis incorporating construction induced pore pressures as well as the long term residual strength analysis incorporating post peak softened strength in the silty clay foundation soils. The design of the embankment raise was completed using limit equilibrium analysis methods and the Slope/W (Bentley, 2026) stability analysis program.

4.2 Soil Model Definition

A combined soil model was developed for both the upper and lower silty clay layers based on various site investigation data including drillhole logs, laboratory index testing, cone penetration testing, in situ Nilcon vane tests, laboratory CU triaxial testing and laboratory direct simple shear (DSS) testing on intact samples.

Two soil models were developed for the Upper Silty Clay, including one for peak strengths and one for residual (softened) strengths. The peak strength model for the Upper Silty Clay is referred to as the 32-25-0.22 model, while the corresponding residual strength model is referred to as the 32-5-0.17 model. The friction angle for both soil models was set to 32 degrees based on typical correlations (Carter and Bentley, 2016) with the median plasticity index of 21%. The minimum undrained shear strength was set as 25 kPa based on the lower bound results of in situ Nilcon vane tests and CPT tests. The peak undrained shear strength ratio was estimated as 0.22 based and the results of laboratory DSS tests at normal stresses representative of the projected embankment loading and typical correlations with plasticity index (Ladd and DeGroot, 2003). The residual strength ratio was estimated as 0.17 based on the DSS test results, statistical analysis of the residual strength estimated from the CPT analyses and was consistent with typical reductions from peak strength (Makdisi and Seed, 1978; Idriss and Boulanger, 2008). Similarly, the peak and corresponding residual strength models were developed for the Lower Silty Clay (32-50-0.22 model and 32-40-0.17 model, respectively). The combined soil models are illustrated on Figure 8 and were input as SHANSEP functions (strength vs. vertical effective stress) into the Slope/W stability analysis.

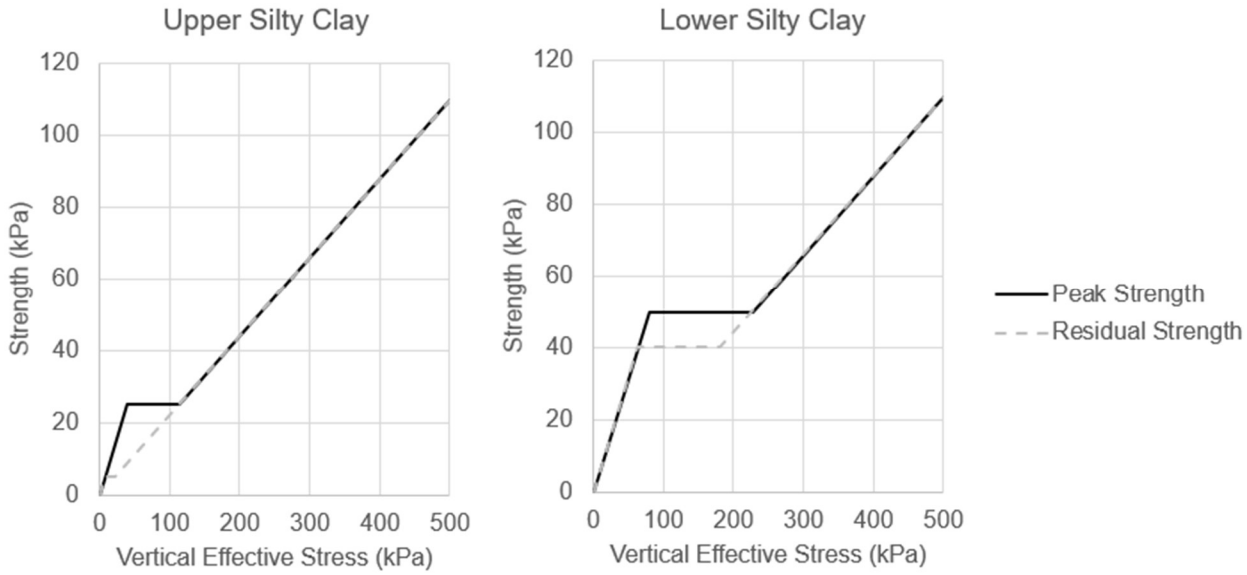

Figure 8: Combined soil models for the Upper Silty Clay and the Lower Silty Clay

4.3 Construction Pore Pressure Model

A simplified block model based on one-dimensional consolidation was initially developed for the raise to El. 5,016.3 m (i.e. the first 4.8 m raise to be completed over approximately 1 year) and is conceptually illustrated on Figure 9. The block model focused on estimating the degree of consolidation, U, at different points in time for the silty clay foundation under the buttress. The U was calculated based on methods described for one-dimensional consolidation by Terzaghi et al (1996). The B-Bar was then computed as 1-U. Using the above approach, the actual pore pressures are not computed, rather, the B-Bar is based on time and degree of consolidation only. The actual pore pressures are computed in the Slope/W model as a function of the B-Bar and Add Weight materials.

The buttress geometry was divided into nine blocks comprising three zones laterally (Zones 1, 2, and 3), and up to 4 lifts vertically (Lifts A, B, C, and D). Each lift was modelled as 2 m high for the preliminary analysis prior to defining the final configuration.

Figure 9: Simplified Block Model for Construction to El. 5,016.3 m

An approximate construction schedule was adopted whereby fill for each block (i.e. 1A or 2B etc.) would be placed over a defined period. One-way drainage (upward, to surface) was specified based on the site investigation data, though it is likely that some drainage will occur downward through the underlying

granular soils. The coefficient of consolidation for the Upper Silty Clay was estimated based on the results of one dimensional oedometer and constant rate of strain (CRS) laboratory testing results. Pore pressure generation and consolidation in the Lower Silty Clay was considered to be negligible based on the observed strength and density of the material during the site investigations.

The equivalent overall B-Bar for each zone (1, 2, and 3) at the end of each lift (A, B, C, and D) was computed by averaging the B-Bar for each block vertically. For example, the B-Bar in the foundation for Zone 1 at the end of placement of Lift C is calculated based on the following:

- Pore pressures induced by placement of Block 1A have had longer to dissipate than Block 1B and Block 1C
- The degree of consolidation for Block 1A was thus higher than Block 1B and 1C, and were calculated to the nearest 10%
- The B-Bar corresponding to placement of Block 1A was thus lower than Block 1B and Block 1C and were calculated to the nearest 0.1.
- The overall B-Bar in the foundation due to the time placement of Blocks 1A, 1B and 1C was the average of the incremental B-Bars and calculated to the nearest 0.1)

The calculations identified that the initial construction was to be completed at such a rate that there was little time for pore pressure dissipation, and a B-Bar of 0.8 was applied to the stability analysis with the Add Weight corresponding to the full fill height for the embankment raise at any given point in time. Field measurements from VWPs following fill placement have since confirmed that a B-Bar of 0.8 was a representative value for the raise to El. 5,016.3 m and that elevated pore pressures were fully dissipated after approximately 4 months following the end of construction. A B-Bar of 0.8 has been carried forward for subsequent construction, though the Add Weight zones have been adjusted to account for construction completed each season, recognizing that the pore pressures from the past season's construction have fully equilibrated.

4.4 Benefits of using the Integrated Approach and Combined Soil Model

Design of the embankment raise required many different analyses to identify a geometry that satisfied the various loading conditions and required FoS and evaluated all relevant slip surfaces for each section. The various iterations are summarized as follows:

- Sections: The embankment geometry and foundation conditions, namely the thickness of the silty clay foundation layer, varied significantly along the length of the embankment. In total, stability analyses were completed for 10 different sections around the perimeter of Cell 7, six of which were controlled by slip along the Upper Silty Clay or the Lower Silty Clay and relied upon the combined soil model for analysis.
- Loading Conditions: Stability analyses were completed for a total of five loading conditions, including the end of construction with excess pore pressures, long term loading conditions considering both peak and residual strengths, pseudo-static loading conditions, and the inflow design flood case.
- Slip Surfaces: Multiple slip surfaces were evaluated for each loading condition, including circular slip surfaces and block type slip surfaces following the weak foundation layers (Upper Silty Clay and Lower Silty Clay, peat layers). Slip surfaces impacting the embankment crest and that could result in an unplanned release were evaluated along with other large slip surfaces representing the stability of the wide buttress as shown on Figure 10. A minimum of 6 different slip surfaces intersecting the silty clay foundation layers were evaluated for each section and loading condition, with additional slip surfaces evaluated as needed.

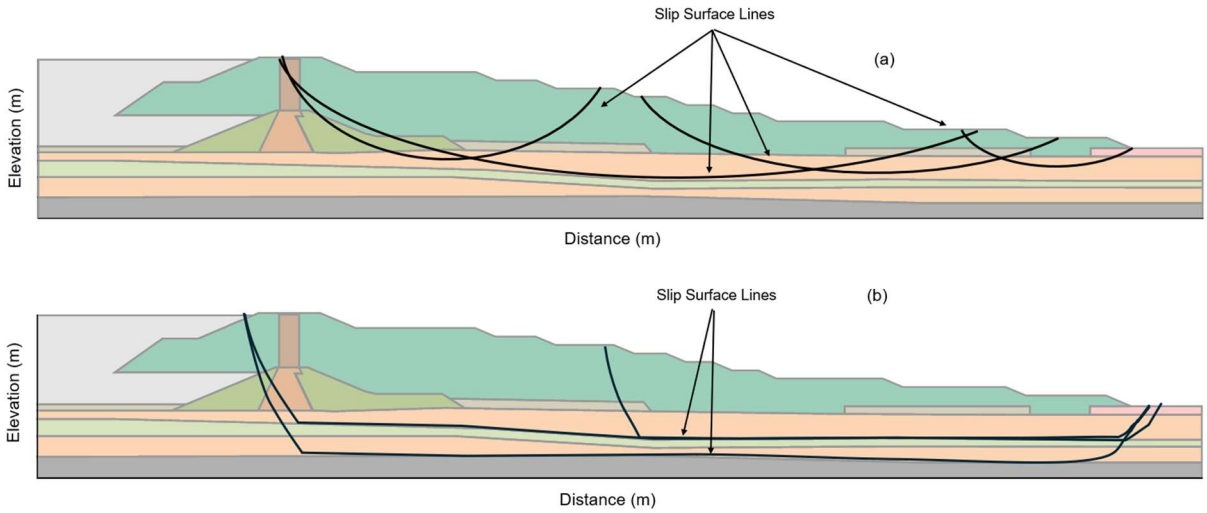

Figure 10: Conceptual illustration of different slip surfaces evaluated along the Upper Silty Clay and Lower Silty Clay layers including (a) circular slip surfaces and (b) block type slip surfaces along weak layers

Based on the above, a minimum of 300 separate analyses needed to be completed to design the final geometry of the Cell 7 embankment raise. Several iterations were completed for each section before a design satisfying every requirement was achieved. Additional analyses were completed to evaluate the geometry of interim stages of construction with varying buttress configurations and to develop Vibrating Wire Piezometer (VWP) trigger levels for each interim stage of construction. The methodology to define trigger levels is discussed separately by Bains et al (2026).

Manually dividing the foundation into different behavioural zones and applying different strengths to each zone depending on the actual loading and pore pressure conditions across this many different analyses would have been labour intensive, time consuming, and prone to errors. Use of the Integrated Approach and combined soil model to estimate the strength as a function of effective stress (embankment geometry and construction induced pore pressure) proved very useful for simplifying the design analyses and allowed the design to focus on varying the embankment geometry and pore pressure conditions as appropriate.

Ultimately there have been changes to the construction schedule since the design was prepared and initial construction stages completed. Each proposed change to the construction schedule that involved placing fill faster than originally planned necessitated re-evaluation of the stability with the actual and projected new pore pressures. Use of the combined soil model facilitated faster updating to the stability analyses as only the pore pressure conditions and embankment geometry needed to be adjusted, resulting in a faster response to the proposed schedule changes.

5 SUMMARY AND RECOMMENDATIONS

This paper presents an integrated methodology to accurately and easily evaluate the stability for large embankments such as tailings dams, water dams, mine waste storage piles or other civil engineering infrastructure constructed over silty clay foundation soils whose behaviour may vary from drained to undrained over the length of the structure. The integrated methodology is based on well known soil mechanics and uses a combined soil model to evaluate the soil strength over a range of effective stress, integrating the drained and undrained strengths into one function and accounting for shear induced pore pressures. Load induced pore pressures are incorporated via a complementary pore pressure model to correctly compute the effective stress and strength using the combined soil model. This approach simplifies the stability analysis of embankments by allowing the designer to focus on evaluating changes in

embankment geometry and pore pressure, rather than sub dividing the silty clay foundations into different behavioural and strength zones.

The combined soil model can be readily defined based on site investigation data including typical correlations with material type and laboratory index parameters, in situ testing results, and advanced laboratory testing results. The combined strength model can be input into the stability model as a strength vs. vertical effective stress function such as a SHANEP function in Slope/W (Bentley, 2026). Construction induced pore pressures can be estimated using one dimensional consolidation equations and input into the stability model as B-Bars and corresponding Add Weight zones.

Use and benefit of the integrated approach has been illustrated via a case history for the Cell 7 embankment raise at the Casa Berardi Mine which is founded over thick layers of silty clay foundation zones. Design of the final embankment required over 300 separate analyses. Additional analyses were also completed to evaluate each construction stage and develop VWP trigger levels. Use of individual soil models such as the UU, CU, and CD analyses would have required manual subdivision of the foundation into different zones based on the varying effective stress and would have been labour intensive, time consuming, and prone to errors. Use of the Integrated Approach and combined soil model to estimate the strength as a function of effective stress (embankment geometry and construction induced pore pressure) was thus essential to simplify the design analyses and allow the design to focus on varying the embankment geometry.

6 REFERENCES

Anctil, F., C. Perrin and V. Andréassian. 2003. "ANN output updating of lumped conceptual rainfall-runoff forecasting models." *J. American Water Resources Association*, Vol.39: pp 1269-1279.

Bentley Systems Incorporated (Bentley), 2026. GeoStudio 2025.2.1. Version 25.2.1.39. Calgary, Alberta.

Brown, B. and Gillani, I., 2016. Common errors in the slope stability analyses of tailings dams. Proceedings of the First Asia Pacific Slope Stability in Mining Conference (APSSIM). Retrieved from: https://papers.acg.uwa.edu.au/p/1604_36_Brown/ (accessed May 15, 2025).

Carter, M. and Bentley, S.P., 2016. Correlations of Soil Properties. Second Edition. John Wiley and Sons, Ltd., Cardiff University, U.K.

Idriss, I.M. and Boulanger, R.W., 2008. Soil Liquefaction during Earthquakes. In: Earthquake Engineering Research Institute Original Monograph Series. Eds: Agbabian, M.S and Becker, D. Series No. MNO-12. Earthquake Engineering Research Institute, Oakland, California, USA. 243 pages.

Ladd, C. C., and DeGroot, D. J., 2003. Recommended Practice for Soft Ground Site Characterization: Arthur Casagrande Lecture. 12th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, Massachusetts Institute of Technology. June 22- 25. Cambridge, MA.

Ladd, C.C. and Foott, R., 1974. New Design Procedure for Stability of Soft Clays. Journal of the Geotechnical Engineering Division, American Society of Civil Engineers (ASCE), Vol. 100, No. GT7. Pp. 763-786.

Makdisi, F.I. and Seed, H.B. 1978. Simplified Procedure for Estimating Dam and Embankment Earthquake-Induced Deformations. Journal of the Geotechnical Engineering Division, American Society of Civil Engineers. Vol 104, No. GT7. pp 849-867.

Shewbridge, S., 2019. Undrained Strengths and Long-Term Stability of Slopes. August 8. Institute of Water Resources. US Army Corps of Engineers.

Terzaghi, K., Peck, R. B. Mesri, G. 1996. Soil Mechanics in Engineering Practice. Third Edition. United States of America, John Wiley and Sons Inc.

US Army Corps of Engineers (USACE), 2003. Engineering and Design – Slope Stability – Engineer Manual. October 31. Washington, D.C., Ref. No. EM 1110-2-1902. Retrieved from: https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1902.pdf (accessed May 15, 2026).