Instability of unsaturated compacted soil slope due to rain infiltration

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ABSTRACT
The stability analyses of compacted embankments are conventionally determined extending the mechanics of saturated soils using saturated shear strength parameters. This approach is considered to be conservative; however, it may not always be reliable as other scenarios may contribute to compacted embankments failure. In many cases, the instability of compacted embankments is associated with the loss of suction values due to rainfall induced infiltration. A rational procedure for studying the embankment stability should take account of the variation of matric suction and the coefficient of permeability associated with different rainfall events. In the study presented in this paper, stability analyses were carried out on a homogeneous embankment constructed using typical glacial till from Western Canada. Three different types of triaxial shear tests were performed to determine shear strength parameters of compacted soil specimens for four possible scenarios of failure taking account of both saturated and unsaturated conditions using conventional and modified triaxial shear apparatus. Finite element analysis was undertaken using GEO-SLOPE software considering infiltration of water into embankment due to different rainfall events. The results of study show that typically shallow circular failures above water front occur due to infiltration rather than infinite slope type failures in compacted embankments.

RÉSUMÉ
L'analyse de la stabilité des remblais compactés est conventionnellement basée sur la mécanique des sols saturés en utilisant les paramètres de résistance au cisaillement à l'état saturé. Cette approche est jugée conservatrice; cependant, celle-ci n'est pas toujours fiable puisque d'autres facteurs pourraient contribuer à la rupture des remblais compactés. Dans de nombreux cas, l'instabilité des remblais compactés est associée à la perte de succion en raison de l'infiltration d'eau lors de précipitations. Une procédure rationnelle pour étudier la stabilité du remblai doit tenir compte de la variation de la succion matricielle et du coefficient de perméabilité associés à différents événements de précipitations. Dans l'étude présentée dans le présent article, les analyses de stabilité ont été effectuées sur un remblai homogène typique construite en utilisant un till glaciaire de l'Ouest canadien. Trois différents types d'essais de cisaillement triaxial ont été effectués pour déterminer les paramètres de résistance au cisaillement de spécimens de sol compacté pour quatre scénarios possibles de rupture en tenant compte des conditions saturées et non saturés en utilisant un appareil triaxial de cisaillement cenventionnel aussibien que modifié. L'analyse par éléments finis a été effectuée à l'aide du logiciel GEO-SLOPE et considérant l'infiltration d'eau dans le remblai sous différents événements de précipitations. Les résultats de l'étude montrent que généralement, dans des remblais compactés, des plans de rupture circulaires de faible profondeur se produisent au-dessus du front d'eau en raison de l'infiltration plutôt que des plans de rupture de pente infinie.

1 INTRODUCTION

There has been a steady increase in the world population growth over the last several decades both in developing and as well as the developed countries. As a result, to meet the continuously increasing demands of the public needs for transportation facilities, there has been a steady rise in the construction of new facilities such as roadways and railway lines. These facilities are not only necessary to prevent traffic congestion but also to alleviate economic losses associated with the lack of them.

In many situations these transportation facilities have to be built on compacted embankments constructed using locally available materials such as glacial tills or other fine-grained soils. In several cases, embankment design analysis is focused on the displacement of foundation ground rather than embankment itself (Loganathan et al., 1993). In addition, the variation of pore-water pressure with time during the construction of embankments is taken into account in the design when the foundation material at the construction site is cohesive in nature (Seo and Swan, 2001).

In several situations, the instability of embankments is commonly attributed to the loss in the contribution of suction (i.e. wetting-induced collapse) and subsequent increase in positive pore-water pressures (Lawton et al., 1992). Due to this reason, embankment stability analyses are usually performed using conventional limit equilibrium method extending Mohr-Coulomb failure criterion assuming embankment is in a state of saturated condition. This assumption is believed to provide a conservative design approach in the assessment of the stability of slopes constructed with compacted soils.

The above discussed approaches in the design of embankments may not always be valid. Since compacted embankments are typically in a state of unsaturated condition, it is appropriate to design them using the mechanics of unsaturated soils. In other words, reasonable embankment stability analysis can be assured only when the distribution of suction within the embankments are taken into account. Ridley et al. (2004)

emphasize the importance of direct observation of pore-water pressure in embankments as they are significantly influenced by seasonal variation of climate, permeability properties of the surface layers and vegetation on the slopes. Rahardjo et al. (1995) study demonstrates that infiltration of rainfall into unsaturated slopes forms a wetted zone which may likely trigger shallow slip failures. This implies that embankment stability analysis should be carried out considering infiltration condition besides limit equilibrium method.

In the present study, an attempt was made to study how factor of safety (FS) of a typical embankment constructed with a compacted glacial till will be influenced considering different practical scenarios.

long term stability of the embankment assuming saturated condition with and without rainfall infiltration into the embankment ;

long term stability of unsaturated embankment with and without considering rainfall infiltration into the embankment; and

short term stability analysis of compacted unsaturated embankment assuming undrained loading conditions.

A glacial till is chosen as candidate soil in this research program as they are commonly used in the construction of embankments in many regions of Canada. The chosen soil is from Indian Head, Saskatchewan. The analyses were carried out using the shear strength test results conducted on compacted specimens both in saturated and unsaturated conditions. Finite element analysis was undertaken using GEO-SLOPE software considering infiltration of water into the compacted embankment due to different rainfall events. Several conclusions of engineering practice interest are derived from the present study and summarized in this paper.

2 BACKGROUND

2.1 Definition of infiltration

The movement of water into a soil due to rainfall or irrigation activity is known as infiltration. Infiltration of water into soil is controlled by the relationship between the rate of water application or rainfall and soil infiltrability. If the rate of water application exceeds the soil infiltrability, ponding or runoff occurs over the soil surface (Williams et al., 1998). The infiltration rate is relatively high in the early stages of rainfall which decreases with time up to the values of the saturated coefficient of permeability (k_s) (Figure 1).

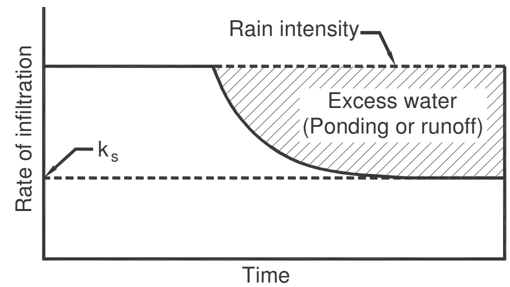

Figure 1. Variation of rate of infiltration with time (after Hillel, 1982)

Recent studies by several investigators demonstrate that shallow slip failures parallel to the slope surface are possible due to rainfall infiltration (Blatz et al, 2006; Huat et al, 2006). This characteristic failure behaviour allows analyzing instability of unsaturated soil slopes assuming them as infinite slopes regardless of the type of slopes (i.e. infinite or finite slopes) (Cho and Lee, 2002; Babu and Murthy, 2005). Therefore, the factor of safety (FS) can be calculated using the equation given below:

$$FS = \frac{c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b}{\gamma_t z_w \sin\alpha \cos\alpha} \quad [1]$$

where, c' is effective cohesion, ϕ' is effective internal friction angle, $(\sigma_n - u_a)$ is net normal stress, $(u_a - u_w)$ is matric suction, ϕ^b is internal friction angle with respect to suction, γ_t is total unit weight of soil, z_w is vertical depth of saturated soil and α is slope angle.

The above described concept can also be extended in the stability analysis of compacted embankments.

2.2 Effects of hysteresis on infiltration

The water flow behavior associated with rainfall infiltration is required to assess the embankment stability. This is possible using the coefficient of permeability function for unsaturated soils as an input parameter in the slope stability analysis. The coefficient of permeability function is the relationship which describes the variation of coefficient of permeability with respect to suction values. This relationship can be predicted using the soil-water characteristic curve (SWCC) and the coefficient of permeability under saturated condition (van Genuchten, 1980; Fredlund and Xing, 1994). The wetting SWCC is significantly different from the drying SWCC due to the influence of hysterisis (Figure 2).

The instability of unsaturated compacted embankments is likely to be induced due to the decrease in suction values caused by infiltration associated with snowmelt or rainfall activity. Therefore, in this study the SWCC following wetting path was used in the stability analyses.

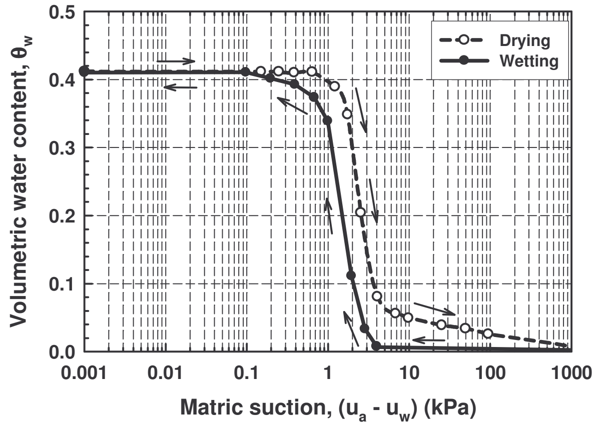

Figure 2. Hysteresis of soil-water characteristic curve (after Tami et al., 2004)

3 TESTING PROGRAM

3.1 Sample preparation

A glacial till obtained from Indian Head, Saskatchewan was used in the present study. The natural soil collected from the site was air-dried and then subjected to gentle pulverization to separate the individual soil particles. The soil sample was then passed through a 2 mm sieve.

The prepared soil was carefully mixed with different water contents and placed in sealed polyethylene bags for at least 5 days to ensure uniform distribution of water throughout the sample. When the sample reached equilibrium condition, the variation of dry unit weight with water content was determined using static compaction stress equal to 750 kPa (Figure 3). All the required input parameters for conducting the stability analysis (i.e., the shear strength parameters and the SWCC) were determined on specimens prepared at a water content of 13.2% and dry unit weight of 17.5 kN/m^3. This water content is chosen because clays or tills are typically compacted slightly dry of optimum conditions in the construction of embankments.

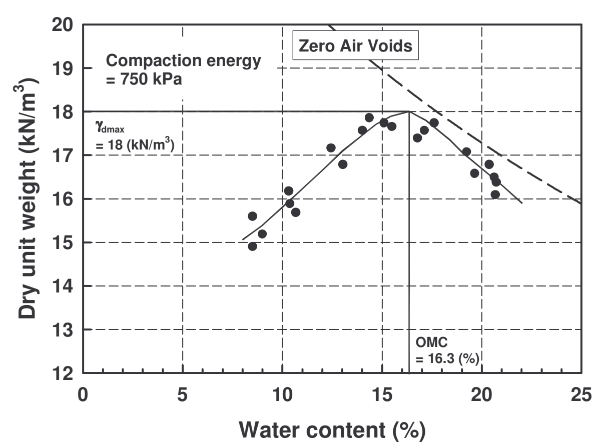

Figure 3. Compaction curve for Indian Head till

Table 1 summarizes several properties of the Indian Head till.

Table 1. Physical properties of the soil used in the study

Liquid Limit, w_L (%)	17.0
Plastic Limit, w_P (%)	32.5
Plasticity Index, I_p	15.5
Specific gravity, G_s	2.72
Max. dry density, $\gamma_{d(max)}$ (kN/m^3)	18.0
Optimum moisture content, OMC (%)	16.3

3.2 Triaxial shear tests

The soil specimens of 50 mm in diameter and 100 mm in height were prepared by static compaction in five layers using a vertical stress of 750 kPa. Three different types of triaxial shear tests were conducted to determine shear strength parameters in the present study using conventional or modified triaxial equipment.

3.2.1 Consolidated undrained test for saturated soil ($\overline{CU}$)

The prepared statically compacted specimens (50 mm in diameter and 100 mm in height) were first saturated using back-pressure and then sheared under three different effective confining pressures (i.e. 100, 200 and 300 kPa). The pore-water pressures were measured during the shearing stage after the consolidation. The effective cohesion and effective internal friction angle were estimated as 36.8 kPa and 23.1°, respectively.

3.2.2 Isotropic confinement undrained test for unsaturated soil (IU)

The compacted specimens (50 mm in diameter and 100 mm in height) with initial matric suction value (i.e. 200 kPa) were sheared immediately after the application of isotropic confining pressure (i.e. 100, 200, 300 and 400 kPa) under undrained loading conditions using conventional triaxial equipment. The total cohesion, c and total internal friction angle, ϕ were estimated as 86.9 kPa and 11.2°, respectively.

3.2.3 Modified triaxial tests for unsaturated soil (MTT)

A series of modified triaxial tests were carried out to determine the internal friction angle with respect to matric suction value, ϕ^b following the procedures described in Fredlund and Rahardjo (1993). The compacted unsaturated specimens were first allowed to imbibe water through the ceramic disk (air entry value = 500 kPa) of the modified triaxial equipment before shearing. The tests were performed following wetting path to simulate infiltration condition. When the specimens attain equilibrium conditions with respect to both matric suction, $(u_a - u_w)$ and volume change under the applied confining pressure, the specimens were sheared under undrained loading conditions. The angle of internal frictional due to the contribution of matric suction (i.e., ϕ^b value) was estimated as 12.3° at $(u_a - u_w)$ = 200 kPa. This value corresponds to the initial matric suction of the specimens at water content equal to 13.2%. The matric suction value of the specimen was measured using axis translation technique.

4 METHOD OF ANALYSIS

4.1 Possible scenarios

Embankment stability analyses were undertaken considering four different scenarios as shown in Table 2.

Table 2. Summarization of the analyses details

Scenario	Details of analysis
A	• Conventional stability analysis of embankment assuming saturated conditions • Assuming no infiltration • Shear strength parameters (test type) Case 1: c' (= 36.8 kPa), ϕ' (= 23.1°) ($\overline{CU}$) Case 2: c' (= 5 kPa), ϕ' (= 23.1°) (CD)
B	• Stability analysis of saturated embankment • Assuming infiltration equal to k_s (= 10^{-7} m/sec) • c' (= 5 kPa), ϕ' (= 23.1°) (CD)
C	Stage 1 • Stability analysis of unsaturated embankment • c' (= 5 kPa), ϕ' (= 23.1°) (CD) and ϕ^b (= 12.3°) (MTT) • No infiltration • Long term stability (uniform suction of 200 kPa) Stage 2 • Stability analysis of unsaturated embankment • c' (= 5 kPa), ϕ' (= 23.1°) (CD) and ϕ^b (= 12.3°) (MTT) • Infiltration with UCP function • Long term stability (uniform suction of 200 kPa)
D	• Stability analysis of unsaturated embankment • c (= 86.9 kPa), ϕ (= 11.2°) (IU) • No infiltration • Short term stability (uniform suction of 200 kPa)

1) Scenario A: (Conventional stability analysis): This approach is conventionally used for the stability analysis of slopes in engineering practice assuming the soil is in a state of saturated condition. The effective shear strength parameters (i.e. c' and ϕ') are required to determine the long term stability of the embankment.

2) Scenario B: (Ponding condition): A compacted unsaturated embankment can be saturated due to a variety of reasons such as mounding of water table, low intensity rainfall for a prolonged period of time or gradual snow melting. Ponding condition or runoff occurs if the rainfall continues for a prolonged period of time after saturation of the embankment as shown in Figure 1. The effective shear strength parameters (i.e. c' and ϕ') and the coefficient of permeability under saturated condition (k_s) are required for the stability analysis.

3) Scenario C: (Stability analysis for unsaturated conditions): In this scenario, two different stages may be considered. In the first stage, the compacted embankment is in a state of unsaturated condition. However, this characteristic of the embankment will considerably change due to rainfall. This is the second stage of the scenario. Hence, stability analyses can be carried out for both non-infiltration (Stage 1) and infiltration (Stage 2). The shear strength parameters (i.e. c', ϕ' and ϕ^b) are required for both Stage 1 and Stage 2. In addition, for Stage 2 the unsaturated coefficient of permeability function (UCP function) is required for the analyses.

4) Scenario D: (Short term stability analysis for unsaturated condition): This case is to simulate a scenario where an embankment is likely to fail within a short period of time after the construction. Total cohesion, c and total internal friction angle, ϕ are required for the analysis.

The details and the shear strength parameters used in the analyses of the four different scenarios are summarized in Table 2. More details about the shear strength tests are not presented in this paper due to space limitations. However, in later sections some key details of the shear strength tests are highlighted.

4.2 Infiltration and stability analysis

The infiltration and slope stability analyses were performed using commercial finite element software, SEEP/W and SLOPE/W (GEO-SLOPE International Ltd, 2004), respectively for a homogeneous compacted embankment (i.e., height of 3m and slope of 45°) shown in Figure 4. The initial suction distribution and infiltration induced pore-water pressure profile within the embankment was simulated using SEEP/W. Stability analyses were then conducted using SLOPE/W based on the pore-water pressure profiles obtained by SEEP/W.

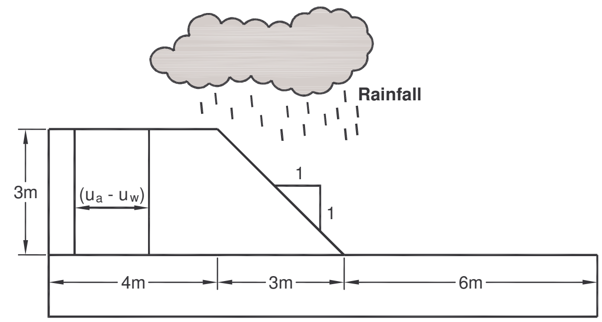

Figure 4. Cross-section of the embankment used in the present study

The position of the critical surface with lowest factor of safety was determined using two methods, namely; 'grid and radius method' and 'block method'.

i) The grid and radius method: This method is used to find the critical circular slip surface. Each grid point is the circle center for the trial slips considered in the analysis to determine the lowest factor of safety (FS) value (Figure 5).

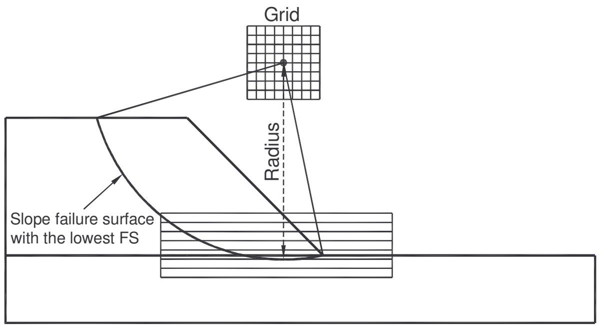

Figure 5. The grid and radius method of specifying trial slip surfaces

ii) Block method: This method is useful to find the critical slip surface which is likely to be parallel to the slope (i.e. infinite slope failure mode observed in slopes in which failures are associated with infiltration) (Figure 6).

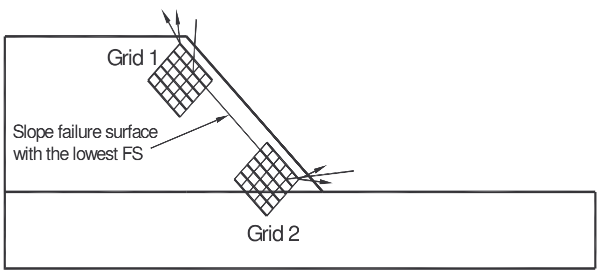

Figure 6. Grids in block specified method

The FS values were determined for both methods using Bishop's approach. The soil suction value within the embankment was assumed to be constant and equal to 200 kPa (i.e. suction value of the specimen compacted with an initial water content equal to 13.2%) throughout the embankment.

4.3 Unsaturated coefficient of permeability

The variation of coefficient of permeability with respect to suction (i.e., unsaturated coefficient of permeability function, UCP function) was predicted using Fredlund and Xing (1994) method using the wetting SWCC and the saturated coefficient of permeability. This method is useful for predicting the UCP function for all types of soils (Vanapalli and Lobbezoo, 2002). The wetting SWCC was determined using specially designed Tempe cell equipment developed at the University of Ottawa (Power et al., 2007) based on axis translation technique. The saturated coefficient of permeability for the compacted embankment was chosen as 1×10^{-7} m/sec referring to the previous studies on glacial till (Krahn, 2004). This value is also in acceptance with the studies undertaken by Johnston and Haug (1992) and Vanapalli et al. 1997

The SWCC and the UCP function for unsaturated conditions used for this study are shown in Figures 7 and 8 respectively.

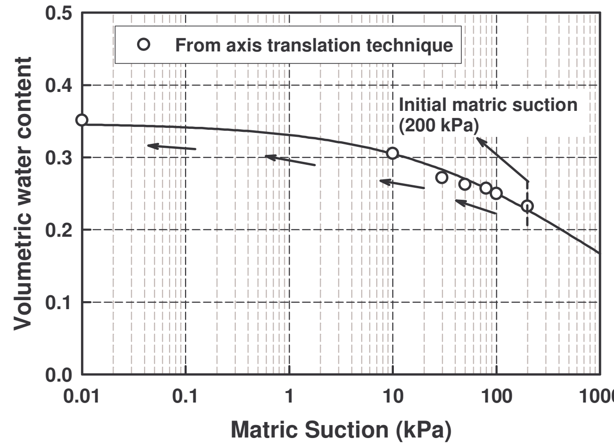

Figure 7. Wetting soil-water characteristic curve of the Indian Head till

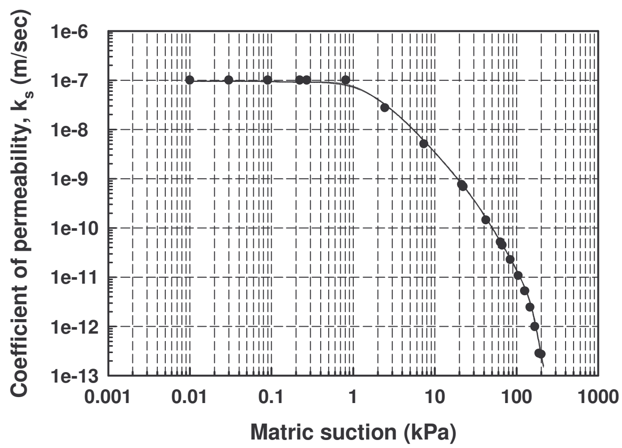

Figure 8. The variation of coefficient of permeability with respect to matric suction of glacial till

5 ANALYSIS RESULTS

5.1 Scenario A: (Conventional stability analysis)

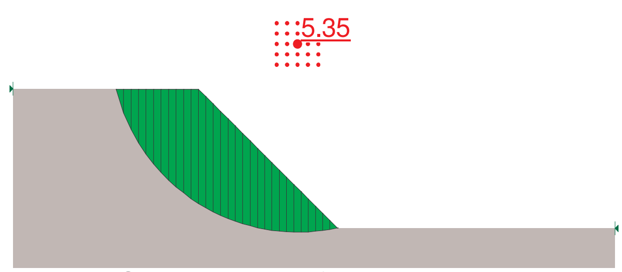

Figure 9. Stability analysis for saturated condition with $\overline{\text{CU}}$ results (c' = 36.8 kPa)

The factor of safety (FS) was estimated as 5.35 (Figure 9). This result suggests that the embankment is safe when it is analyzed using conventional engineering practice principles extending the mechanics of saturated soils (Scenario A – Case 1). The high FS value may be attributed to higher effective cohesion, c' value of 36.8 kPa measured from $\overline{CU}$ tests.

Vanapalli et al. (1997) performed consolidated drained (CD) tests on the same soil used for this study at a shear rate of 0.045 mm/min. The effective cohesion, c' was equal to 4 kPa. However, the effective friction angle, ϕ' was found to be the same (i.e. 23°) although the shear rate was different. The FS was re-evaluated for the same condition using a lower effective cohesion value (i.e. c' = 5 kPa, Scenario A – Case 2).

The use of a lower value of effective cohesion can be justified based on two reasons i) the effective cohesion component of compacted soil is likely decrease with time and ii) the measured effective cohesion value is dependent of the shear rate used.

The FS for Scenario A – Case 2 (i.e. c' = 5 kPa, ϕ' = 23.1°) was equal to 1.35 (Figure 10). This value is 25% of the FS value obtained using higher effective cohesion (i.e. 36.8 kPa, Scenario A – Case 1). The remainder of the analyses were performed using lower cohesion value (i.e. 5 kPa) for conservative analysis.

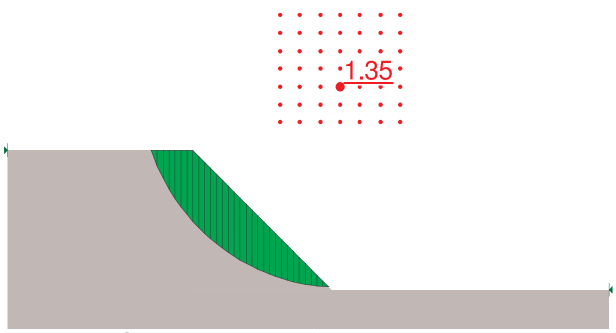

Figure 10. Stability analysis for saturated condition using CD results (c' = 5 kPa)

5.2 Scenario B: (Ponding condition)

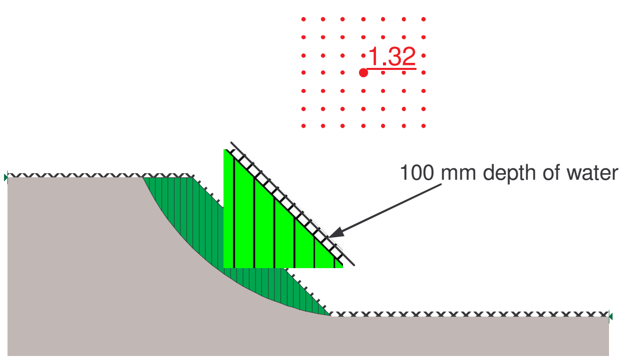

Figure 11. Stability analysis for ponding condition for saturated embankment

The influence of infiltration condition for this scenario can be neglected. This is because the rate of infiltration significantly decreases as the embankment approaches saturation condition. The embankment stability analyzes however can be undertaken by simulating a ponding condition over the entire embankment surface (Figure 11). A uniform ponding depth of 100 mm was assumed in the present study. The FS value for this ponding depth is the same as that of no infiltration condition (i.e. Scenario A – Case 2) (see Figure 10). However, FS decreases with an increase in the ponding depth (i.e. for values greater than 100 mm). The extra height of ponding is similar to an applied overburden pressure on the embankment which contributes to a decrease in FS. The analysis described in this section (i.e. Scenario B: Ponding condition) should be undertaken using the information of maximum rainfall from environmental data in the region where the embankment is constructed.

5.3 Scenario C: (Stability analysis for unsaturated conditions)

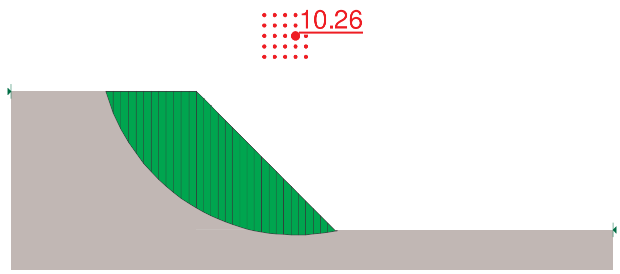

Figure 12. Long term stability analysis for unsaturated condition without rainfall infiltration

The stability analysis for unsaturated condition without rainfall (Scenario C – Stage 1) showed a FS of 10.26 (Figure 12), which is 8.5 times higher than that of saturated condition (i.e. Scenario A – Case 2). This FS value was arrived by assuming that the matric suction value within the embankment was uniform throughout the depth (i.e. 200 kPa: initial matric suction of the compacted embankment at a water content equal to 13.2%).

The stability analysis for unsaturated condition considering different infiltration conditions (i.e. 5, 10, 20 and 40 mm/hour) was also carried out using both 'grid and radius method' and 'block method' (Scenario C – Stage 2). The internal friction angle with respect to matric suction, ϕ^b of 12.3° (see Table 2) and the UCP function shown in Figure 8 were used in the analysis. Figures 13 and 14 show the stability analysis results for Scenario C – Stage 2 with infiltration conditions assuming a rainfall intensity of 40 mm/hour using 'grid and radius method' and 'block method', respectively.

These results indicate that shallow circular failure (FS = 1.27) occurs prior to infinite slope type (FS = 1.86) failure. The FS values were also approximately the same for different rainfall intensities considered in the analysis (i.e. 5, 10 and 20 mm/hour).

Figure 15 shows the matric suction distribution within embankment due to rainfall intensity of 40 mm/hour when the embankment slope failure occurs. The depth of the water front, z_w (see Equation [1]) was around 100 mm at this failure condition. The FS value using Equation [1] was estimated as 0.96 when the water front depth was equal to 100 mm. This result supports the rationale of using Equation [1] for the stability analysis of Scenario C – stage 2.

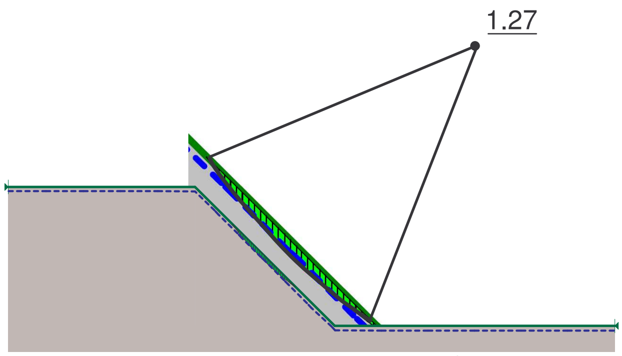

Figure 13. Long term stability analysis for unsaturated condition considering rainfall infiltration (Grid and radius method)

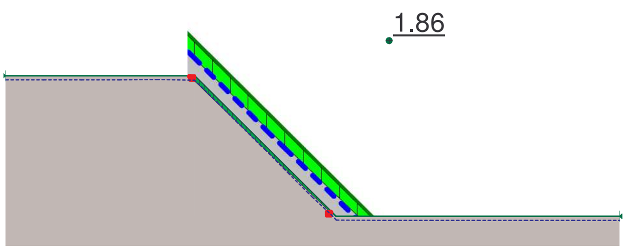

Figure 14. Long term stability analysis for unsaturated condition considering rainfall infiltration (Block method)

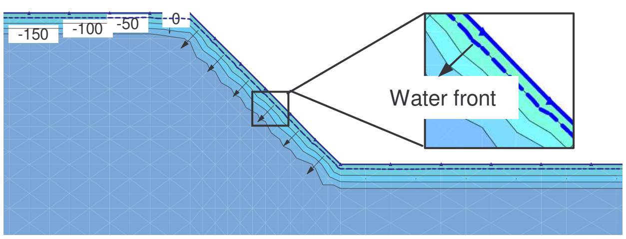

Figure 15. Pore-water pressure profile within embankment due to rainfall (40 mm/hour) at the moment of failure

5.4 Scenario D: (Short term stability analysis for unsaturated condition):

The FS for Scenario D was estimated as 10.35 (Figure 16). This result was compared with Scenario C – Stage 1 (See Figure 12). It is of interest to note that the FS for both cases are approximately the same. This is because the effect of suction is included in the IU results. These results suggest that the short term stability analysis can be carried out using IU results. In other words, modified triaxial tests which are time consuming may not be necessary in analyzing the stability for homogeneous unsaturated embankment for assessing the short term stability.

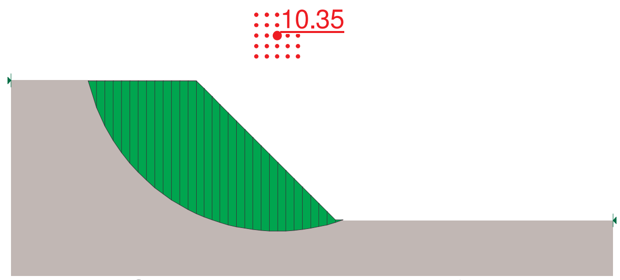

Figure 16. Short term stability analysis for unsaturated condition using IU results

The analyses results are summarized in Table 4.

Table 4. Variation of FS for each scenario

Scenario	Case or Stage	FS
A (Saturated)	Case 1 c' = 36.8 kPa, ϕ' = 23.1°	5.35
	Case 2 c' = 5 kPa, ϕ' = 23.1°	1.35
B (Saturated + Ponding)	Infiltration equal to k_s (= 10^{-7} /sec) c' = 5 kPa, ϕ' = 23.1°	1.32
C (Unsaturated)	Stage 1 c' = 5 kPa, ϕ' = 23.1°, ϕ^b = 12.3° Long tem stability without infiltration	10.26
	Stage 2 c' = 5 kPa, ϕ' = 23.1°, ϕ^b = 12.3° Long term stability with infiltration	1.27
D (Unsaturated)	c = 86.9 kPa, ϕ (= 11.2°) Short term stability	10.35

6 SUMMARY AND CONCLUSIONS

In this study, stability analyses for a homogeneous compacted unsaturated embankment constructed using glacial till were undertaken. Four possible scenarios which include long term and short term stability analyses for both saturated and unsaturated conditions were studied. Table 4 summarizes the results of all the analysis.

The critical instability condition arises when rainfall infiltrates into embankment which is initially in a state of unsaturated condition. However, it is recommended to analyze the embankment stability for all the different scenarios discussed in this paper to understand the critical condition such that a conservative design approach can be used in the construction of the embankment. The main conclusions obtained from the study are as follows:

1) The $\overline{CU}$ results can produce a relatively high effective cohesion, c', which results in a higher FS. High cohesion value from the tests may be attributed to the reason that the compacted soils behavior is similar to that of an overconsolidated soil. It is important to use relatively

slower shear strain rates for $\overline{CU}$ tests or CD tests to reliably determine the effective cohesion, c'.

2) The stability of compacted embankment is dependent on ponding depth (Scenario B: Ponding condition). The analysis for this scenario should be undertaken using the environmental data information of maximum rainfall for the region where the embankment is constructed.

3) The results of stability analyses performed using MTT (Scenario C – Stage 1) and IU (Scenario D) results without considering infiltration are approximately the same although there is slight difference in the shape of failure surface. This result implies that the stability analysis for homogeneous unsaturated embankment may also be carried out using IU results. In other words, the MTT results which are time consuming may not be necessary in analyzing the stability for homogeneous unsaturated embankment for short term stability analysis. Similarity in the FS for both these methods may be attributed to the reason that the effect of suction is included in the IU results. More studies along this direction would provide credence to this conclusion.

4) Rainfall is likely to cause shallow circular failure above water front due to infiltration prior to infinite slope type failure. The depth of water front at this failure was approximately equal to 100 mm in the present study. When the stability analysis was performed using Equation [1] with z_w 100 mm, the FS was estimated as 0.96 which is close to unity. Therefore, this conclusion provides justification of using Equation [1] for Scenario C – Stage 2.

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