Numerical simulation of volcanic soil slope failure under coupled freeze-thaw and rainfall infiltration effects

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ABSTRACT

Slope instability issues due to freeze-thaw action, rainfall and seismicity are common in cold regions like Hokkaido. It is essential to study the varied impacts of temperature difference and infiltration due to rainfall on soil slope stability. The main objective of this study is to find a suitable slope stability assessment method considering the effects of freeze-thaw and rainfall. An embankment slope failure study performed by previous researchers has been numerically simulated. A modelling methodology to perform freeze-thaw, seepage and limit equilibrium slope stability analysis has been adopted and followed. Crucial parameters for slope stability i.e. initial moisture content, moisture content distribution during failure were obtained from the simulation and then compared with the measurement data. The numerical results compared with the measured data provide rational satisfaction and demonstrate the applicability of the software code in order to predict the stability of slope. The numerical modelling approach used in this study is found useful in analysing the rational stability of soil slopes and to simulate the moisture content distribution of slopes subjected to freeze-thaw and rainfall infiltration.

Keywords: volcanic soil, slope failure, freeze-thaw, rainfall infiltration, numerical modelling

1 INTRODUCTION

Soil slope failures due to annual temperature difference, rainfall and earthquake incidences are common in cold regions like Hokkaido. Hokkaido Island is covered by many type of volcanic soil of relatively less geological age. Large number of embankments and cut slopes are constructed using volcanic soils all over Hokkaido. The impact of freeze-thaw cycles, rainfall and seismicity tend the slope to deform in a complex manner. It is essential to study the varied impacts of temperature difference and infiltration due to rainfall on soil slope stability. Kawamura and Miura (2013) performed freeze-thaw and rainfall experiments on model soil slopes and suggested that the initial water content of the slope prior to freezing and water content at failure has a major role in determining the stability of volcanic soil slopes. Kawamura et al. (2013) studied the volcanic slope failure behaviour using field monitoring of physical model slope. Matsumura (2014) studied the laboratory and insitu mechanical properties of volcanic soil by sampling the physical model slope. The objective of this study is to find an applicable stability evaluation method for volcanic soil slopes considering the effects of freeze-thaw and rainfall infiltration. Based on this objective the volcanic soil slope model has been simulated using numerical modelling. To simulate the variation in moisture content due to freezing, thawing and rainfall infiltration, freeze-thaw and rainfall infiltration analysis has been performed using a finite element numerical modelling tool. Through coupling the moisture content of the slope with unsaturated soil shear strength theory, a slope stability analysis has been performed using limit equilibrium method. Factor of safety of slope for the entire freeze-thaw and rainfall cycle has been obtained. The advantages and shortcomings in simulating the freeze-thaw coupled rainfall slope failures using the methodology adopted in this study are discussed.

2 DESCRIPTION OF THE PHYSICAL SLOPE MODEL

A frontal model view of the physical slope is given in Figure 1. In two-dimensional cross section, the slope is inclined in an angle of 45°and has 5m in elevation and 7.7m length at the base. The slope has been monitored with installed thermometers and soil moisture meters for temperature and moisture content respectively as given in Figure 2. The monitoring instruments were installed in different cross sections i.e. L, R and C sections. In this study L cross section has been chosen for analysis. The monitoring instruments
installed in L cross section are shown in Figure 2.

Rainfall has been monitored using rainfall gauges. Further, the embankment slope was covered by impervious sheets at the bottom and side to prevent mutual moisture movement from the ground. A prescribed amount of water (approximately 1m³/day) has been supplied to the slope using water supply pipes at constant intervals. The construction and setting up of monitoring instruments were finalised and monitoring started on November 9, 2012 (09-11-2012). The monitoring continued until the day of slope failure on October 17, 2013 (17-10-2013). Total monitoring time was around 343 days. The monitoring data is the key in data for numerical analysis performed in this study.

**Fig. 1.** Volcanic soil slope (Matsumura, 2014).

**Fig. 2.** Cross-sectional view of physical slope model.

**3 NUMERICAL MODELLING APPROACH**

In order to simulate the slope failure process, a non-isothermal seepage flow analysis followed by slope stability analysis has been performed. A numerical modelling approach to simulate freeze-thaw and rainfall infiltration has been adopted and followed as given in Figure 3. The initial moisture content distribution of the slope has been derived using initial thermal and seepage analysis. After setting up the initial conditions of the slope, freeze-thaw and rainfall infiltration analysis has been performed by keying in a transient temperature and infiltration boundary condition at the slope surface with a specified time length of 343 days (09-11-2012 to 17-10-2013).

Using the derived moisture content distribution from the freeze-thaw and rainfall infiltration analysis, a long term slope stability analysis (343 days) has been performed based on unsaturated soil shear strength theory and limit equilibrium method. Factor of safety of the slope for the entire duration of monitoring has been estimated.

**4 NUMERICAL SIMULATION USING FINITE ELEMENT MODELLING**

GeoStudio is a finite element based two dimensional numerical analysis software suit capable of performing thermal, seepage, dynamic and slope stability analyses (Krah, 2012). These thermal, seepage, dynamic and slope stability modules of GeoStudio were named as TEMP/W, SEEP/W, QUAKE/W and SLOPE/W respectively. In this study, TEMP/W and SEEP/W modules are used to perform non-isothermal seepage flow and SLOPE/W module has been used to analyse the slope stability.

**4.1 Slope geometry and material properties**

The slope geometry for numerical simulation prepared in consideration to the actual slope model is given in Figure 4. The model has a total height of 10m with an inclination of 45°.

**Fig. 4.** Finite element model for numerical analysis.
The two-dimensional numerical slope model has been considered based on the configuration of physical slope given in Figure 2. The numerical model is larger in comparison to the physical model in order to avoid the boundary effects on numerical results. In the numerical model there are layers of very low permeability configured inside the slope to establish condition of the impervious sheets covered at the base and side parts of the physical slope. The soil material properties used for numerical simulation has been summarised in Table 1. The soil properties were obtained from laboratory measurements (Matsumura, 2014).

| Property                             | Value          |
|--------------------------------------|----------------|
| Dry density of soil \( \rho_d \)     | 1.020 g/cm³    |
| Porosity \( n \)                     | 0.63           |
| Hydraulic conductivity of saturated soil | 6.00 x 10⁻⁶ m/s |
| Water content of soil at 0°C \( \theta_c \) | 0.19          |
| Water content of saturated soil \( \theta_s \) | 0.63          |
| Unfrozen thermal conductivity        | 107.8 kJ/Day/m²°C |
| Frozen thermal conductivity          | 171.7 kJ/Day/m²°C |
| Unfrozen heat capacity               | 3372 kJ/m³/°C  |
| Frozen heat capacity                 | 1193 kJ/m³/°C  |
| Cohesion                             | 0 kPa          |
| Angle of internal friction \( \phi' \) | 35°            |
| Phi b \( (\phi') \)                  | 17.5°          |

### 4.2 Initial thermal and seepage analysis

The numerical simulation using GeoStudio has been performed stage by stage as described in Figure 3. Initial thermal and seepage analysis was performed in order to derive the initial temperature and moisture content of the slope. For this reason some boundary conditions were assumed as given in Figure 4. The temperature at the top of the slope has been configured as 6.7°C and the temperature at the bottom of the slope has been considered as 12°C during initial analysis. For hydraulic boundary conditions, non-drainage boundary is imposed on both lateral sides and the bottom surface is specified with a fixed pore pressure hydraulic boundary (-16kPa). The reason for choosing -16kPa pore water pressure is explained below. It should be noted that the slope has been compacted with an optimum water content of 40.5% \( (w=40.5%) \) (Matsumura, 2014). After the compaction, the slope was in wet condition with a water content range determined as 41.2-43.5% (Matsumura, 2014). In consideration to this situation in initial analysis the slope has been set up with the average volumetric water content in the numerical model. To set the volumetric water content corresponding to the average water content \( (w) \), all the nodes in finite element mesh has been given a constant pore water pressure (-16kPa) same as the boundary condition at the bottom surface. The pore water pressure corresponding to the optimum volumetric water content has been determined from the SWCC (Soil Water Characteristic Curve) of Shikotsu volcanic soil (Matsumura, 2014). All the nodes of the finite element mesh in initial analysis have the same volumetric water content corresponding to the average water content after compaction. After setting the initial water content, the model has been cycled for 24 hours duration under transient conditions. During 24 hour transient cycling, the pore water pressure and moisture content at FE nodes are not constant and changes based on the flow of moisture due to gravity. At the end of 24 hours the volumetric water content has been measured and compared with the monitoring data as shown in Figure 5. This measurement corresponds to the initial day 09-11-2012. A close similarity is observed for moisture content at locations SML1 but the moisture content of SML2 is deviating up to 2%. From this observation it is considered that the slope has been configured with the possible moisture content distribution corresponding to the first day (09-11-2012).

Fig. 5. Comparison of moisture content after initial analysis.

### 4.3 Freeze-thaw and rainfall infiltration analysis

To perform freeze-thaw and rainfall infiltration analysis real temperature and rainfall data have been used as transient boundary conditions on the slope surface. The measured temperature and rainfall data for the entire monitoring period is given in Figure 6. To analyse the effect of temperature change in soil slope stability a heat transfer analysis and seepage analysis has been performed considering temperature changes and rainfall infiltration on the slope surface.

Fig. 6. Temperature and rainfall data for transient boundary conditions.

The temperature and hydraulic boundary conditions for freeze-thaw rainfall infiltration analysis are same at the lateral sides of the slope as initial analysis. Non-drainage hydraulic boundary condition is applied at the bottom for freeze-thaw rainfall infiltration analysis. The slope surface and top has been specified with transient boundary conditions as given in Figure 4. The temperature, snowfall and rainfall data given in Figure 6 has been used as transient boundary conditions in order to simulate the freeze-thaw and rainfall...
infiltration phenomenon. The hydraulic boundary condition of the finite element nodes inside the slope is not constant as it was in initial analysis and the pore water pressure and moisture content changes based on the applied transient and water supply boundaries as given in Figure 4. A constant volume of water (1m³/day) was supplied to the physical soil slope throughout the monitoring period (Matsumura, 2014). The locations of the water supply pipes are as given in Figure 2. In L section, two water supply pipes were configured. One was installed at the slope top at a depth of 1.6m during 27-07-2013 to 06-08-2013 and the other was installed along SML1 at a depth of 2m from slope surface during 11-10-2013 to 18-10-2013. The water supply pipes have holes of 5mm diameter at the bottom part, the holes were distributed between 200mm spacing. In order to include the constant water supply during the prescribed days in the simulation, a boundary condition has been specified in freeze-thaw rainfall infiltration analysis as given in Figure 4. The water supply in the finite element model is considered as a point boundary at a particular node in order to simplify the assumption.

During the course of simulation the volumetric water content has been recorded. The soil moisture readings from SML1 and SML2 at 0.6m depth from the slope surface had chosen for comparison. The water content obtained from numerical simulation is plotted in Figure 7 for locations SML1 and SML2 along with the measured data. A close observation in similarity between the simulation and measured data is found for locations SML1 and SML2 with a marginal difference of about 0.5%. From Figure 7 it can be observed that, for the initial 150 days of time there is no larger increase in water content of the slope. Due to the effect of freezing, the water content tends to decrease until 150th day. The decreasing water content describes the freezing phenomenon. Due to penetration of freezing isotherm into the soil ground the moisture content of the soil reduces as the water concealed in the soil particles starts to form ice. Later, the temperature of the ground increases more than zero (>0), then the frozen water in the soil particles start melting which results in increase in overall moisture content of the slope. Further, the rainfall infiltration adds more amount of increase in moisture content. After the end of freezing period, there was heavy rainfall around 09-04-2013 and the corresponding temperature on that day is above 0°C (Figure 6). This rainfall should eventually increase the moisture content of the slope. The increase in moisture content around 09-04-2013 can be clearly observed from Figure 7. Starting that day the moisture content of the slope gradually increases whenever there was rainfall. From this observation, it is clear that increase in moisture content of the slope is more rigorous during the thawing period due to snow melting and rainfall infiltration.

![Fig. 8. Distribution of moisture content on the day of failure obtained from numerical analysis (left) and physical slope (right).](https://example.com/image)

The water content during the day of failure is plotted in Figure 8. The water content during failure is more crucial to analyse the slope stability as the amount of moisture content in soil determines the soil’s shear strength based on SWCC. The moisture content has got variedly distributed all through the slope. It can also be observed, the maximum degree of saturation lies at the bottom of the slope. The physical slope model reaches a maximum degree of saturation up to 95% at the bottom part. Similar moisture content distribution has been obtained from numerical simulation. In numerical model the slope gets completely saturated at the bottom just above the impermeable layer. This observation suggests that the moisture content distribution of the slope can be predicted for anticipated freeze-thaw cycles and rainfall infiltration using the method adopted in this study. If an agreeable prediction of the moisture content is made then the stability of the slope can be evaluated using unsaturated shear strength theory.

### 4.4 Slope stability analysis

Limit equilibrium slope stability analysis has been done using the moisture content distribution from the freeze-thaw rainfall infiltration analysis. The shear strength of unsaturated soil is defined as given by Fredlund et al. (1978),

\[
\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi
\]  

where, \( \tau \) = shear strength, \( c' \) = effective cohesion, \( \sigma_n - u_a \) = net normal stress, \( \phi' \) = effective angle of internal friction, \( u_a \) = pore air pressure, \( u_w \) = pore water pressure, and \( \phi \) = an angle defining the increase in shear strength for an increase in suction. The material properties used for slope stability analysis is given in Table 1. It should be noted that the shear strength of frozen soil will be larger than unfrozen soil. In this study the shear strength of soil is considered same for
both frozen and unfrozen soils. Larger shear strength will increase the overall stability of the slope during freezing period which will eventually result in higher safety factor. As the analysis simulates the slope failure during thawing and rainfall period, the increase in frozen shear strength is not considered. The angle of internal friction of the soil has been estimated as 35°. The $\phi^b$ has been roughly considered as half of the angle of internal friction in this study as there is no direct triaxial data available (Olooo and Fredlund, 1996). The use of $\phi^b$ gives a rough estimation of the increase in shear strength as a function of soil suction. The unsaturated shear strength of soil in this study has been considered using Equation 1. The drawback of the use of $\phi^b$ is that the unsaturated strength envelop is assumed to be linearly increasing with soil suction which tends to overestimate the unsaturated shear strength when the soil suction is very high (beyond the residual suction value). The unsaturated shear strength of soil is also expressed based on Bishop’s effective stress principle by Vanapalli et al. (1996) as given in Equation 2.

$$\tau = c' + (\sigma_n - u_n)\tan \phi' + (u_n - u_w)[\chi \tan \phi']$$

where, $\chi = \text{parameter related to degree of saturation}$. According to Vanapalli et al. (1996) the magnitude of parameter $\chi$ can be expressed in terms of volumetric water content as,

$$\chi = \frac{\theta_u - \theta_r}{\theta_u - \theta_r}$$

where, $\theta_u = \text{volumetric water content}$, $\theta_s = \text{saturated volumetric water content}$ and $\theta_r = \text{residual volumetric water content}$. The residual volumetric water content is assumed to be equal to 30% of the saturated volumetric water content based on SWCC of Shikotsu volcanic soil (Matsumura, 2014). When estimating the unsaturated shear strength using Equation 2, $\phi^b$ is calculated based on the water content of the particular finite element node. In this situation, $\phi^b$ is not a constant value and its magnitude depends on the SWCC. It will be prudent to analyse the stability of slope using different shear strength description approach of unsaturated soil. Based on this viewpoint, in this study the factor of safety of the slope was estimated using Fredlund and Bishop’s shear strength equations and plotted in Figure 9. The safety factor by using Bishop’s (1959) shear strength equation reaches a value close to 1 (i.e.1.111) on the day of failure (17-10-2013) and the safety factor by using Fredlund (1978) shear strength equation reaches below 1 (i.e. 0.984). It is considered that both the values represent slope failure. An additional analysis was performed considering only rainfall infiltration and ignoring the effect of freeze-thaw considering Bishop’s shear strength equation. Then, to visualise the effect of unsaturated shear strength, an analysis considering $\phi^b=0$ was done. Figure 9 shows the factor of safety for cases of Fredlund’s shear strength, Bishop’s shear strength, rainfall alone analysis and $\phi^b=0$. From Figure 9, it can be observed that the safety factor of the slope initially decreases and again increases until around 09-04-2013 for three cases except for the case $\phi^b=0$.

![Fig. 9. Factor of safety of slope for entire slope failure process.](image)

In the case of $\phi^b=0$ the slope is in failure state from the beginning and shows some variation in safety factor when there was heavy rainfall around 07-04-2013 to 09-04-2013. This implies the importance of unsaturated soil shear strength theory in analysing the stability of volcanic soil slopes subjected to freeze-thaw and rainfall infiltration. By comparing Fredlund and Bishop’s shear strength equations it can be observed, almost equal difference in safety factor. The reason for this variation is the effect of SWCC on shear strength. In addition, during freezing period the safety factor is almost horizontal for the cases of Fredlund and Bishop’s shear strength equations. The reason for almost constant safety factor throughout the freezing period could be the effect of moisture content. Due to the effect of freezing the moisture content of the slope reduces, as the matric suction which is defined as pressure difference between the ice and water interface in a frozen soil increases due to increase in ice pressure. The above phenomenon happens until around 09-04-2013 prior to the snow melting period. After that the safety factor reduces gradually due to increase in moisture content by snow melting and by rainfall. In contrast to this, the rainfall alone analysis shows a larger increase in safety factor until there is heavy rainfall. It is interesting to note that the safety factor for rainfall alone analysis shows no failure. Until 19-11-2012 the safety factor for rainfall analysis is same as freeze-thaw rainfall analysis. The safety factor reduces for all cases during heavy rainfall period, but the reduction is more for freeze-thaw rainfall cases than rainfall alone analysis. A similarity in moisture content is observed for rainfall analysis and freeze-thaw rainfall analysis until around 19-11-2012 as shown in Figure 10 for location SML1. After that a moderate amount of rainfall occurred during 19-11-2012 to 4-12-2012. The rainfall caused increase in moisture content of the slope in which freeze-thaw rainfall analysis shows a little increase and rainfall alone analysis shows a larger increase in moisture content. This variation in moisture content could be due to the effect of freezing. More
amount of moisture content maintains the safety factor lower for rainfall analysis until 09-02-2013, after that the safety factor increases. Whereas for freeze-thaw rainfall analysis, even there is less rainfall the safety factor does not increase rapidly due to effect of freezing. The freezing effect tends to reduce the moisture content more and due to reduction in moisture content the safety factor does not increase. During heavy rainfall and snow melting period the moisture content increase is more for freeze-thaw rainfall analysis than rainfall analysis due to the effect of snow melting coupled with heavy rainfall. Likewise the reduction in safety factor is more for freeze-thaw rainfall cases during heavy rainfall period. During freezing the moisture content of the soil gradually decreases. The volumetric water content of soil during freezing is 0.19 at 0°C. As freezing proceeds the moisture content is transferred into ice. During thawing period, once the temperature increases above 0°C the contained moisture in the form of ice starts melting and provides additional amount of moisture to the soil. There is clear difference in moisture content between freeze-thaw rainfall analysis and rainfall analysis until slope failure. The additional amount of moisture resulted due to melting of ice content during phase change is maintained until 17-10-2013 and reduces the stability of the slope. This comparison shows how the freeze-thaw actions affect the moisture content and reduce the slope stability.

The minimum safety factor of the soil slope reduces to less than 1 (0.984) during 343rd day, the day of slope failure 17-10-2013. The failure surface of the slope shows a thin layer of slip line as given in Figure 11. The slip surface has an elevation of 4.5 m and a depth of 0.6–0.9 m. In field conditions the failure surface was about 3 m in height and 0.6–0.8 m in depth. By comparing the field observations, the failure surface from the finite element analysis is little larger in elevation and has almost same depth similar to the physical model. From this comparison it is clear that the finite element analysis performed in this study is useful to predict the anticipated stability of soil slopes subjected to freeze-thaw and rainfall infiltration.

5 CONCLUSIONS

An embankment slope composed of Shikotsu volcanic soil has been simulated from the day of construction to failure. The freeze-thaw and rainfall infiltration analysis performed in this study is useful in order to analyse the varied fluctuation of moisture content throughout the period of freeze-thaw cycle and successive rainfall. Further, the use of simple limit equilibrium method provided with unsaturated shear strength theory, to analyse the rational stability of soil slope is helpful to directly relate the moisture content distribution of the slope to stability. It should also be noted that the simulations performed in this study does not consider the particle breakage of soil due to freezing and fine particles runoff during rainfall which account for reducing the shear strength of soil. Using this slope stability analysis method the rational stability of soil slope can be predicted. Elaborate studies need to be performed by simulating more volcanic slope failure case histories in order to substantiate the applicability of the stability evaluation method used in this study.

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