Unsaturated behavior of an earthfill dam during coupled initial impoundment and a prolonged rainfall

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ABSTRACT

Newly constructed earth-fill dams in a residual soil rich area have a high probability of failure occurrence in the first five years of operation. Monitoring a rate of the first impoundment of the dams is critical for monitoring the effectiveness and designed function of the dam over its service life. However, stability of the dams is uncertain under influential factors such as variability of soil properties of support foundations, simultaneous increases of water level in the upstream and infiltration in downstream dam surface from prolonged heavy rainfall event. In this study, failure mechanism for an earth-fill dam due to concurrent rises in water level upstream and rainfall infiltration was investigated using saturated-unsaturated soil principles. Seepage was analyzed using Finite Element Method and slope stability was analyzed using Limit Equilibrium Method. Results of the failure mechanism were compared and discussed with respect to varying stiffness of residual soil support foundation, coupled rising water reservoir and applied prolonged rainfall.

Keywords: unsaturated earthfill dam, residual soil, prolonged rainfall, dam stability

1 INTRODUCTION

Initial construction of water storage facilities such as earthfill dams in a residual soil rich area is often encountered with issues of partially saturated condition or unsaturated soil condition. Failures of the facilities caused by rainfall infiltration and flood are associated with unsaturated soil properties both in the earthfill materials and soil foundations. Affected by climate conditions and cyclic saturation-unsaturation processes, newly constructed dam requires attention on monitoring of variation of engineering properties that are prone to change as a result of soil-water interaction. For example, variation in volume change, shear strength and permeability of the soils.

Residual soils are weathered soils distributed widely in tropical regions. The characteristics of residual soils depend considerably on weathering conditions such as temperature, rainfall and vegetation. Decomposed granite soils are the typical residual soils (Blight, 1997). The soils are commonly situated above the groundwater table and are often unsaturated with negative pore-water pressure relative to atmospheric conditions (Fredlund and Rahardjo, 1993).

Newly completed earth-fill dams have been reported to have a high probability of failure occurrence in the first five years of operation. Rate of first water filling to the dams is critical to the safety of the dams. The dams are still undergoing transition from unsaturation to saturation after the completion of construction. As a positive pore-water pressure is building up over time in the dam body under influences of groundwater level rise and/or rainfall infiltration, it is expected that the unsaturated soil properties of the dam play a crucial role during this unsteady state or transient condition. In case of simultaneous increases in reservoir water level from a flood and rainfall infiltration from a prolonged rainfall, the dam safety could be severely compromised. Therefore, this study was initiated to investigate the unsaturated behavior of a residual soil earthfill dam by considering rising reservoir water level, a prolonged rainfall, and varying soil properties of support foundation.

2 METHODS

2.1 Hydrological design for water reservoir filling

Rate of initial impounding or filling of a reservoir is important to the stability of an earthfill dam. In general, it is uncertain to design the rate of impounding from hydrological data such as hydrograph due to uncertainty from effect of climate change. Filling rates during 180 days (6 months) of a 16 m height reservoir at maximum of 14 m water level can be designed in a number of ways as shown in Figure 1. In this study, one case of steady rising or linearly filling rate (14 m water level rise for the duration of 180 days or at 0.078 m/day) was selected in this study.
2.2 Design of rainfall hyetograph

Rainfall has tremendous impact to trigger environmental hazard and disasters (e.g. soil erosion, debris flow, flood and landslide). Design of rainfall hyetograph for an earth dam construction is important to assess the service life and safety of the dam. However, rainfall is spatially and temporal varying in terms of amount, intensity and frequency. This causes difficulty to select the representative rainfall hyetograph. In cases, preliminary design of an earthfill dam does not adequately take into account the influence of rainfall events. This is because dam design persons believe that compacted soils unlikely to rainfall-induced failure. However, this believe does not hold true in practice. In this study, rainfall hyetograph was derived using total amount of 2500 mm of rainfall during 180 days. Figure 2 shows the triangular rainfall hyetograph with linearly increase rate and its cumulative amount.

![Fig. 1. Hydrological design of water reservoir filling rates.](image1)

![Fig. 2. Design of quasi-prolonged rainfall.](image2)

2.3 Material properties, model geometry and initial conditions

The geometry of the modelled embankment dam consists of embankment soil, transition zone, horizontal drain and rockfill toe drain. The main dam body is constructed using borrow materials using residual soils. The dam is underlain by residual soil foundation and weathered bedrock. The sand filter size was 0.5 m thick for horizontal filter and 1.0 m thick for vertical filter. Freeboard of 2.0 m below the crest top. Initial conditions were established by setting initial water table at the ground level.

2.4 Equation for water movement in soils

Theoretically, a governing equation for water flow in porous mediu under a transient and two dimensional (2D) seepage analysis is expressed by equation (1). The computed pore-water distribution is sequentially used as entry data for slope stability analysis. Geoslope SEEP/W, a commercial software embedded with Finite Element algorithm, was used for seepage analysis and equation (2) was incorporated to the software to simulate water flow in soils.

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + Q = \frac{\partial \theta}{\partial t} \\
\frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + Q = m_w \gamma_w \frac{\partial \theta}{\partial t}
\]

Where, \( \theta \) = volumetric water content, \( m_w \) = slope of soil-water retention curve (1/m), \( H \) = total head (m), \( t \) = time (s), \( k_x \) = coefficient of permeability with respect to water as a function of matric suction in the \( x \)-direction (m/s), \( k_y \) = coefficient of permeability with respect to water as a function of matric suction in the \( y \)-direction (m/s), \( Q \) = applied flux at the boundary (m³/m²s).

| Materials          | Unit weight (kN/m³) | Cohesion (kPa) | Angle of internal friction (°) |
|--------------------|--------------------|---------------|-----------------------------|
| Embankment soil    | 18                 | 15            | 29                          |
| Filter sand        | 19                 | 0             | 30                          |
| Toe drain rockfill | 21                 | 0             | 37                          |
| Foundation soil 1  | 17                 | 5             | 25                          |
| Foundation soil 2  | 17                 | 5             | 28                          |
| Foundation soil 3  | 18                 | 25            | 25                          |

![Fig. 3. Geometry of the residual soil earthfill dam.](image3)
2.5 Equations for hydraulic properties of materials

Soil-water retention curve (SWRC) or soil-water characteristic curve (SWCC) defines a unique and dynamic water retention property of a soil under internal stress (e.g., suction). SWRC is a useful index to analyze unsaturated soil behavior. Moreover, SWRC also plays a role for indirect estimation of the hydro-mechanical properties such as hydraulic conductivity, volume change and shear strength. Hysteresis or two distinct behavior of a soil under suction are the desorption (drying) and the adsorption (wetting). The hysteresis is the result of gaseous and liquid movement in soil’s micropores and micropores.

In this study, drying SWRC, which is mathematically mimicked by van Genuchten (1980)’s equation, equation (3), with Mualem’s modified parameter, was used in this study. Permeability function of materials for earthfill dam was derived using proposed equation by van Genuchten-Mualem, equation (4).

\[
S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[ 1 + \left( \frac{u_n - u_w}{a} \right)^n \right]^{\frac{1}{n}} 
\]

(3)

\[
k_w = k_s = \frac{\left[ 1 + \left( \frac{a(u_n - u_w)}{u_n - u_w} \right)^n \right]^{\frac{1}{2}}}{\left[ 1 + \left( \frac{a(u_n - u_w)}{u_n - u_w} \right)^n \right]^{\frac{1}{2}}} 
\]

(4)

Where \( S_e \) = effective saturation, \( \theta \) = volumetric water content, \( \theta_s \) = saturated volumetric water content, \( \theta_r \) = residual volumetric water content, \( u_n - u_w \) = matric suction (kPa), \( u_n \) = pore-air pressure (kPa), \( u_w \) = pore-water pressure (kPa), \( a \) = empirical fitting parameter (kPa), \( n \) = empirical fitting parameter, \( k_w \) = hydraulic conductivity, \( k_s \) = saturated hydraulic conductivity (permeability).

2.6 The modelled hydraulic conductivities.

Natural slope and compacted embankment exhibit heterogeneity in soil properties both spatially and temporally. Major influencing factors to the heterogeneity of the soil properties are associated with physical, chemical, and biological processes. In terms of hydro-mechanical processes, variability of soil properties such as the soil-water retention curves (SWRCs) attributes significantly to stability of the soil structured facilities. However, more complex analysis is required when taking into account of the variability of the SWRC. Therefore, for simplification, in this study the SWRC was obtained from literature data. Fitting the literature data by equation (3), continuous curves were created as indicated in Figure 4. Figure 5 shows the permeability functions or unsaturated coefficient of permeability for each SWRC.

SWRC of the embankment soil was derived from a compacted residual soil. The saturated volumetric water content (VWC) is relatively small (0.22 m³/m³) in comparison to its natural condition (about 0.3-0.6 m³/m³). Matric suction plays a little role for toe drain rockfill as water can be drained quickly under small matric suction. The residual VWC of both sand and rockfill is about 0.05 m³/m³ due to the modeled equation. The unsaturated coefficient of permeability was cut off at approximately 10⁻¹³ m/s to reflect the physical water flow and to reduce computation time. The measured matric suction in field is 40-90 kPa.
2.7 Slope stability analysis using Limit Equilibrium Method.

Shallow slope failure is influenced by saturated and unsaturated soil properties, rainfall, and groundwater table. Slope stability can be analyzed by Limit Equilibrium Method (LEM) and Finite Element Method (FEM). The former method is commonly used due to simplicity of problem. Geoslope SLOPE/W, a commercial software, was embedded with the LEM algorithm to analyze the force and moment equilibrium and factor of safety (FOS). Before analyzing the FOS, steady-state seepage was initialized and established. The initial water table obtained from the steady-state condition was subsequently used for analyzing the FOS. Unsaturated condition was used to analyzed seepage behavior of the dam body, and saturated analysis was selected for foundation soils. In this study, the Morgenstern-price method with half sine function was selected to obtain the variation of the FOS over time.

3 RESULTS AND DISCUSSION

3.1 Steady-state phreatic surfaces and factors of safety

Figure 6 shows the result analyses of saturated and unsaturated behavior of embankment dam under steady state seepage condition under steadily rising reservoir water without rainfall. The critical FOS for each analysis was 1.781, 1.877 and 2.081 for cases of soil foundations 1, 2 and 3, respectively. Significance of the result analyses was the difference in the FOS values, which were caused by the soil properties selected in this study. Stiffness of foundation soils are in increasing order from foundation soils 1, 2, and 3. Soil properties are shown in Table 1. Saturated and unsaturated behavior in the dam are apparently divided by the phreatic line or line of zero pore-water pressure. Above the phreatic line, distribution of negative pore-water pressure or matric suction (in the range of 0-80 kPa) toward the downstream slope was apparent and uniformed. The higher the phreatic line rose, the lesser the negative pore-water pressure or matric suction, and the lesser the factor of safety. Case of foundation soil 1 had the higher phreatic surface, and the lesser safety factor of safety. From result analyses, it was also observed that there was a building up of pore-water pressure behind vertical filter on the downstream side. Figures 8, 9 and 10 showed the variation of pore-water pressure over time under cases of foundations 1, 2 and 3, respectively. Results showed that the entire earthfill dam completely underwent saturation starting from about day 80.

Fig. 6. Steady-state behavior of seepage and factors of safety under (a) foundation soil 1, (b) foundation soil 2, and (c) foundation soil 3.
3.3 Effect of soil foundation on the stability of downstream slope of embankment

Figure 11 shows the results of the FOS obtained under cases of foundations soils 1, 2, and 3. It was evident that the prolonged rainfall with linearly increase in intensity and amount during 180 days (total amount of 2500 mm) contributed substantially on the influence of the FOS of the embankment dam slope. The FOS against piping in the foundation soil was not investigated in detail in this study. The factor of safety obtained was the global factor of safety. There is localized failure or shallow slope failure has not identified in the embankment. There is a possibility that localized failure may develop due to composite dam construction with sand filter and rockfill toe drain. The localized stability of the vertical filter and horizontal sand filter and rock compaction and ground support underneath the rockfill is vital because deformation underneath may cause overall or global deformation to the dam embankment.

From the result analyses, it is clearly shown that the stiffer the soil foundation, the higher the factor of safety. However, values of factor of safety was changed with time under rainfall. It was found that the higher factor of safety was results from soil parameters used such as cohesion, angle of internal friction, and unit weight, and pore water distribution under slip surface. Changes of factor of safety for all three cases were followed similar patterns. It can be observed that three zones of variation can be established. Firstly, the FOS was gradually decreased. This reflects that the dam was still in unsaturated condition during the steadily rising of the phreatic surface due to rising reservoir level and rainfall infiltration. Then, the FOS path followed by sharply decreased before turning to gradual declination again. The abrupt inflection point indicated that the dam body underwent complete saturation. The FOS variation path can be explained three zones: water entrance, transition, and residual zones. This transformation of the FOS is similar to the path of SWRC.

Fig. 7. Pore-water pressure distribution under coupling condition for (a) foundation 1, (b) foundation 2 and (c) foundation 3.

Fig. 8. Pore-water pressure variation vs elevation Y under foundation soil 1: (a) without rainfall and (b) with rainfall.
Fig. 9. Pore-water pressure variation vs elevation Y under foundation soil 2: (a) without rainfall and (b) with rainfall.

Fig. 10. Pore-water pressure variation vs elevation Y under foundation soil 3: (a) without rainfall and (b) with rainfall.

Fig. 11. Variation of factors of safety over time.

4 CONCLUSIONS

Saturated-unsaturated soil mechanics was utilized to investigate slope stability of a compacted residual soil earthfill dam was evaluated using finite element method for seepage and limit equilibrium method for factor of safety for three study cases of support foundation: residual soil foundation 1, residual soil foundation 2 and residual soil foundation 3. Seepage under steady increase water reservoir rise and coupling rise in water reservoir level and prolonged rainfall infiltration have been obtained. Factors of safety of the three cases have been obtained. Under coupling in rise of water reservoir and prolonged rainfall, factor of safety of the compacted residual soil still performed well.

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