Influence of groundwater seepage on the stability of a laterally confined dip slope in centrifuge models

〇Pongsakorn WONGCHANA, Shanzhi TAO, Thirapong PIPATPONGSA, Yosuke HIGO

Abstract

This research aims to investigate seepage-induced instability in a thrust-loaded dip slope using centrifugal modeling. The study specifically focused on the failure mechanism induced by groundwater seepage. The study concluded that the failure mechanism in a dip slope involves losing support at the toe of the slope, and progressive failure occurring depending on the rise in groundwater level. Employing centrifuge modeling, it replicates seepage-induced landslide conditions and utilizes gauges to measure some quantities for assessing slope failure to validate the conceptual framework proposed in the previous study.

Materials and Methods

The slope model utilized Hiroshima sand with a permeability coefficient of 2.4×10^{-5} m/s, positioned on a porous stone acting as a permeable rock layer with a coefficient of 5.0×10^{-5} m/s. This porous stone, with dimensions of 20 mm thick, 400 mm wide, and long, facilitated more efficient water flow than the soil model. The Hiroshima sand, compacted to 90% degree of compaction and 8% water content, was used. The model, illustrated in Fig. 1, featured a 40° slope angle, 30-mm thickness, 400-mm breadth, and 200-mm length, with measuring devices placed for monitoring water seepage and observing slope behavior (Fig. 2).

In the experimental procedure, the slope model was triggered by both surcharge, serving as a moving boundary to push the slope in the model test, and watering, simulating groundwater seepage. Initially, the centrifugal acceleration was loaded and maintained at a constant 20G. Subsequently, the slope failure was triggered by applying surcharge (2.4kg) first, followed by the supply of water to observe the subsequent failure.

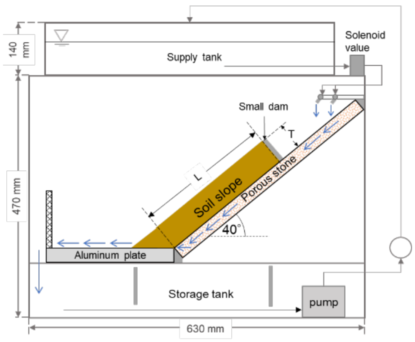

Fig. 1 Schematic diagram of the experimental setup

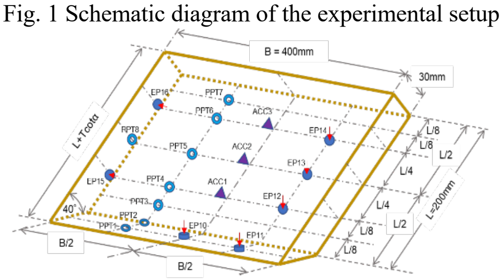

Fig. 2 Slope model with instrumentations

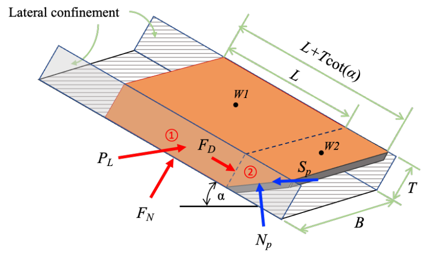

Fig. 3. Laterally confined slope lying on bedding plane and toe support.

Theocratical Calculation

This study employs the concept of dip slope with lateral confinement and toe support. The configuration of the inclined surface is illustrated in Fig 3, where the slope is stabilized by lateral, and toe supports. Consequently, the dip slope can be divided into two distinct sections: ① the main slope block, and ② the toe segment. The gravitational forces acting on the soil are represented by Eqs. (1) and (2). Furthermore, the components of the soil's weight in terms of the normal forces, F_N, determined by Eqs. (5) and (6) and the driving force, F_D, determined by Eq. (4), are regulated by the amounts of surcharge (ΔW) and water supply ($n_w, water\ ratio$) as appeared in Eq. (3).

$$W_1 = \gamma BTL \tag{1}$$
$$W_2 = \frac{\gamma BT^2}{2}\cot(\alpha) \tag{2}$$
$$\gamma = \gamma_t(1-n_w) + \gamma_{sat} n_w \tag{3}$$
$$F_D = W_1\sin(\alpha) + \Delta W(sin(\alpha) - tan\,(\phi_r)\cdot cos\,(\alpha)) \tag{4}$$
$$F_{N1} = W_1\cos(\alpha) \tag{5}$$
$$F_{N2} = W_2 \tag{6}$$

The shear resistance along the bedding plane (R_B) is governed by the contact area of the interface. Additionally, the lateral shear resistance (R_L) is dictated by the contact areas of the lateral support and can be calculated by the frictional force relying on the average pressure exerted on the laterally confined surface (P_L). Consequently, the equations for determining R_B and R_L are provided in Eqs. (7) to (10) respectively.

$$R_B = F_{N1}tan(\phi_i) + c_iLB \tag{7}$$
$$P_{L1} = \frac{F_{N1}}{BL}K_p + 2c_d\sqrt{K_p} \tag{8}$$

Shear strength reduction ratio (r_d), (Dawson et al., 1999[2]) is defined as follows.

$$r_d = \frac{\tan(\phi_d)}{\tan(\phi)} = \frac{c_d}{c} \tag{9}$$
$$R_L = \int_o^T (P_{L1}tan(\phi_s) + c_s)Ldt \tag{10}$$

Furthermore, the force that remains (F_P) from the upper portion of the slope exerts pressure on the toe segment, following Eq. (11). The potential for toe sliding emerges when F_P surpasses the resistance of the toe segment. At the termination point of the slope, the toe support holds the equilibrium of three forces: the normal force (N_p), the shear force (S_P), and the lateral resistance (Rs). These three forces can be described by Eqs. (14), (15) and (13), respectively.

$$F_P = F_D - R_B - 2R_L \tag{11}$$
$$P_{L2} = \frac{F_{N2}}{BT\cdot csc(\alpha)}K_p + 2c_d\sqrt{K_p} \tag{12}$$
$$R_s = \int_o^T (P_{L2}tan(\phi_s) + c_s)t\cdot cot(\alpha)dt \tag{13}$$
$$S_P = F_P\cos(\alpha) - 2R_s \tag{14}$$
$$N_P = F_P\sin(\alpha) + W_2 \tag{15}$$
$$S_P = N_P\tan(\phi_t) + c_tBT\cdot csc(\alpha) \tag{16}$$
$$F_P = P_s = \frac{(c_tBT\cdot csc(\alpha) + 2R_s)\cos\,(\phi_t) + W_2\sin(\phi_t)}{\cos\,(\alpha+\phi_t)} \tag{17}$$

Therefore, total resistance (R_T) can be combined as Eq. (18) and the corresponding factor of safety can be calculated as Eq. (19)

$$R_T = R_B + 2R_L + P_s \tag{18}$$
$$\text{FS} = R_T/F_D \tag{19}$$

Results and discussion

Following Pipatpongsa et al. (2022), r_d is computed with Eq. (20), considering both σ_h' and σ_v'. Also, r_d can be derived from earth and water pressures at the same level. r_d ranges from -1 (active) to +1 (passive).

$$r_d = \frac{\sigma_h' - \sigma_v'}{2\sqrt{(\sigma_v'\tan\phi + c)(\sigma_h'\tan\phi + c)}} \tag{20}$$

In the comparison of theoretical predictions and experimental results (Fig. 4), the surcharge weight was set at 2.4 kg, and r_d=1 for a passive slope in the prediction line. Groundwater was predicted for slope failure (n_w=0.11). Experimental results show a stable FS with the surcharge(2.4kg), decreasing after water supply (n_w=0.15) and reaching collapse when water increasing (n_w=0.20).

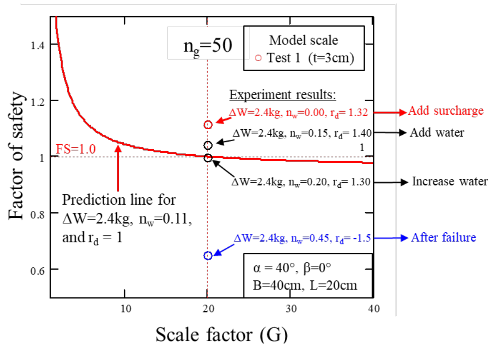

Fig. 4. Comparison between theoretical prediction and experimental results

Conclusions

This study confirms that groundwater rise significantly impacts slope failure. The comparison shows good agreement between predictions and experiments, highlighting water rise as a destabilizing factor. However, the experimental r_d, larger than the predicted r_d=1, leads to larger groundwater seepage triggering the slope collapse.

Reference

1. T. Pipatpongsa, K. Fang, C. Leelasukseree and A. Chaiwan (2022): Stability analysis of laterally confined slope lying on inclined bedding plane, Landslides, 1-19.
2. Dawson, E.M., Roth, W. and Drescher, A. (1999): Slope stability analysis by strength reduction, *Geotechnique,* 49(6), 835–840.