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EFFECTS OF SCOUR AND HYDRAULIC GRADIENT ON THE STABILITY OF GRANULAR SOIL SLOPE

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Small scale model tests were conducted to study the effect of scour on the stability of granular soil slope. The results show that scour will lead to flow slide of the entire slope or localized instability at the toe of a granular soil slope. The type of failure and the extent of instability are affected by the size of the scour and the slope angle. Model tests on a granular soil slope subjected to seepage of different hydraulic gradients were also conducted to study the effect of hydraulic gradient on the stability of slope. The results show that the presence of seepage will destabilize a slope which would otherwise be stable without seepage. Relationships between the hydraulic gradient and slope angle are established experimentally and compared with theoretical predictions.

1 Introduction

It is well known that loose granular soil deposits are susceptible to liquefaction. Another type of failure associated with loose granular soil is flow slide. Since Terzaghi published his case studies on submarine flow failure (Terzaghi 1956), numerous other cases have been reported (Eckersley 1985, Kramer 1988, Kraft et al. 1992, Lade 1993; Hight et al. 1999). Although flow slides often occur in relatively loose sand, there are also reports on flow slides occurring in relatively dense sand (Hadala & Torrey III 1989, Fleming et al. 1989, Sassa 2000). Static liquefaction has often been identified as one of the main factors causing the development of flow slide. This may be the case for flow slides occurring in loose or contractive sand. However, such an explanation may not be applicable to flow slides occurring in relatively dense sand. Based on observations made from a limited number of case studies (Hadala & Torrey III 1989, Kraft et al. 1992, Hight et al. 1999), scour at the toe of a slope appears to be an important factor affecting the stability of dense granular soil slopes.

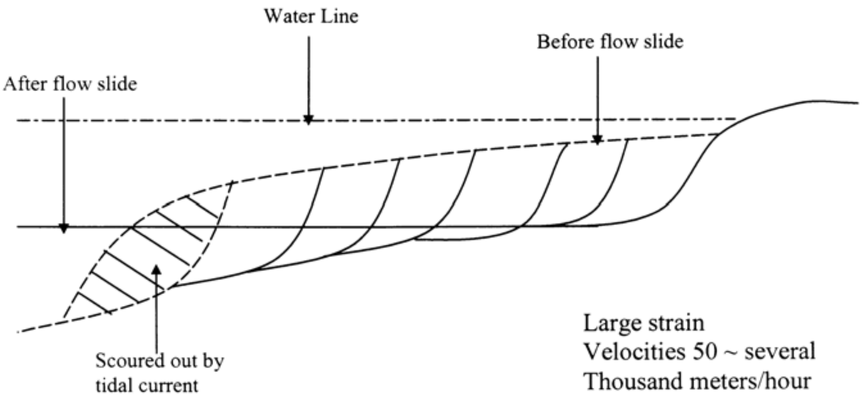


Figure 1. Retrogressive flow slide due to scour (after Koppejan et al. 1948)

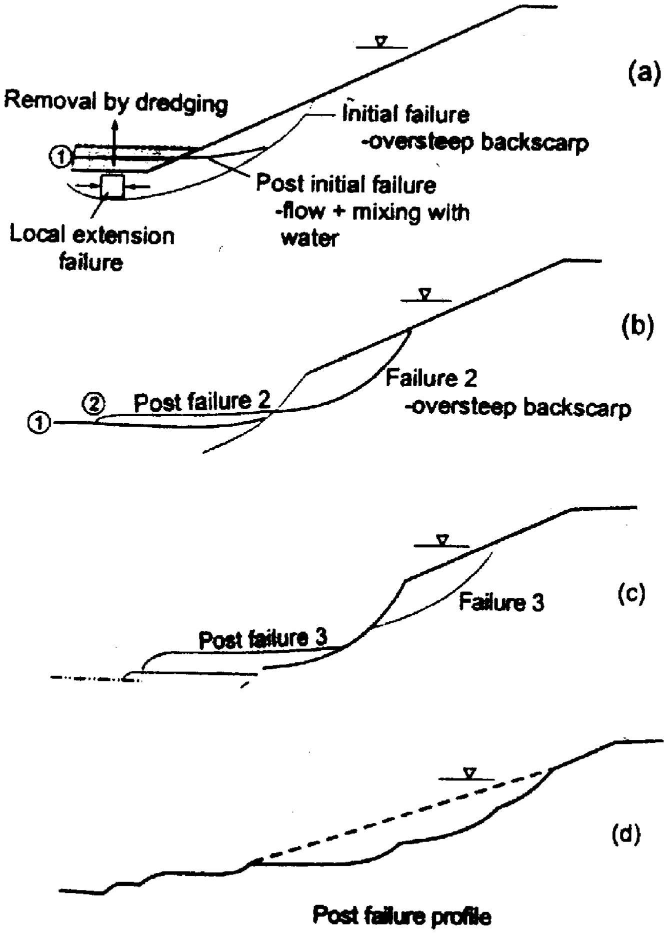


Figure 2 Retrogressive flow failure due to dredging (after Hight et al. 1999)

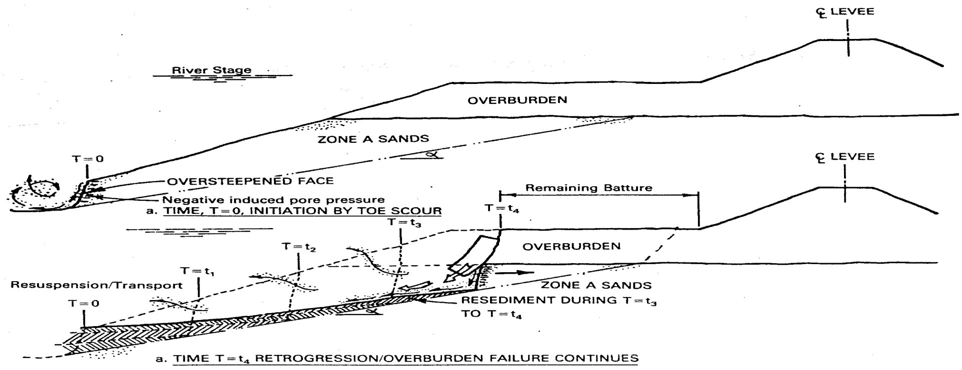


Figure 3 Retrogressive slide development along Mississippi Rivebank (after Hadala & Torrey III 1989)

For underwater slopes, scour can be an important detrimental factor. As shown in Fig. 1, scour near the toe of a slope can cause retrogressive flow slide along an underwater slope. The dredging alone the toe of a slope can have the same effect as illustrated in Fig. 2. It should be pointed out that such failures can occur in both loose and dense sand. The retrogressive slide developed along Mississippi riverbank, as shown in Fig. 3, was in relatively dense sand (Hadala and Torrey III 1989). So far, we still have not understood fully how the slide develops with scouring and what are the mechanisms that control the slide along a relatively dense granular soil slope. For this purpose, some small-scale model tests have been conducted to investigate how the scour process affects the stability of a dense granular soil slope.

Another factor that affects the stability of riverbanks or underwater slopes is seepage due to the variation in water levels or hydraulic gradients. The effect of seepage on the stability of an infinite-slope has been evaluated analytically (Teunissen and Spierenburg 1995, Budhu and Gobin 1996). The seepage direction also affects the stability of a slope. Water seeping in a generally horizontal direction destabilizes slopes, whereas water seeping vertically downward produces no destabilizing forces and no pore pressures. The effect of seepage and hydraulic gradient on the stability of slope is also discussed in this paper.

2 Effect of Scour

2.1 Model Tests

The small-scale model tests were carried out using a model of 500 mm long, 400 mm high and 50 mm wide as shown schematically in Fig. 4. A schematic diagram of the model is shown in Fig. 4. As the problems under studied can be simplified as under plane strain conditions and the shear strength of sand are frictional in nature, the granular soil grains were modeled by aluminum pins of 50 mm long and 3 or 1.5 mm in diameter as shown in Fig. 6.

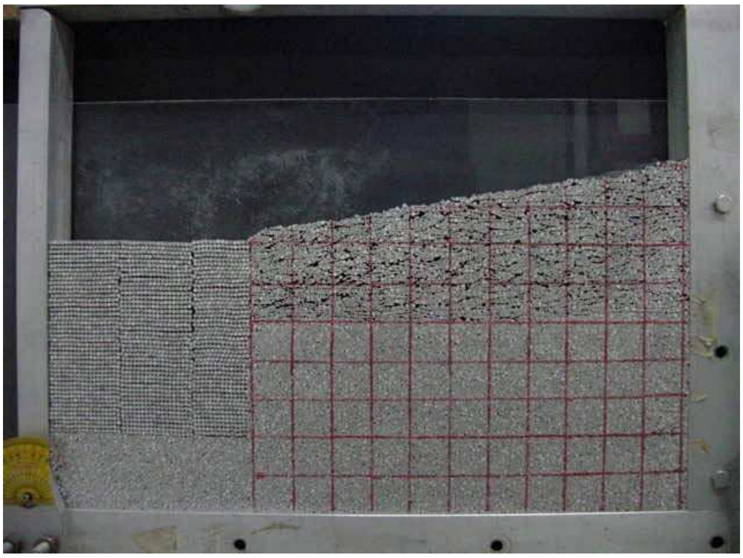


Figure 4. Model used in this study

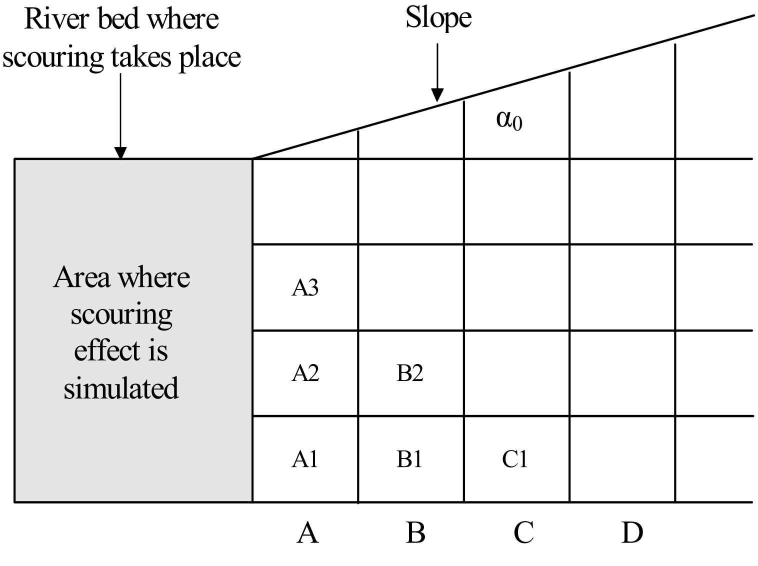


Figure 5. Configuration of small-scale model test.

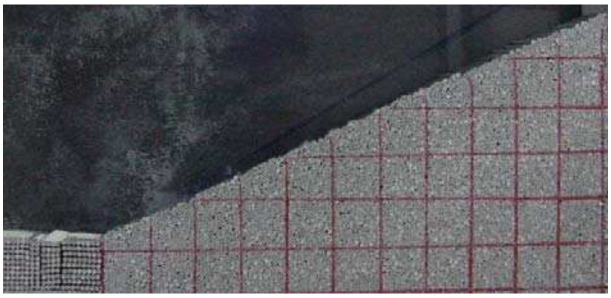
Figure 6. Pins used for the model tests.

To model slopes that are relatively densely packed, the pin mass was compacted. To simulate loose packing with the presence of mica (Hight et al. 1999), tiny pieces of transparency of various shapes and sizes were placed randomly in between the aluminium rods. The angle of repose of the pins, as measured using a tilting table, was 23.7^0 at dense packing and 15.4^0 at loose packing respectively. The aluminum pins were placed by hand to form the required slope. The scouring effect was simulated by removing the aluminum pins, layer by layer or block by block from the top of the 'river' bed which is right in front of the toe of the slope (Fig. 4). The model tests were performed on slopes of both dense and loose packing. The slope angle varied from the angle of repose to 1 in 5 (11.3^0). The slope was perfectly stable before 'scour' took place. For the convenience of observation, the slopes in all the model tests were marked with square grids as shown in Fig. 4.

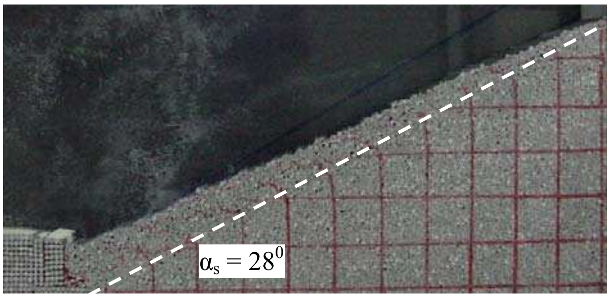
2.2. Results

Flow Slide along Entire Slope

As a first step, tests were conducted on slopes at both dense and loose states to establish the slope angles at which flow slide would occur by subjecting to a small disturbance. Slopes with slope angles close to the angles of repose of the pins at both dense and loose states were prepared. A small disturbance was introduced by removing a small block of pins of 25 mm wide by 30 mm deep. This was to simulate one scouring action. The model test results indicate that there is a critical slope angle at which the slope is stable without disturbance. However, once a disturbance is introduced in the form of removing a small block, a slide surface will develop from the toe all the way to the top of the slope, as shown in Fig. 7b for the dense slope case and in Fig. 8b for the loose case. For the convenience of discussion, the following 3 different angles are defined, as illustrated in Fig. 9: the angle of original slope, α_0, the angle of debris, α_d, and the angle of the slip surface, α_s. For the test shown in Fig. 7 for dense slope, $\alpha_0 = 25^0$, $\alpha_d = 24^0$ and $\alpha_s = 28^0$. This slope angle of 25^0 is very close to the angle of repose of the aluminum pins of 23.7^0 as estimated using the tilt table under dense condition. On the other hand, for the test shown in Fig. 8 for loose slope, $\alpha_0 = 20^0$, $\alpha_d = 20^0$ and $\alpha_s = 22^0$. This slope angle of 20^0 differs from the angle of repose of the aluminum pins of 15.4^0 estimated using the tilt table. However, the difference can be attributed to the bedding direction of the transparencies with respect to the inclination of the slope, as discussed by Loke (2002). It can be concluded from the above two tests that when the slope angle is close to the angle of repose of the soil, only a small perturbation in the form of scour can cause a flows slide to develop along the entire slope.



(a) Before scour



(b) After scour

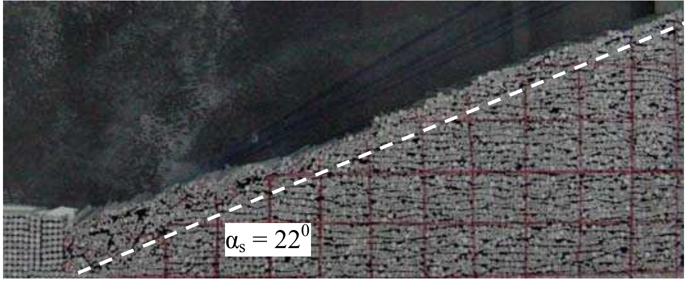
Figure 7 Model test for dense sand slope with initial slope angle of $\alpha_0 = 25^0$.

Effect of Scour to Gentle Slopes

Model tests were also conducted to study the effect of scour on gentle slopes, that is, slopes with a slope angle much less than the angle of repose of the soil. In this case, one scour action only causes localized slips along the slope. The extent of the slip is controlled by the dimension of the scour hole. With a series of scour actions, a series of slip surfaces are formed in a way similar to what is illustrated Fig. 1. Eventually, the whole slope will fail after a series of scour actions.

The results of Model Test 1 conducted on a loosely packed slope are presented in Fig. 10. The first slip occurred as soon as the first layer of aluminum pins was removed. However, this slip was highly localized and only affected a small area at the toe. When more layers of pins were removed, the slips expanded upward along the slope. The sliding stopped as soon as the removal of the pins ceased. As shown in Fig. 10b, the ‘debris’ rested at an angle, $\alpha_d = 15^0$. The angle of the slip α_s was 25^0 and the original slope, α_0 was 11.3^0.

(a) Before scour



(b) After scour

Figure 8 Model test for loose sand slope with initial slope angle of $\alpha_0 = 20^0$.

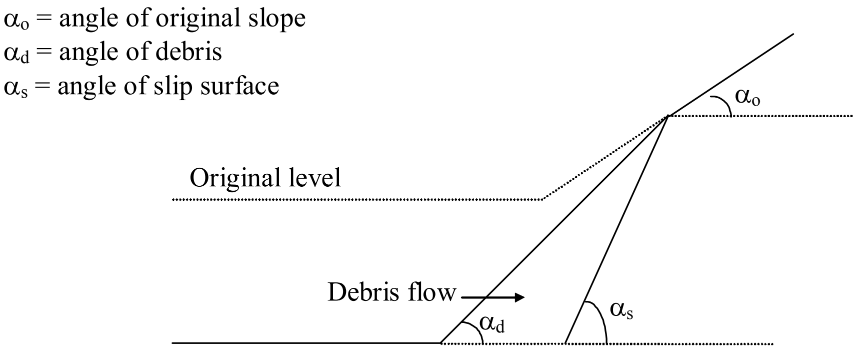
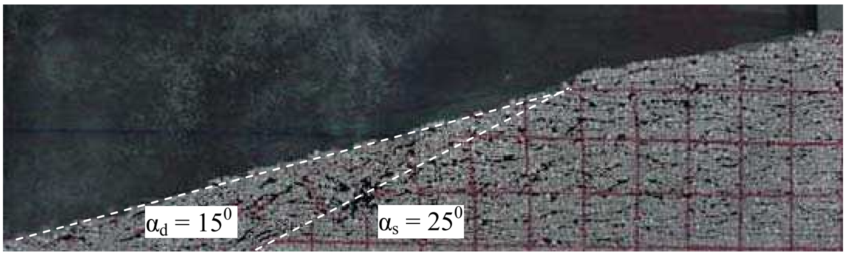


Figure 9 Angles for describing the profile of slope before and after slip

The results of Model Test 10 conducted on a densely packed slope are presented in Fig. 11. A failure mode similar to that shown in Fig. 10 was observed. The first slip occurred after the second layer of aluminum pins was removed. However, this slip was highly localized and affected only the toe. When more layers of pins were removed, the slips expanded upward along the slope. The slip took place instantly as the pins were removed. As shown in Fig. 11b, the angle of the slip, α_s, was 40^0, the `debris' rested at an angle, α_d, of 18^0. The original slope, α_0, was 11.3^0.

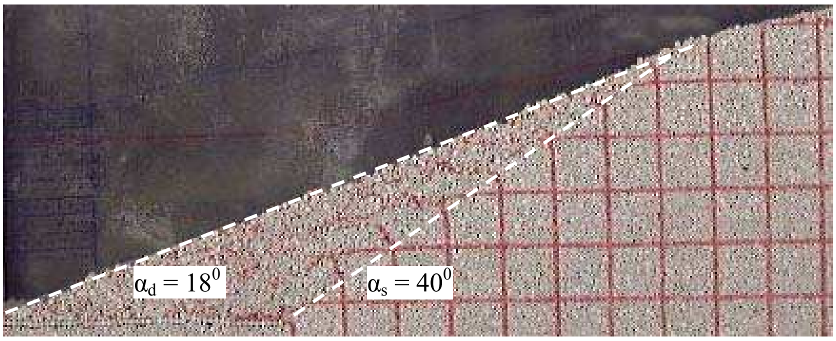
(a) Initial state



(c) Final state

Figure 10 Model test for loose sand slope with initial slope angle of $\alpha_0 = 11.3^0$

(a) Initial state



(b) Final state

Figure 11 Model test for loose sand slope with initial slope angle of $\alpha_0 = 11.3^0$

Summary of Observations

More model tests on both loose and dense slopes were conducted and reported in Loke (2002). The model test results for dense and loose slopes can be compared as follows. Under dense conditions (Fig. 11), the angle of the slip surface, α_s, ranges from 38.0° to 40.0°, while the angle at which the 'debris' rested, α_d, ranges from 18.0° to 20.0°. Under loose conditions, α_s ranges from 25.0° to 32.0° and α_d ranges from 15.0° to 16.0°. The results from the model tests suggested that scour at the toe of the slope alone could have triggered the initial failure in both dense and loose granular slopes, leaving an over-steepened and unsupported back-scarp as suggested by Hadala & Torrey III (1989) as shown in Fig. 3. Under loose conditions, the values of α_s and α_d were found to be generally lower, and the failure slip surface also covers a slightly larger extent. These observations suggested that in loose granular slopes, a larger slip surface may develop and that the 'debris' may tend to flow through a longer distance and rest at a shallower angle when compared with dense granular slopes.

The model tests results showed that multiples or sustained scouring/dredging is required to form multiple slip surfaces retrogressively. The observations from the model tests showed that the development of the slip surface is not a continuous process, but relies on subsequent scouring. This is different from the common belief that when a flow slide occurs in granular soil, the slip surface will develop continuously and cause the whole slope to collapse within a short time. Therefore, from the above observations, it may be concluded that sustained scouring/dredging is necessary for retrogressive flow failure to develop in both dense and loose granular slopes. In fact, this observation is consistent with that made by Hadala & Torrey III (1989) on the Mississippi Riverbank flow slides. From the model tests observations, it also appears that retrogressive failures are inevitable when there is sustained scouring at or near the toe of the slope.

3. Effect of Hydraulic Gradient

3.1 Theories

It should be noted that the above model tests were conducted under a dry condition in which the effect of hydraulic gradient is neglected. The slope will become unstable at a smaller slope angle if the effect of seepage is taken into consideration.

For the case of an infinite slope with flow parallel to the slope, the critical slope angle can be calculated as (Teunissen and Spierenburg 1995):

$$\left(\frac{\gamma}{\gamma-\gamma_w}\right)\tan\alpha = \frac{\sin(\phi_{cv}+0.8\psi)con\,\psi}{1-\sin(\phi_{cv}+0.8\psi)\sin\psi} \qquad (1)$$

Where: γ is the unit weigt of the soil, γ_w is the unit weight of water, α is the slope angle, ϕ_{cv} is the friction angle at the critical state, ψ is the dilatancy angle. For loose sand, ψ = 0. Eq. (1) becomes:

$$\left(\frac{\gamma}{\gamma-\gamma_w}\right)\tan\alpha=\sin\phi_{cv} \tag{2}$$

For ϕ_{cv} = 30 and γ = 18 kN/m^3, the slope angle calculated using Eq. (2) is 12.5^0. Therefore, if there is seepage parallel to the slope of loose sand, the slope will become unstable when the slope angle is higher than 12.5^0. For relatively dense sand with a ψ of 10^0, the critical slope angle calculated using Eq. (1) is 16.8^0. Therefore, the critical slope angle increases with the density of the soil.

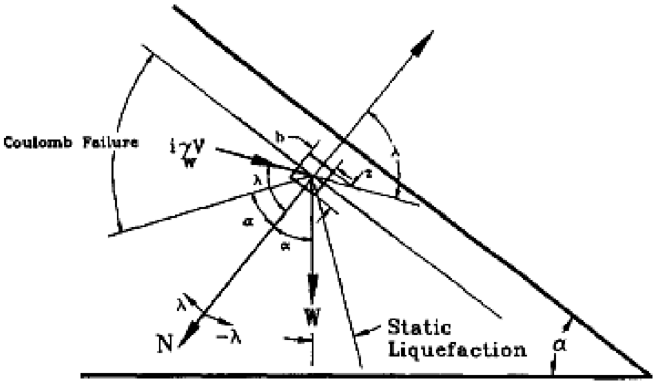


Figure 12. Forces on elemental volume of soil (after Budhu and Gobin 1996)

For a more general case where the seepage vector is assumed to be inclined at angle λ, as shown in Fig. 12. The following relationship has been derived by Budhu and Gobin (1996) based on the force analysis shown in Fig. 12:

$$\tan\phi=\frac{(\gamma'/\gamma_w)\sin\alpha+i\sin\lambda}{(\gamma'/\gamma_w)\cos\alpha+\sin\alpha\cot\lambda} \tag{3}$$

where: $\gamma' = \gamma - \gamma_w$ is the submerged unit weight of soil. For seepage parallel to slope, λ = 90^0, Eq. (3) reduces to:

$$\tan\phi=\frac{\gamma}{\gamma-\gamma_w}\tan\alpha \tag{4}$$

The difference between Eq. (2) and Eq. (4) is in the assumption of failure mode (Teunissen and Spierenburg 1995). Eq. (2) sets the lower bound of the solution. However, Eq. (4) is commonly used in soil mechanics. Based on Eq. (3), the relationship between the slope angles and the seepage directions and the hydraulic gradient for friction angle φ = 30^0 are depicted in Fig. 13. It can be seen from Fig. 13 that the slope is most critical when seepage is parallel to the slope with λ = 90^0. For loose sand with φ = 30^0, the critical slope angle is around 17^0, which is about the same as calculated using Eq. (2). However, Fig. 13 does not show directly how the critical slope angle is affected by the hydraulic gradient.

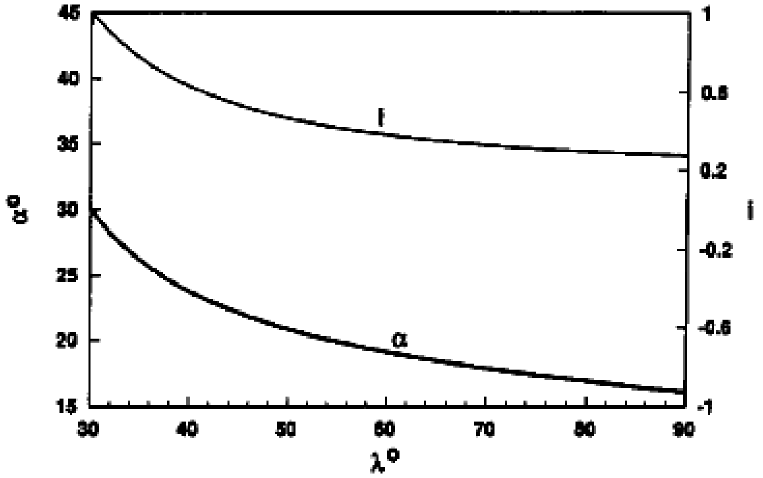


Figure 13 Slope angles for different seepage directions and corresponding hydraulic gradient for φ = 30^0 (after Budhu and Gobin 1996).

When the seepage force or the hydraulic gradient becomes too large, quicksand will occur in soil. The condition for quicksand to occur is defined by the hydraulic gradient i_{cr} which can be calculated as:

$$i_{cr} = \frac{\gamma_s - \gamma_w}{(1+e)\gamma_w} \tag{5}$$

where γ_s is the unit weight of the solids. Eq. (5) shows the relationship between the critical hydraulic gradient and the void ratio of the soil –the looser the soil, the smaller the critical hydraulic gradient, the easier for quicksand to occur. Eq. (5), however, does not relate the hydraulic gradient to the critical slope angle.

The influence of seepage on stability of sandy slope was also examined by Van Rhee and Bezuijen (1992) by adopting both the continuum mode and the single-particle mode. They have derived the following two relationships between the hydraulic gradient *i* and the slope angle α for a soil with friction angle φ as follows:

Based on the continuum mode:

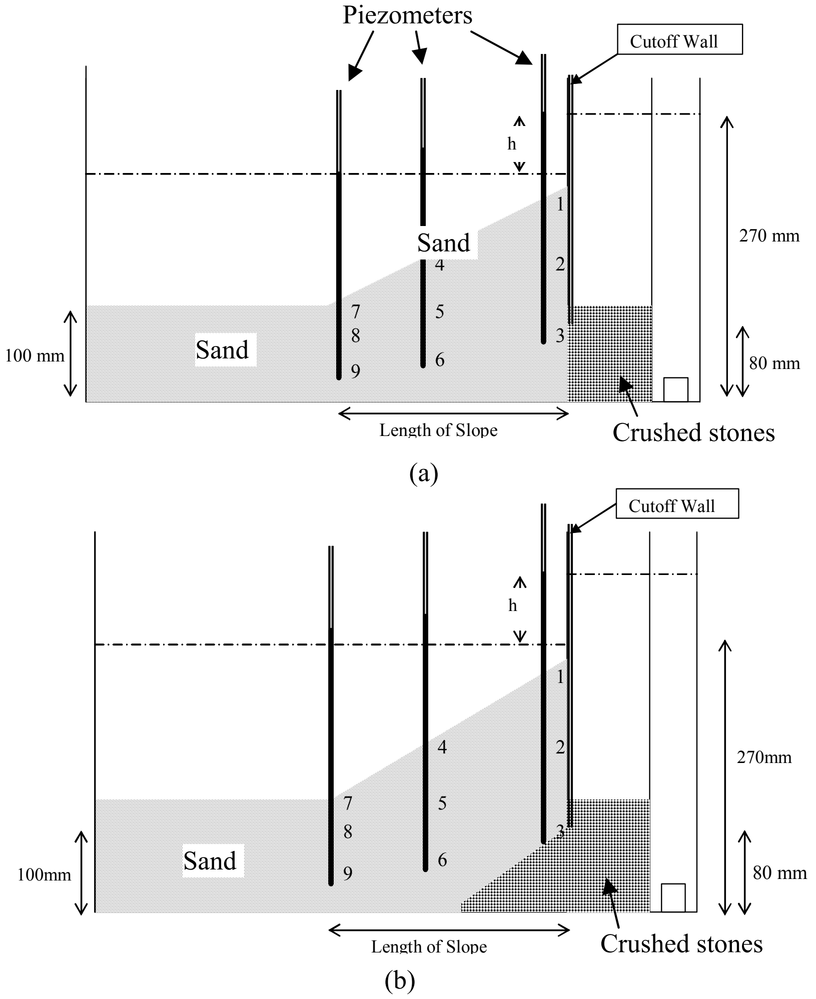
$$i = -(1-n)\frac{\rho_s - \rho_w}{\rho_w}\frac{\sin(\phi-\alpha)}{\sin\phi} \tag{6}$$

where: n is the porosity of the soil and i is positive for flow into the slope.

Based on the single-particle mode:

$$i = -\frac{4(\gamma_s - \gamma_w)}{3\gamma_w} \frac{\sin(\phi - \alpha)}{\sin\phi} \tag{7}$$

3.1 Model Tests



(a)

(b)

Figure 14 Schematic illustration of the seepage model test arrangement

To investigate how the stability of slope is affected by the hydraulic gradient, some model tests were conducted using a hydraulic flume as shown schematically in Fig. 14. An impervious vertical cutoff wall with a permeable filter screen install at the bottom 80 mm of the wall was used behind the slope. Crushed rocks were placed on the other side of the wall into two configurations as shown in Fig. 14(a) and 14(b). For each configuration, two types of tests were conducted: (i) rapid drawdown of water from the slope side and (ii) a rapid rise in the water level behind the slope. Piezometers were used to measure the total heads at different depths and locations.

The model tests were conducted on medium loose sand slopes with slope angles of 26.6^0, 31.0^0 and 33.7^0. The sand used was uniformly graded coarse sand with the mean grain size of 1.47 mm. The friction angle at medium loose state was 36^0.

For each case, computer software, SEEP/W, was used to calculate the hydraulic gradient distributions in the slope. The calculated total heads were compared with those measured using piezometers. Good agreements were achieved in most cases. Based on the model tests and the computer analyses, the total head and hydraulic gradient distribution in the slope at the moment where failure occurred was determined. The maximum hydraulic gradient calculated is plotted versus the slope angle in Fig. 15. Theoretical predictions using Eqs. (6) and (7) are also plotted in Fig. 15 for comparison. It can be seen that all the experimental data are bound in between of the lines given by the two equations.

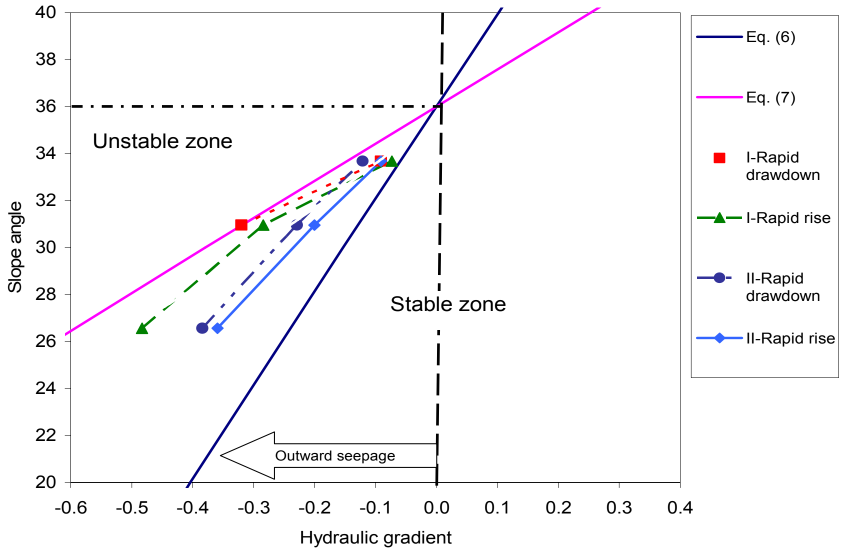


Figure 15 Comparison of measured and calculated slope angle versus hydraulic gradient relationship for sandy slope.

4. Conclusions

The following conclusions can be obtained from studies presented in this paper:

(1) Scour or dredging at or near the toe of a granular soil slope will cause an otherwise stable slope to collapse irrespective of the density of the soil. For

gentle slopes, the entire slope does not collapse instantly. Local slip surfaces occur near the toe first and gradually expand upward along the slope when the scouring action is sustained.

(2) Seepage or hydraulic gradient affects the stability of slopes. Without the presence of seepage and liquefaction, flow slide type of failure can only occur along the entire slope when the slope angle is close to the angle of repose of the soil. With seepage directing out of the slope surface, the critical slope angle, that is the slope angle at which flow slide can occur, becomes much smaller than the angle of repose of the soil. The higher the hydraulic gradient and the looser the soil, the smaller the critical hydraulic gradient. A relationship between the critical slope angle and the hydraulic gradient is established and compared with some theoretical predictions.

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