Scale Model Tests of the Dynamical Stability of Saturated Sand

Interprétation des essais sur modèles de la stabilité dynamique du sable saturé

by Z. BAZANT Jr., Professor of Foundation Engineering, Techn. University, Prague, Czechoslovakia

Summary

Scale model tests of the dynamical stability of sand slopes are expressed in a form not susceptible to dimensional analysis. The author suggests dimensionless factors which may be computed from measured data. The data from three examples of dynamical stability show applications of this method.

Sommaire

Les essais sur modèles de la stabilité dynamique des talus de sable sont souvent exprimés sous une forme non compatible avec les résultats de l'analyse dimensionnelle. L'auteur propose les variables sans dimensions, à faire intervenir dans l'interprétation des résultats des mesures. Les Figs 2, 3 et 4 donnent l'application de sa méthode à trois cas expérimentaux.

Dimensional Analysis

The author regards the dynamical stability of saturated sand as a problem of equilibrium in two dimensions. Dynamical stability is the stability of sand exposed to vibration, either natural (by earthquake) or artificial (by machinery or explosives). He considers that a sand is dynamically stable when its density is such that there is no measurable settlement of the surface under vibration. The problem of dynamical stability is vital for the solution of stability of slopes of various kinds, e.g. upstream slopes or earth dams, slopes of irrigation canals and subsoil beneath machine foundations. Dynamical stability being governed by too many variables, it cannot be determined by analysis, and the author has therefore suggested scale model tests. Interpretation of model tests demands a knowledge of factors to be measured and scale model laws to be fulfilled.

Let us assume the general case of dynamical stability of slope *ab* of saturated sand through which water flows. The stability may be expressed by the function (Fig. 1).

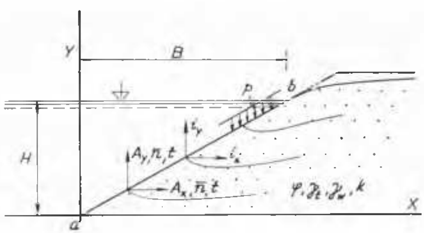

Fig. 1 Diagram of arguments considered in stability analysis. Schéma des variables considérées dans l'étude de la stabilité.

$$f(\varphi, \gamma_t, \gamma_w, i_x, i_y, H, B, k, A_x, A_y, n, t, p) = 0 \qquad (1)$$

φ denotes angle of internal friction of saturated sand, γ_t unit weight of combined soil and water, γ_w unit weight of water, i_x, i_y components of hydraulic gradient of seepage at the surface of sand at a critical point, which may be supposed on the surface of the upper third of a slope, H is the height of slope *ab*, B the horizontal projection of slope *ab*, k the coefficient of permeability of sand, and p the pressure produced by static surface surcharge, A_x and A_y are components of amplitude of vibration, $\bar{n}$ frequency of vibration, t the time elapsed from the beginning of vibration to the failure of dynamical stability (settlement of slope) or the time required to vibrate the whole mass of sand.

In equation (1) sand is assumed to be subjected to vibration over its whole mass and therefore damping may be neglected. The hydraulic gradients i_x, i_y represent gradients of dynamical seepage, which is produced by the combined effects of vibration and gravitation. Vibration seepage occurs at the beginning of vibration of sand, when porosity decreases and water is squeezed out of the pores; this effect is not normally observed owing to its relatively great velocity. Dynamical seepage may be defined as seepage caused by vibration alone.

Eq. (1) we reduce to dimensionless form :

$$f(\pi_1, \pi_2, \ldots\ldots \pi_9, \pi_{10}) = 0$$

where π denotes a dimensionless factor.

Applying dimensional analysis to the method previously used by the author (BAŽANT, Jr., 1957) we obtain the function :

$$f\left(\varphi, i_x, \frac{i_y}{i_x}, \frac{\gamma_t}{\gamma_w}, \frac{H}{B}, \frac{H}{A_y}, \frac{A_y}{kt}, \frac{A_y}{A_x}, \frac{A_y\bar{n}}{k}, \frac{p}{A_y\gamma_w}\right) = 0 \quad \ldots. \quad (2)$$

The unknown function f in equation (2) is found by model tests.

Model Laws

Model tests will correctly reveal what occurs at full scale if model laws are obeyed. We can choose three scales of reduction : force 1 : λ, length 1 : λ and time 1 : τ. Thence we can compute model laws from the condition that similitude exists when dimensionless factors of model and prototype are equal.

From analysis it follows that scale model laws require geometric similarity of length and seepage 1 : λ and reduction of time 1 : τ. Coefficient of permeability should be changed in the ratio 1 : (λ/τ). We use the same sand in the scale model and in the prototype, so that $k_1 = k_2$, values which can be obtained only when $\lambda = \tau$. The pressure on surface of slope should be changed in ratio 1 : λ. The amplitude should be decreased by the ratio 1 : λ and frequency increased τ : 1.

Results of Model Tests

Tests are not available for providing a solution in accordance with equation 2. Only results for simplified cases are known. Nevertheless, these data are commonly published in dimensional form, not suitable for practical use, and furthermore the necessary measurements are often neglected. The author has derived functions from dimensional analysis for interpreting tests results, and suggested charts which may be used as guidance for tests. It is necessary to emphasize that the dynamical behaviour of each sand may be very different. Therefore, it has been necessary to test each sand separately and thus obtain appropriate data of its dynamical stability. It is not possible to consider Figs. 2 to 4 as general rules for all sands.

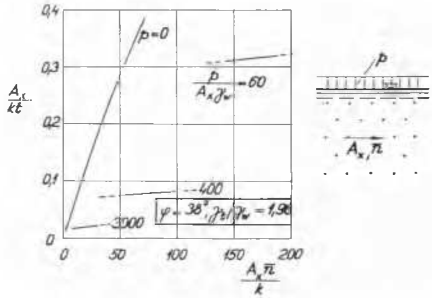

Fig. 2 Horizontal vibration of saturated sand with horizontal surface and surcharge.
Vibration horizontale du sable saturé à surface libre horizontale avec surcharge.

Tests results for horizontal surface of saturated sand with surcharge, horizontal vibration and without seepage were published by N.T. Valishev (1959). The author suggests interpretation of his results as follows. Equation (2) can be simplified to the function :

$$f\left(\varphi, \frac{\gamma_t}{\gamma_w}, \frac{A_x}{kt}, \frac{A_x\bar{n}}{k}, \frac{p}{A_x\gamma_w}\right) = 0 \qquad (3)$$

Dynamical stability of saturated sand was measured after the method of N.N. Maslov and defined as acceleration of vibration which is not producing measurable settlement of sand. From published results it is possible to compute dimensionless arguments and to plot Fig. 2. The sand from the river Volga near Stalingrad had $\varphi = 38°$, $\gamma_t/\gamma_w = 1{\cdot}96$, $R_d = 0{\cdot}2$, $k = 2.10^{-2}$ cm/s. Grain size was medium ($D_{50} = 0{\cdot}3$ mm), surface of the grains was rough, and their shape was angular.

The effect of inclination of vibration on sand with horizontal surface without seepage was studied again by N.T. Valishev (1959). The author suggests the following method for interpreting the results of the tests by simplifying equation (2) as follows :

$$f\left(\varphi, \frac{\gamma_t}{\gamma_w}, \frac{A_x}{kt}, \frac{A_y}{A_x}, \frac{A_x n}{k}\right) = 0 \quad \ldots\ldots \quad (4)$$

The results of tests are plotted in Fig. 3. The sand (beach of Sestroreck by Leningrad) had $\varphi = 34°$, $\gamma_t/\gamma_w = 1{\cdot}94$, $R_d = 0{\cdot}2$, $k = 4.10^{-2}$ cm/s. Grains were of medium size ($D_{50} = 0{\cdot}37$ mm), with a rough surface and angular shape. The amplitude during the tests was maintained at 0·3 mm, which means that the shape of the lines in Fig. 3 can only be guessed. For limiting case $A_y = 0$ the line was derived after Fig. 2.

Test results for horizontally vibrating slope without seepage were published by P.A. Grishin (1958). The author has suggested that his results can be treated in the following manner by symplifying equation (2) as follows :

$$f\left(\varphi, \frac{\gamma_t}{\gamma_w}, \frac{H}{B}, \frac{H}{A_x}, \frac{A_x}{kt}, \frac{A_x\bar{n}}{k}\right) = 0 \quad \ldots\ldots \quad (5)$$

Equation (5) shows that dynamical stability depends on the height of the slope. The sand used was fine ($D_{50} = 0{\cdot}18$ mm) with a rough surface and angular shape. The estimated results are given in Fig. 4.

Fig. 3

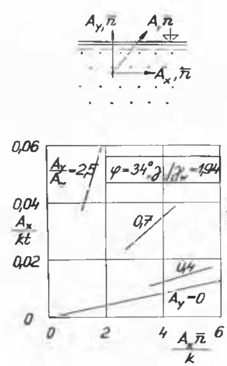

Fig. 4

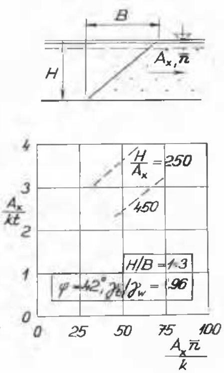

Fig. 3 Inclined vibration of saturated sand with horizontal surface.
Vibration inclinée du sable saturé avec surface libre horizontale.

Fig. 4 Horizontal vibration of saturated sand slope.
Vibration horizontale d'un talus de sable saturé.

The author also suggests the function of stability for vibrating slope with surcharge but without seepage. For unidirectional horizontal vibration A_x the resulting dimensionless function is :

$$f\left(\varphi, \frac{\gamma_t}{\gamma_w}, \frac{H}{B}, \frac{H}{A_x}, \frac{kt}{A_x}, \frac{A_x\bar{n}}{k}, \frac{p}{H\gamma_w}\right) = 0 \qquad (6)$$

which it is possible to plot with coordinates $(A_x)/kt$, $(A_x\bar{n})/k$ and with $H/(A_x)$ as the system of curves, φ, γ_t/γ_w, H/B, $p/(H\gamma_w)$ being constants. The stability depends as in the previous case on the height of slope, and is improved by the influence of surcharge.

References

[1] Bažant, Z., Jr. (1957). Influence of vibration and seepage on stability of cohesionless soil. *Proc. 4th International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2, pp. 278-281 ; Vol. 3, p. 265.

[2] Grishin, P. A. (1958). Influence of vibration on stability of submerged slopes (in Russian). *Scientific Works of the Institute of Civil Engineering in Leningrad*, Vol. 28, pp. 70-86.

[3] Valishev, N. T. (1958). Remarks on appraisal of dynamical stability of sand in subsoil and in hydraulic structures (in Russian). Printed Summary of Master Thesis, Institute of Civil Engineering, Leningrad.