Investigations on Stability of Saturated Sand Foundations and Slopes against Liquefaction

Recherches sur la stabilité des fondations et des talus en sable saturé dans le but d'éviter le phénomène de la liquéfaction

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Summary

The author discusses how a saturated sand mass liquefies under dynamic action, pointing out that the key to the solution of the liquefaction problem is to find out the relationship connecting the developed pore pressure, the density of the sand, the intensity of the dynamic action and the state of stress of the sand mass. Experimental determination of this relationship is described, and methods of adapting the experimental findings to the stability analyses of saturated sand foundations and slopes are discussed.

Sommaire

L'auteur discute comment un massif de sable saturé soumis aux actions dynamiques se liquéfie. Il indique que la clef de la solution du problème de la liquéfaction est de trouver la relation entre la pression interstitielle développée, la densité du sable, l'intensité de l'effort dynamique et l'état des contraintes du massif de sable. La détermination expérimentale de cette relation est décrite et les moyens utilisés pour adapter les résultats expérimentaux à l'analyse de la stabilité des fondations et talus en sable saturé sont discutés.

The problem of liquefaction of a saturated sand mass subjected to earthquakes, blastings and other dynamic actions has been actively studied by many investigators for more than two decades [1 to 6]. Yet much controversy still exists, and a satisfactory criterion for the stability of saturated sand foundations and slopes against liquefaction has yet to be established.

The particles of loose sand will be consolidated when subjected to repeated change of state of stress due to vibration, and for saturated sand mass such compaction will undergo two stages. Vibrations will loosen the mutual contacts between the sand particles and throw them successively into suspension. During this stage the total pressure acting on the sand mass will be gradually transmitted from the soil skeleton to the pore water, and the pore pressure will gradually increase until a maximum value is reached. At this instant the shear strength of the sand mass is greatly reduced, and it may start to flow as a viscous fluid. During the second stage, due to the establishment of the pore pressure, drainage of the pore water begins, and the suspended sand particles will gradually settle out and rearrange themselves into a more compacted state. The pressure will then be transmitted from the water to the soil skeleton, and this re-establishment of effective pressure will restore the stability of the soil mass.

The magnitude of the maximum pore water pressure developed in the sand mass during the process of vibration has been found to be affected not only by the density and other physical properties of sand, but also by the intensity and other characteristics of the dynamic action, and, moreover, in a very important way by the original state of stress in the sand. Hence the key to the solution of the liquefaction problem of a given sand mass is to find out the relationship connecting these factors.

Experiments performed so far [1, 2, 4, 6] were carried out on saturated sands packed in laterally confining cylinders. In such cases the ratio between the induced lateral pressure σ_3 and the vertical pressure σ_1 acting on the surface of the sand mass is always equal to the coefficient of earth pressure at rest K_0, or

$$\sigma_3/\sigma_1 = K_0$$

Since this kind of experiments represents only one very specific state of loading to which the sand mass is subjected, it is evident that the testing results thereby obtained cannot be applied directly to solve the liquefaction problem of sand foundations or slopes, wherein the ratio σ_3/σ_1 of the stressed sand mass at any point is generally different from K_0.

In order to obtain more general testing results so that they may be used to solve the liquefaction problems of sand foundations and slopes, experiments should be performed on triaxial compression machine with specific loading devices.

Let σ_1 and σ_3 be respectively the maximum and minimum principal stress due to static loading at any point in a given sand foundation or slope, and let $\pm\Delta\sigma_1$ and $\pm\Delta\sigma_3$ be respectively the increments of the maximum and minimum principal stress due to dynamic loading. In order to find the maximum pore pressure developed at the same point under a given dynamic action, the experimental sample must be loaded vertically and laterally within the prescribed limits $\sigma_1 \pm \Delta\sigma_1$ and $\sigma_3 \pm \Delta\sigma_3$ respectively. For simplification the test may be performed on an ordinary triaxial compression machine with the lateral pressure kept constant at $\sigma_3 - \Delta\sigma_3$ during test. The machine is laid on a vibration table which can be vibrated vertically, and the sample is loaded vertically with weights. When the table is set into vibration with acceleration "a", the vertical stress on the sample will change between the specified limit $\sigma_1 \pm \Delta\sigma_1$, in which $\Delta\sigma_1 = \sigma_1\frac{a}{g}$. A typical set of test results are given in Figs 1-3 inclusive in order to illustrate how the developed pore pressure (u) varies with the density (γ_d) of a given sand (a silty sand with $d_{50} = 0{\cdot}09$ mm and uniformity coef. = 1·4), the intensity of vibration and the original state of stress in the sand mass.

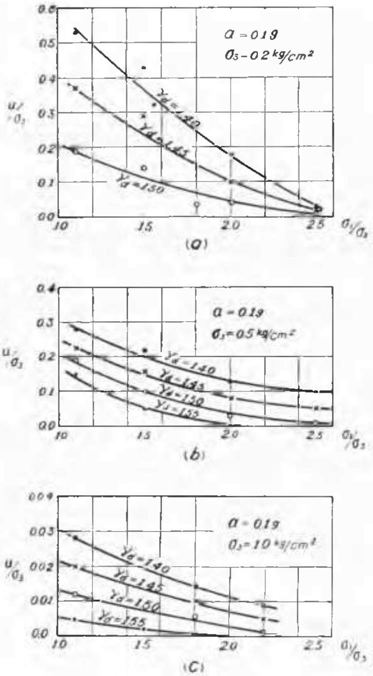

Fig. 1 The relation among u/σ_3 (developed pore pressure/min. principal stress), σ_1/σ_3 (max. principal stress/min. principal stress) and γ_d (dry density of sand) when the min. principal stress " σ_3 " and the intensity of dynamic action " a " are kept constant.

Relation entre u/σ_3 (pression interstitielle développée/contrainte principale minimum), σ_1/σ_3 (contrainte principale maximum/contrainte principale minimum) et γ_d (densité sèche du sable) lorsque la contrainte principale minimum « σ_3 » et l'intensité de l'effort dynamique « a » sont restées constantes.

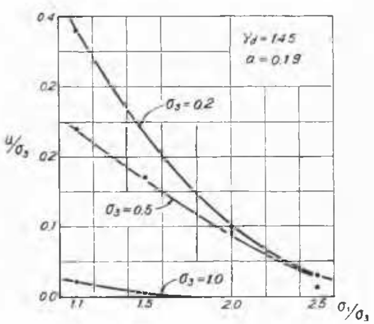

Fig. 2 The relation among u/σ_3 (developed pore pressure/ min. principal stress), σ_1/σ_3 (max. principal stress/min. principal stress) and σ_3 (min. principal stress) for a given dry density of sand $\gamma_d = 1{\cdot}45$ gm/cm³ and a given intensity of dynamic action $a = 0{\cdot}1$ g cm/sec.².

Relation entre u/σ_3 (pression interstitielle développée/contrainte principale minimum). σ_1/σ_3 (contrainte principale maximum/contrainte principale minimum) et σ_3 (contrainte principale minimum) pour une densité sèche donnée du sable γ_d = 1,45 gm/cm³ et une intensité donnée de l'effort dynamique a = 0,1 g cm/sec.².

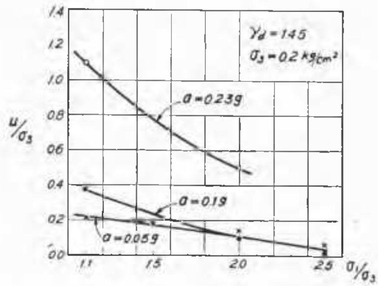

Fig. 3 The relation among u/σ_3 (developed pore pressure/ min. principal stress), σ_1/σ_3 (max. principal stress/ min. principal stress) and a (intensity of dynamic action) for a given dry density of sand $\gamma_d = 1{\cdot}45$ gm/cm³ and a given min. principal stress $\sigma_3 = 0{\cdot}2$ kg/cm².

Relation entre u/σ_3 (pression interstitielle développée/contrainte principale minimum), σ_1/σ_3 (contrainte principale maximum/contrainte principale minimum) et a (intensité de l'effort dynamique) pour une densité sèche donnée du sable γ_d = 1,45 gm/cm³ et une contrainte principale minimum donnée σ_3 = 0,2 kg/cm².

Using the experimental results thus obtained, it is possible to determine the maximum pore water pressure developed at any point in a given sand foundation or slope under any given dynamic action. The shear strength at any point along any assumed rupture surface can thus be determined, and the stability safety factor of the foundation or slope can be calculated, for example, by the usual sliding circle method.

By means of the method suggested above, it is possible to determine in a quantitative manner whether the foundation or slope is stable against liquefaction under any dynamic action. Should there be any danger of liquefaction, measures for its prevention can be devised according to the following principles. They are : (1) reduction of the intensity of the dynamic action, (2) increase of the density of sand, (3) improvement of the stress condition of the foundation or slope (e.g., increase of σ_3 or decrease of ($\sigma_1 - \sigma_3$), and (4) provision of effective drainage. The preventive measures usually adopted in the case of barrages on sand foundations include the decrease of the intensity of vibration through the reduction of discharge per unit length and the modification of the shape of the cross-section of the structure; the use of an upstream or downstream blanket to increase the surcharge on the sand mass; the compaction of loose sand foundations by means of blasting or vibroflotation; and the removal of a loose sand layer by excavation. In addition, one of the best preventive measures is to drive sheet piles around the foundation, because by so doing the lateral pressure in the region enclosed by the sheet piling is increased, and the liquefaction of that portion of foundation outside the sheet piling will not extend to the enclosed portion. To prevent liquefaction of sand slopes the most usual measures adopted include the increase in the degree of compaction of sand the decrease of slope (i.e., to increase the σ_3/σ_1 ratio) and the increase of the thickness of the surface riprap (i.e., to increase the value of σ_3). Stability against liquefaction is also largely influenced by the permeability of the sand. In the case of fine sand with small permeability, liquefaction will last longer, and thus during the time interval that the energy wave due to vibration is being transmitted through the sand mass, the maximum degree of liquefaction might occur simultaneously at all points in the foundation or slope. On the other hand, in the case of coarse sand with large permeability, this type of synchronism is more unlikely to occur. For the same reason, it is evident that by providing more effective drainage in a sand mass its stability against liquefaction will be definitely improved. In the experiments described in the present paper no drainage is provided, so that the results err towards safety.

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