Liquefaction of Saturated Sandy Soils

Liquéfaction de sols sableux saturés

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Summary

The authors give results obtained from theoretical and experimental research on the liquefaction of saturated sandy soils undertaken by them, in the Laboratory of Soil Mechanics of the Institute of Mechanics of the U.S.S.R. Academy of Sciences and in the Leningrad Polytechnic Institute.

Laboratory investigations have been carried out on various kinds of disturbances affecting saturated sandy soils and causing their liquefaction. The authors also give the results of studies on the grain-size composition and density of sands, shape of particles, entrapped gas content, initial stress condition, intensity and character of disturbances causing a collapse of the structure of the soil. Theoretical relationships are given which connect the process of consolidation in the liquefied soil with the time during which the sand is in a liquid state. These relationships largely determine the probable movements of both structures and liquified masses of soil.

Finally, the « method of standard blasting » worked out by V. A. Florin and widely used in the Soviet Union is recommended as being suitable for field investigations of the phenomenon reviewed.

Sommaire

Le présent rapport contient quelques résultats des études théoriques et expérimentales des phénomènes de liquéfaction de sols sableux saturés qui ont été effectuées aux Laboratoires de Mécanique des sols de l'Institut de Mécanique de l'Académie des Sciences de l'U.R.S.S. et de l'Institut Polytechnique de Leningrad.

Les auteurs décrivent des études de Laboratoire de la liquéfaction de sols sableux soumis à diverses influences.

Ils exposent l'influence sur les phénomènes de liquéfaction de la granulométrie et de la densité apparente des sables, de la forme des grains, de la teneur en gaz occlus, de l'état initial de contraintes du sol, de l'intensité et du caractère des influences provoquant la rupture de la structure du sol.

Ils proposent des relations théoriques, relatives au processus de consolidation des particules d'un sol liquéfié permettant en particulier, le calcul de la durée pendant laquelle le sable se trouve à l'état de liquéfaction. Ces relations déterminent en grande partie les mouvements possibles d'ouvrages et de masses de sol liquéfié.

Pour les études « in situ » du phénomène de liquéfaction, on propose d'employer « la méthode d'explosions uniformes » mise au point par V. A. Florin. La méthode est largement employée en U.R.S.S.

The liquefaction of saturated sandy soils may be described as the mechanical breakdown of the structure of the sand as well as by physical and chemical processes which tend to occur in soils, and in particular, by thixotropy. (This is the property possessed by some gels of becoming fluid when stirred, and of returning to the jelly state when stirring ceases).

This paper discusses only those cases of soil liquefaction which are observed in pure sands and which are of a mechanical nature. The phenomenon of complete or partial loss of the bearing capacity of a soil, also the transition of the sand into the state of flow due to collapse of the structure and displacements of grains of saturated sand followed by the formation of a new, denser sediment and by the decrease of the porosity of the sand, should be described as liquefaction of sandy soil.

Liquefaction consists in breaking down the structure, and liquefying the soil mass itself with subsequent consolidation. Thus the conditions necessary for liquefaction are : the collapse of the structure, with the possibility of sand consolidation and either partial or complete saturation of the sand with water.

Because of the great variety of factors causing the collapse of a sand structure, the authors propose that the criterion of collapse of the soil structure should be not the "critical void ratio" or the density of the sand, but "critical" values of the intensity of dynamic disturbance, stress condition of the soil or weight of surcharge, and hydraulic gradient of water flow through it.

Sands may pass into a state of either complete or partial liquefaction. Considering individual particles of the sand or different areas in homogeneous soil, regardless of the static homogeneity of the total volume of soil, the stress condition is different for each individual particle. Different shape and size of isolated particles account for a different number of contacts between them and different stresses. As a result, even insignificant disturbances like filtration will cause not only complete but also partial collapse of the structure of the sand due to displacements of individual unstable particles of sand subjected to minimum stress. By averaging the variable quantity of the displaced sand particles, the authors obtain "the degree of break-down", of the structure of the sand and as a result "the degree of liquefaction", of the sand. The degree of breakdown of the structure, or liquefaction may be expressed as a percentage of the breakdown of contacts, displacement of all particles and complete liquefaction of the soil.

The effect of liquefaction on the strength and stability of structures is evaluated not only by its amount of liquefaction, but also by its character. The possible movements of structures are largely influenced by the time during which the sand in a liquid state and by the viscosity of the liquefied mass of the soil.

The time of liquefaction depends upon the thickness of the liquefied stratum of the sand, the permeability of the sand, variation in the volume of voids in the process of consolidation, intensity of draining, location of the drainage system in the body of a structure and the duration of dynamic load causing collapse of the sand structure.

For several years the authors carried out numerous laboratory and large-scale field investigations on several large hydro-electric developments. Under laboratory conditions, tests were performed on special impact-and-vibrating tables and in flumes. Tests were also carried out under practical conditions on sands which were placed both naturally and hydraulically.

The main features of sand transformation into the liquefied state are the decrease of its porosity and a temporary increase of poor water pressure. Under these conditions, measurements have been made of changes in the porosity of the sand by using deeply sited reference points and an electrical method to measure porosity, based on the relationship between the specific electrical conductivity of the soil and that of the pore water. Simultaneously changes in the pore water pressures have been measured using special membrane-type inductive cells. In addition, observations were made on the velocity at which heavy bodies sank into the sand.

In impulse tests, loose saturated sands were readily concerted into a completely liquefied state over the entire depth of the stratum. The curves representing maximum excess hydraulic pressure were of triangle shape (Fig. 1 a) and the

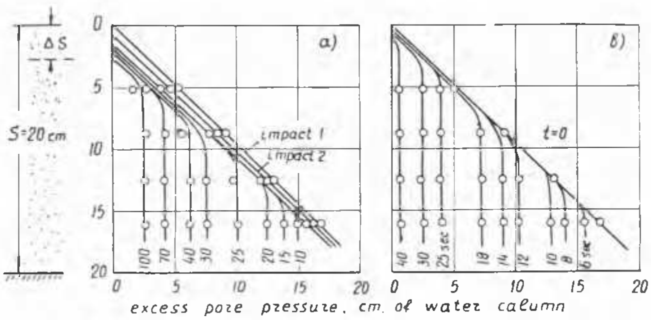

Fig. 1 Fluctuations of maximum excess water pressure due to successive impact influences and consolidation of a sand stratum in completely liquefied state.

Variations des surpressions maxima dans l'eau sous l'effet de percussions successives et consolidation de la souche sableuse totalement liquéfiée.

pressure corresponded to the weight of the waterlogged stratum with suspended sand particles ($\gamma_p \approx 2$ gm/cm^3). With the increase of sand density, the influence of stress condition of the sand determined by the weight of overburden tends to be greater, and in the lower layers of the soil no liquefaction occurs. Because of the pressure of contact between sand particles, greater intensity of dynamic disturbance is required to break down the structure of the sand than the structure of its upper layers, and as a result the curves representing maximum excess pressures at subsequent impulses are of trapezoidal shape (Fig. 1 a).

The consolidation of sand in complete liquefaction does not depend on the intensity of dynamic disturbance, and in the case of local liquefaction the increase of the intensity of dynamic disturbance leads to expansion of the liquefied zone only but not to an increase in density of sand consolidation.

As soon as the sand passes into a state of complete liquefaction, the replacement of particles or sand consolidation takes place followed by squeezing the water out of the voids in the soil. The curves representing the distribution of excess water pressure for different times, are of trapezoidal shape (Fig. 1 b). The shape of these curves is evidence that for each moment of time there is a boundary between the consolidated part of the sand and the sand in a liquid state. The process of particle replacement starts in the lower part of the sand stratum, the boundary between the consolidated and liquefied sand being moved in the direction of the surface of the soil. The upper layers of the soil remain liquefied much longer, and in these layers there is much greater displacements of the liquefied soil or maximum sinking of heavy bodies.

The initial distribution of head in a stratum of completely liquefied sand may be expressed by the following equation (Fig. 2) :

$$h = \frac{\gamma_p}{\gamma_w}(S - x) + x, \qquad \ldots. \quad (1)$$

where :

$\gamma_p = \gamma' + \gamma_w$ — unit weight of completely liquefied soil,
γ' — unit weight of suspended sand,
γ_w — unit weight of water.

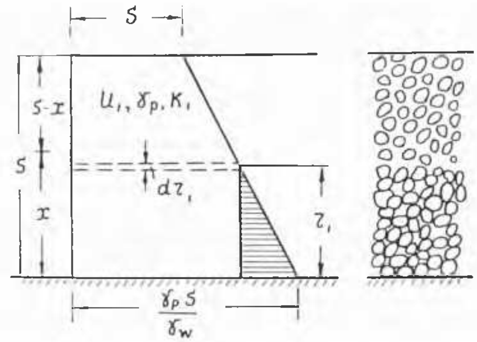

Fig. 2 Distribution of heads in a stratum of completely liquefied sand.

Répartition des charges dans la couche de sol totalement liquéfiée.

The density of the sand changes, in general, at the contact surfaces between the liquefied and non-liquefied sand stratum. Composing the equation of water equilibrium in elementary boundary layer, and considering the conditions for seepage of the squeezed water through a medium, we obtain the following :

$$t = \frac{1}{K} \cdot \frac{\gamma_w}{\gamma'} \cdot \frac{n_0 - n}{1 - n} r_1 \qquad (2)$$

where :

K — coefficient of seepage,
n_0 — initial porosity,
n — porosity after sand consolidation.

The curves representing heads and velocity of movement of the boundary of the liquefied soil obtained by equation (2) agree very well with the experimental values.

In contrast to shocks, vibrations do not cause liquefaction over the whole stratum of the soil. The process proceeds in layers : the first vibrations liquefy the upper layer which carries a comparatively light load. This reduces the pressures of overburden on the lower layers and as a result the latter pass into the liquid state with later vibrations. The zone of liquefaction extends downwards. (Fig. 3a). As soon as the

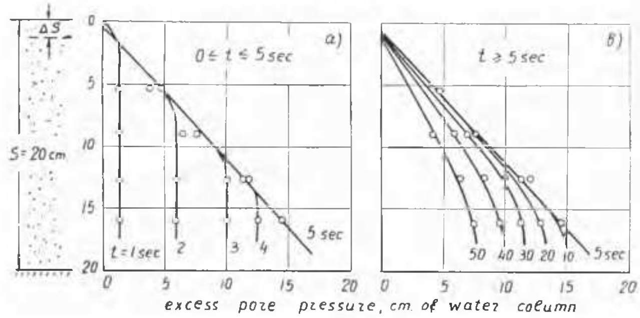

Fig. 3 Distribution of excess pressure in a sand stratum acted on by vibrations.

Répartition des surpressions dans une couche de sable soumise aux effets de la vibration.

entire stratum of sand is liquefied, the process of particle replacement or consolidation occurs, pressures in the pore water decrease and the boundary of the consolidated soil moves upwards.

The supplementary consolidation which takes place in the consolidation portion of the soil is due to the action of continuous vibrations (Fig. 3 c).

Many engineers believe that only fine sands may be liquefied. However, experience based on laboratory investigations has shown that all sufficiently loose, cohesionless soils of any grain-size may be liquefied, becauses this is only an intermediate phase in the process of consolidation of cohesionless soils, acted on dynamically. Due to high permeability, the time during which the liquid state lasts is much less for coarse-grained soils than for fine-grained ones (Fig. 4). Since

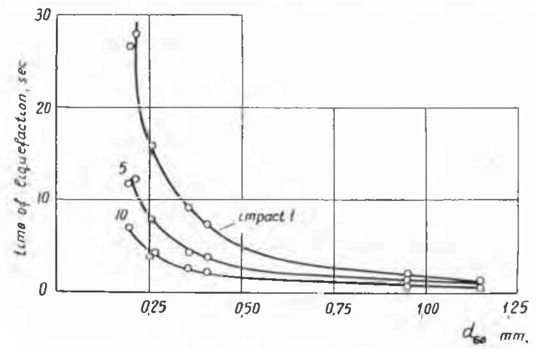

Fig. 4 Influence of grain-size composition of sand on the period of time within which the sand remains liquid.

Influence de la granulométrie des sables sur le temps pendant lequel la couche de sable se trouve à l'état liquéfié.

the liquid state lasts for only a short time, the liquefied masses of soil have no time for displacements, so that there is practically no indication that the phenomenon of liquefaction occurs in coarse-grained soils.

The initial stress condition for saturated sandy soil determined by the weight of the overburden or external applied load, reduces the possibility of sand liquefaction. Increase of loads demands considerable increase of the dynamic disturbance required to cause a collapse of the structure of the sand and to liquefy it. As a result of many field observations, the authors reached the conclusion that at depths ranging from about 10 to 15 metres below ground level, even very loose sand can hardly be liquefied. Surcharge with any material can be used as a method of reducing sand liquefaction.

The use of draining surcharge reduces not only the possibility of sand liquefaction but also, if liquefaction has already occured, the period during which it will continue. As the impulse tests have shown, even small draining surcharge will reduce the time of the liquid state tenfold. (Fig. 5).

With a draining surcharge the process of secondary consolidation of soil goes on simultaneously both in upper and lower parts of the liquefied sand stratum (Fig. 6). In the lower part of the stratum consolidation is due to the weight of particles. This consolidation may be evaluated by equation (2). In the upper part of the stratum consolidation is due to the weight of the surcharge. Considering the conditions for seepage of the water squeezed out of the voids in the soil water, we can obtain the following relationship which enables us to locate the upper boundary of the liquefied stratum at different intervals of time :

$$t = \frac{1}{B}\left\{\frac{A}{B}\ln\left[1 + \frac{B}{A}(S - r_2)\right] - (S - r_2)\right\} \qquad (3)$$

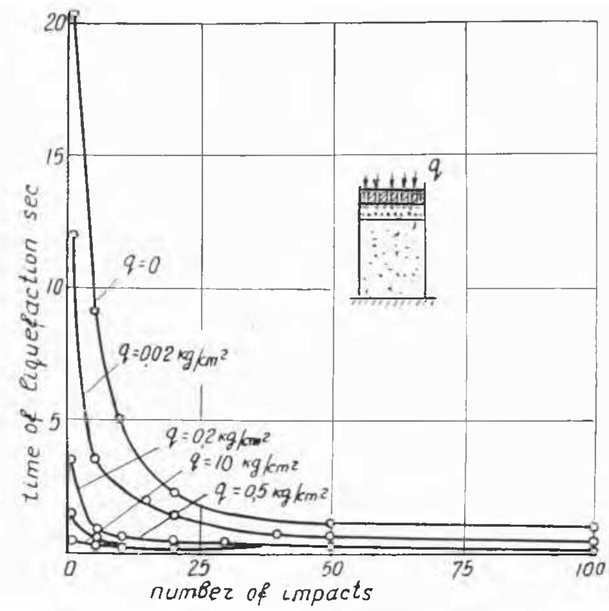

Fig. 5 Influence of the intensity of draining surcharge on the period of time within which the sand remains liquid.

Influence de l'intensité de la surcharge de drainage sur le temps pendant lequel la couche de sable se trouve à l'état liquéfié.

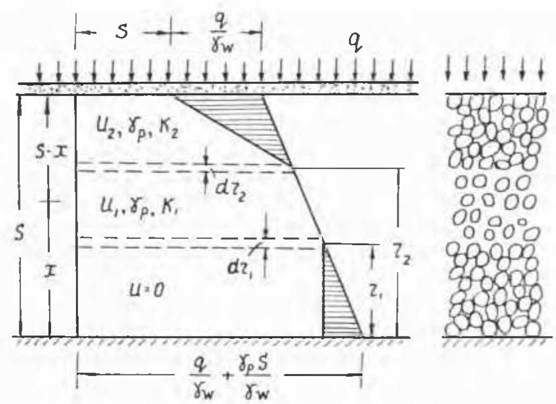

Fig. 6 Distribution of heads in a stratum of liquefied sand influenced by draining surcharge.

Répartition des charges dans la couche de sable liquéfié en présence de la surcharge de drainage.

where :

$$A = -K_2 \frac{q}{\gamma_w} \cdot \frac{1-n}{n_0 - n};$$

$$B = \frac{1}{n_0 - n} \cdot \frac{\gamma'}{\gamma_w}\left[K_1(1 - n_0) - K_2(1 - n)\right].$$

From equations (2) and (3) we can determine the time during which the sand stratum will remain in a liquid state. With the increase of stress due to the weight of the soil itself, or to an externally applied load, the compaction of the sand considerably decreases with the result that the duration of the liquid state will also be reduced.

Drains in the sand mass also provide the conditions for rapid expulsion of water from the voids in the liquefied soil. The time during which a 5-metre thickness of fine sand remains liquefied is given by equation (2) and is 27 minutes, with the draining surcharge of 5 kg/cm^2 — 2 minutes, and with the supplementary drainage at the base of the stratum — it ranges from 20 to 15 seconds. This reduction of the time during which the sand remains liquefied results in improved stability both of liquefied soil and of structures built upon it.

Shear strength of a completely liquefied sand is determined mainly by its viscosity. If the viscosity is sufficiently great, no significant displacements of the liquefied sand occur even at the longer time duration of the sand in a liquid state. With increase of density, the viscosity of the liquefied sand increase 20-30 times, the latter having been observed when the unit weight of the soil is considerably less than that of the soil in the extremely dense condition.

Laboratory and field investigations have shown that the presence of entrapped gas, the content of which may vary from 8 to 20 per cent, greatly influences the process of liquefaction of the sand. The presence of entrapped gas considerably decreases the intensity and velocity of propagation (up to 100 — 50 m/sec at 7 to 8 per cent of gas content) of dynamic disturbances and consequently decreases the zone of liquefaction. With the increase of entrapped gas content the compaction of the sand due to dynamic disturbance decreases, and loose sands with relatively small entrapped gas content do not pass into a liquid state.

The sands which are uniform according to their grain-size composition with the same unit weight or porosity may have different densities due to different shape of particles. For example, the porosity of fine poorly rounded sand which has a limited zone of liquefaction is 45 per cent, while the porosity of sand with analogous grain-size composition but with well rounded particles is 38 per cent. It may be advisable to use the analogy method for evaluating the liquefaction of sandy soil with caution, because this method is applicable only to the grain-size composition of the sand.

Thus, the laboratory tests have shown that in several cases the phenomenon of liquefaction causes neither significant deformation nor failure of structures. Therefore, in the design of structures the assumption regarding the possibility of liquefaction can be made, provided that due allowance is made for possible harmful effects. Liquefaction which is not followed by spreading of the soil causes only a settlement of the surface of the soil, and the permissible value should be determined for each particular case depending on the structure and the purpose for which it is intended. It is noteworthy that most hydraulic-fill dams do not require special measures to be taken againt sand liquefaction.

Investigations also proved that liquefaction propagation of a "chain reaction" type does not exist in nature. If the surface of the soil is horizontal no liquefaction propagation is likely to occur. The local transformation of the sand into a liquid state on the inclined surface of the soil may cause the loss of stability in the adjacent dry soil, followed by failure of this part of the soil. The necessary condition for such propagation is a certain steepness of slope.

Research into the possibility of liquefying saturated sandy soils under field conditions may be successfully performed by using explosives for deep blasting. In order to evaluate the results of investigations and to compare blastings for different soil conditions, tests should be made with charges of equal depths and weights. Blasting of such charges is referred to as "standard blasting". For investigations into the liquefaction of a sand stratum, 8 to 10 metres deep, a charge of ammonite has been chosen as "standard". A weight of 5 kg of explosive and a depth of 4·5 metres of overburden will ensure that there is no expulsion of soil during blasting.

Within a few seconds of firing a standard charge in a loose saturated sandy soil, gas expulsion and surface settlement (Fig. 7), will be followed by squeezing of water through the pores. In some cases the water escapes as a concentrated stream or fountain, which in a loose fine sand may last as long as

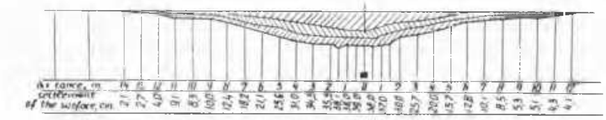

Fig. 7 Settlement of the surface of the soil after blasting of three standard charges.
Tassement de la surface de sol après trois explosions uniformes.

15-25 minutes. Within the limits of the upper non-saturated part of the soil a net of concentric fissures will be formed due to settlement of the surface. The length of some of the fissures was 20-25 m. Heavy bodies tend to sink in a liquefied soil; for example, steel reinforcement bars 50 mm in diameter and 8-10 kg by weight sank as deep as 1·5-2·0 m.

Blasting of standard charges in dense sands results in less settlement, and in several cases it does not occur at all. There is no visible evidence of liquefaction and neither do heavy bodies sink into the liquefied soil.

The main criteria for liquefaction of saturated sandy soils in relation to standard blasting are the magnitude of average settlement of the surface of the soil in a radius of 5 metres from the place of explosion and the ratio of settlement resulted from three successive standard blastings at one place. Tests have shown that in case the average settlement in a radius of 5 metres is less than 8-10 cm there is no need to provide measures against liquefaction. The greater the difference of average settlement after three successive blastings, the looser will be the sand and the greater is the possibility of liquefaction. If the ratio between two successive blastings is greater than 1:0,6 then there is danger of arising of an undesirable spreading of liquefaction.

The method of standard blasting was used to study the possibility of liquefaction of natural and hydraulically filled soil on certain Russian rivers.

The results of some of the tests are presented in the Table, which follows.

No.	*Soils*	*Porosity* per cent	*Ground water level meters*	*Number of explosions*	*Average Settlement in a radius of 5 m* cm	*Radius of settlement extension* m
1	Sand, fine, subrounded	44-45	0·5	1	22	25-30
2	—	43	1·0	1	17	20-22
3	—	41-42	0·3	1	16	16-18
	—	—		2	10	
				3	8	
4	—	—	0·2	1	10	10-12
				2	8	
				3	5	
5	—	—	0·3	1	1	8
6	Sand, fine, well rounded	38	0·2	1	5	10
				2	4	
				3	2	
7	Sand, fine, poorly rounded (above water sluicing)	43	0·0	1	4	10-12
				2	2	
				3	3	
8	— (under-water sluicing)	46	1·0	1	24	20
				2	13	
				3	15	
9	Sand, medium	37-38	0·3	1	7	3-10
				2	7	
10	—	—	0·3	1	0	0

One advantage of standard blasting is the reliability of the results obtained, particularly those associated with the estimation of a large area of soil subjected to blasting effects. Other advantages are simplicity and low cost. This method may be used by geological survey expeditions as well as on construction sites without the need for special supplementary equipment.

All measures against liquefaction of soils may be divided into two main categories : measures preventing liquefaction (sand compaction, loading, etc.) and measures for reducing the decreasing harmful effects of liquefaction (drainages sheet-pile bulkheads, draining surcharges, etc.).

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