LIQUEFACTION POTENTIAL OF SATURATED SAND DEPOSITS UNDERLYING FOUNDATION OF STRUCTURE

Liu Huishan (I)
Qiao Taiping (II)
Presenting Author: Liu Huishan

SUMMARY

This paper presents briefly shaking table tests on liquefiable sand diposits in the presence or absence of a model foundation. The tests conducted for relatively homogeneous deposits and horizontally stratified deposits show that liquefaction process are somewhat different, while the general features are similar. Test results clarify primarily liquefaction process in soil surrounding foundation of structure and agree with the results of earthquake damage investigation.

INTRODUCTION

Most of previous studies on the liquefaction potential of saturated sand were concerned with free-field ground motion, only a few of them took into consideration the liquefaction potential of deposits underlying foundations.

Yoshimi, Oh-oka and Tokimatsu (1974,1977) perfomed a two-dimesional elastic analysis of a foundation under cyclic loading and shaking table tests. They conclude that the zone on a diagonal away from the edge of a foundation would undergo liquefaction earlier than the free-field (Ref 1 & 2). Test results conducted recently on the centrifuge (Ref. 3) were similar to those of earlier tests by Yoshimi. On the other hand, Ferritto and Forrest (1977) conclude that the zone nearby a foundation is less sensitive to liquefaction than the free-field, based on elastic analysis of the major principle stress plane prior to application of dynamic stress. In their opinion liquefaction analysis based on free-field conditions are conservative when applied to the zone nearby foundation.

Fig. 1a and Fig. 1b present the calculated results by Yoshimi and Ferritto respectively. As can be seen from the Fig. , the major difference falls into the zone outside the foundation.

In view of significance of this problem involving safety of structure and proper selection of soil improvement range against liquefaction authors attempted to straightforwardly verify liquefaction development beneath footing. For this purpose authors conducted a series of shaking table tests and an investigation on earthquake damage. The main results are herein presented.

SHAKING TABLE TESTS

Content of Tests

a) Liquefaction tests of homogeneous sand deposits. The objective

(I) Senior Research Engineer, Beijing,China
(II) Civil Engineer, Taiyuan, Shansi, China

is to clarify generation and dissipation behavior of pore pressure of deposits under cyclic loading.

b) Liquefaction tests of homogeneous and stratified sand deposits underlying model foundation. The objective is to clarify effects of foundation on liquefation potential in the deposits.

Test Procedure

The size of sand tank is 1.5m×0.5m×0.3m. It's side walls are made of plexiglass(Fig.2). The model foundation used is shown in Fig.3. The physical properties of test sand are tabulated in Table 1. The sand was pluviated into water and made to reach the desired density by vibration. The maximum viod ratio obtained is 0.92($>e_{max}$ in Table 1).

Sand deposits consolidated under their own weight or foundation loading. Then the tank underwent horizontal sinusoidal excitation. The shaking frequency is 3~5HZ. The excitation stopped after occurrence of one of the following liquefaction phenomena:

1. sand boiling
2. obvious upward water flow or floating of soil grain
3. initial stratification distortion of sand deposits
4. the case that pore water pressure was equal to initial effective vertical stress

10 tests were conducted in this study ,of which 6 tests included the effects of model foundation, while the others did'nt(Table 2).

Liquefaction Tests of Homogeneous Sand Deposits

The main results are:

1. The pore pressure of various points at the same elevation are nearly identical(Fig.2), which indicates good uniformity of deposits.

2. The boundary effect of end wall of sand tank may be ignored in the case of the central part of deposits located over 15cm apart from the end wall.

3. For the normal consolidated soil liquefaction starts from its upper part(Fig.3a), while for the upper-compacted soil liquefaction starts from its lower part (Fig.3b).

4. Dissipation of pore pressure begins from the bottom of soil, while pore pressure of upper part of soil continues to increase.

Liquefaction Tests of Stratified Sand Deposits in the Presence of Model Foundation

The stratified deposits contribute to clarify the liquefaction process occurred in the zone surrounding foundation. Moreover,such deposits may be frequently encountered in practice, so the study of their liquefaction characteristics is of great importance. The method of preparing the stratified deposits is simple and easy: pluviate into water certain quantity of dry sand through the sieve until complection of its consolidation, then start the next pluviating. Repeat this operation many times until the deposits reach their desired thickness. Every time we pluviate sand,we obtain a double-layered deposit with two sublayers .The upper and lower sublayers consist of finer and coarser soil grains respectively. The thickness of the double-layered deposit is about 2cm.

The test results of stratified deposits are shown in Fig. 4~6. The process of pore pressure build-up and the final boiling are clarified by means of development of water interlayer between the sublayers of coarser and finer soil grains, as shown in Fig. 4.When the pore pressure increases, the small horizontal fissures filled with water appear symmetrically or asymmetrically outside the foundation (Fig. 4a). If vibration continues, the fissures grow up rapidly to form water interlayers or water lens. With further build-up of pore pressure water lens located at the same elevation will be interconnected to form a long water interlayer. Meanwhile, the other fissures may appear somewhere (Fig. 4b). With increasing thickness of water interlayer the ground surface is uplifted. Once the first water interlayer reaches its maximum thickness, the water burst out with a noise through the overburden stratum and boiling occurs (Fig. 4c,d).

The earliest boiling hole is always the one nearest to the foundation and has the largest diameter among the holes. The maximum of water interlayer observed reaches 2.5cm (Fig. 5). It takes about 10 sec. to reach such thickness. The diameter of the largest boiling hole is about 6~7cm and remains unchanged hereafter. The boiling matter consists mainly of water with few soil grains. After boiling the water interlayer soon disappears and the fissure is closed.

Fig. 5 presents the soil profiles after boiling and the maximum pore pressure ratio in the tests B-5 and B-6. The maximum pore pressure ratio is calculated by the following formulae:

$$R=u/\sigma_V' \qquad (1)$$

$$\sigma_V'=r'z+\sigma_z \qquad (2)$$

where R-- pore pressure ratio; u-- measured pore pressure; σ_V'--vertical initial effective stress; z-- depth of the assigned point; r'-- buoyant unit weight of soil; σ_v--vertical stress induced by foundation loading on horizontal plane, calculated by elastic theory.

While the criteria of liquefaction under two-dimensional condition are not well defined, we suggest in this paper R=1 as the criteria of liquefaction. From Fig. 5b and 5c it can be seen:

1) The pore pressure ratio directly under the foundation is smaller than that outside the foundation at the same elevation, which shows that the vertical stress induced by foundation load has intense effect on liquefaction potential.

2) By comparing Fig. 5a with Fig. 5b and Fig. 5c with Fig. 5d, it is found that the earliest boiling hole is just located at the place where the pore pressure ratio is highest. It can be concluded that there exists outside the foundation a zone with high pore pressure, which is more sensitive to liquefaction than the one far from the foundation (free-field).

3) The soil structure in the zone deeper than the depth of boiling hole is slightly disturbed, while that nearby the boiling holes is intensely disturbed. The soil structure in the zone directly below the foundation remains unchanged even if liquefaction occurs in the zone

outside the foundation (Fig. 5a and 5c).

Liquefaction Tests of Homogeneous Deposits In the Presence of Model Foundation

If the pluviating of sand grains continues without interruption, the deposits thus obtained are relatively homogeneous. Fig. 6 shows the test results of such deposits. In general, the distribution of pore pressure ratio has a close resemblance to Fig. 5 with the exception of no formation of water interlayers. The vibration in each test lasted until boiling occurred. It was also observed in each test that boiling holes nearby the foundation appeared earlier than in free-field and diameters of the former were larger, but far smaller than in tests B-5 and B-6 (Fig. 5). The total of boiling holes was more than that in Fig.5

DISCUSSION

1. In this study the most interesting is the direct observation of liquefaction development. It reveals that the zones surrounding the foundation show different sensitivity to liquefaction. The doubts have now been dissipated about liquefaction potential beneath foundation of structure due to uncertainty of liquefaction criteria under two-dimensional condition. In terms of growth of water interlayers and the final boiling, it is comfirmed that the zone outside the foundation is the weakest one against liquefaction, where liquefaction occurs earlier than in free-field. This conclusion is supported by the impression made from damage investigation following Tangshan earthquake (1976.7.28, M=7.8). In the investigation it is often noted that more boiling holes and fissures are found nearby the structure than somewhere far away. Fig. 7 shows several typical patterns of such kind of damage.

In analyzing liquefaction hazard and predicting foundation failure the effect of the foundation loading on liquefaction potential should be considered, and the simplified methods of evaluating bearing capacity of liquefiable soil developed.

2. The occurrence of water interlayer may be of universal significance in such cases, where vertical permeability of neighbouring soil layers vary greatly. Due to accumulation of large amount of pore water the installation of gravel drain may help to reduce the pore pressure and protect the soil from liquefaction.

3. In the zone deeper than the depth of boiling holes initial soil stratification remains even if the pore pressure ratio has reached unity (Fig.5and Fig.6). It indicates that liquefaction of deep deposits causes small relative displacement of soil grains and would not result in severe settlement of the overlying structures so long as there occurs no boiling.

4. For preliminary evaluation it seems resonable to take pore pressure ratio R=1 as liquefaction criteria under two-dimensional condition. In all of the tests sand boiling is always observed when R=1 (by formula (1)). Sometimes R is even slightly greater than 1 (the maximum value R=1.18, see Fig. 6).

CONCLUSIONS

The primary conclusions in this study are as follows:

1. The liquefaction potential of liquefiable saturated soil underlying foundation of structure is different at various zones. The zone directly under foundation is less sensitive to liquefy than in free-field, while the zone outside the foundation is more sensitive to liquefy than in free-field.

2. From test B-5 and B-6 the following main impressions are obtained: The liquefaction of stratified deposits differs mainly from homogeneous deposits in formation of water interlayers, little amount of soil grains from boiling holes, few boiling holes and large diameter of boiling hole etc. But the law of build-up and dissipation of pore pressure and the distribution of pore pressure ratio surrounding the foundation are similar.

REFERENCES

Ref. 1. Yoshimi, Y. and Oh-Oka, H. , "Influence of degree of shear stress reversal on the liquefaction potential of saturated sand" Soil & Foundation, Japan, Vol. 15 No.3 Sep. 1974

Ref. 2. Yoshiaki Yoshimi, Kohji Tokimatsu, "Settlement buildings on saturated sand during earthquakes" Soil & Foundation, Japan, Vol. 17 No.1 Sep. 1977

Ref. 3. Robert, V., Whitman & Philip , C. Lambe, "Liquefaction: Consequences for a structure", Soil Dynamics & Earthquake Engineering Conference, 1982

Ref. 4. Ferritto, J. M. and Forrest, J. B.,"Determination of seismically Induced Soil Liquefaction Potential at Proposed Bridge Sites" Volume I-Theoretical Considerations, Report No. FHWA-RD-77-127, Washington, 1977

TABLE 1 Physical properties of sand

Grain size (mm)				d_{60}	d_{10}	C_u	e_{max}	e_{min}
0.5~0.25	0.25~0.1	0.1~0.05	<0.05	(mm)	(mm)			
8.0	51.0	33.0	8.0	0.114	0.053	2.15	0.879	0.464

TABLE 2

No. of tests	presence of model foundation	contact pressure (g/cm^2)	initial void ratio e_o	saturated unit weight (g/cm^3)	input acceleration (gal)	remarks
A-1	no	--	0.788	1.928	22	
A-2	no	--	0.708	1.970	59	
A-3*	no	--	0.920	1.859	50	* upper part of
A-4	no	5.25	0.778	1.917	160	deposits was
B-1	yes	5.25	0.790	1.920	42	compacted
B-2	yes	17.10	0.770	1.938	30	
B-3	yes	13.30	0.790	1.920	160	
B-4	yes	13.30	0.730	1.950	50	
B-5**	yes	5.25	0.820	1.910	30	** straitified
B-6**	yes	9.33	0.760	1.940	30	deposits

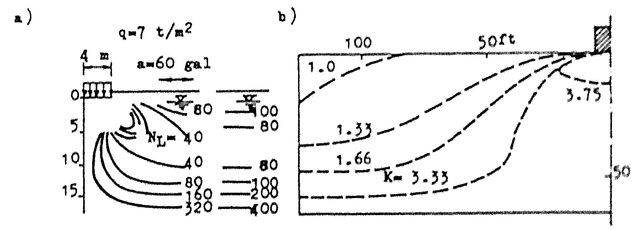

Fig. 1. Liquefaction potential of soil surrounding the foundation
a-- by Yoshimi (Ref. 2); b-- by Ferritto (Ref. 4)
(N_L-- number of cycles to cause liquefaction;
K--- ratio of numbers)

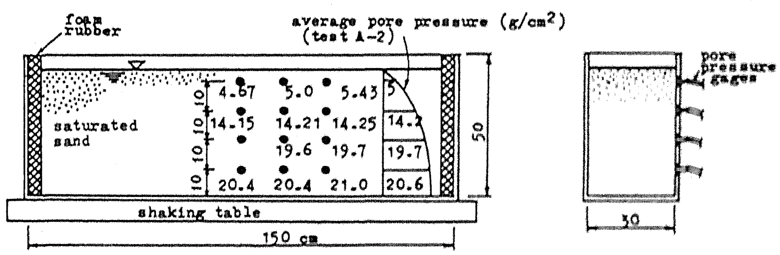

Fig. 2. Model ground and sand tank

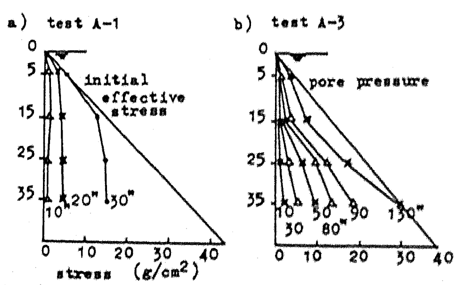

Fig. 3. Generation of pore pressure in homogenuous saturated sand

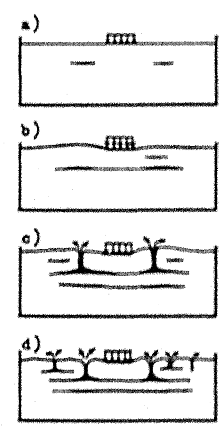

Fig. 4. Information of water interlayers and final boiling

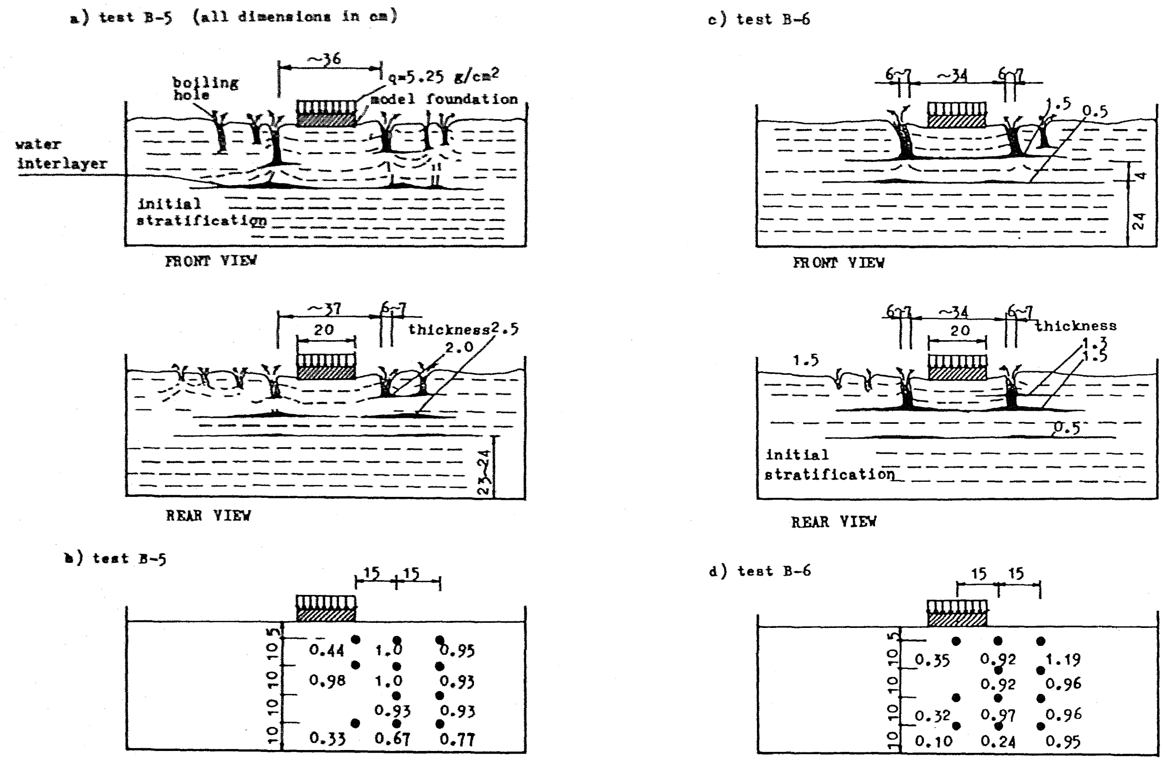

Fig. 5. Liquefaction tests of stratified deposits
(a),(c) — water interlayers and boiling holes
(b),(d) — measured maximum pore pressure ratio

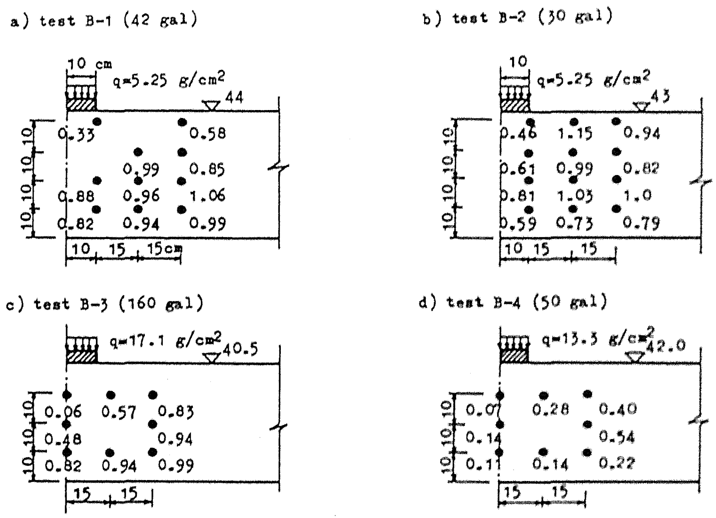

Fig. 6. Measured pore pressure ratio in tests of homogeneous deposits

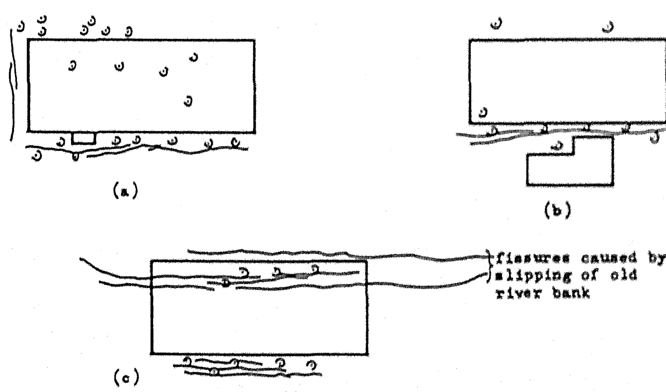

Fig. 7. Boiling holes and fissures nearby three workshops
a—site A; b—site B; c—site C