Experimental Investigation on Excess Pore Water Pressure in Soft Soil-Foundations under Minor Shocks

Zhiying Zhang, Chongdu Cho*, Qiang Pan, Xilin Lu

***Abstract*—**In this study, shaking table tests are performed to investigate the behavior of excess pore water pressure in different soft soil-foundations of soil-structure interaction (SSI) system. The variation of the behaviors under cycled minor shock is observed. Moreover, The generation and variation mechanism of excess pore water pressure under earthquake excitation in different soft soil-foundations are analyzed and discussed.

***Keywords*—**Excess pore water pressure, shaking table tests, soft soil foundation, SSI system.

I. INTRODUCTION

IN most cases, the soil-foundation composed of saturated silt, fine sand or sandy silt have become the focus of earthquake engineering since the liquefaction potential energy are easily accumulated during earthquake action [1]-[4]. However, It is rather scarce to study the characteristic of excess pore water pressure in such soil-foundations with cohesive or clayey silts under earthquake action due to its clay content is thought of relatively high [5]. Although such soil-foundations of higher clay content are not easily susceptible to liquidify, a rise of excess pore water pressure triggered by earthquakes and a drop of effective stress may lead to the soil softening. Also, soil-foundation softening may cause damage to the building.

Today, there is no absolute conclusion [6]-[9] on whether the softening effect of cohesive or clayey silt soils under earthquake excitation should be considered and under what shake condition the damage induced by excess pore water pressure may not be considered in analysis.

Based on shaking table tests, this paper attempts to investigate the changing characteristics of the excess pore water pressure in different soft soil-foundations under small earthquakes. To simulate actual soil-foundation, the soil and structure interaction (SSI) system is considered in this experimental study. The soil-foundation in the test is built with two familiar types of soft soils in Shanghai—clayey silt and silty clay. In order to explore the possible influence of the aftershock on the different soil, the test adopts repeated loading and unloading process. The physical mechanism responsible for variation behavior of the excess pore water pressure in the repeated process is studied. The results of experimental investigation are expected to provide some research basis for softening problems of clayey soil-foundations under earthquake actions.

II. INTRODUCTION OF THE SHAKING SABLE TESTS

A. Test model and sensor arrangement

Considering the SSI effect of in-site building, the SSI system model is adopted in the tests. This model consists of two parts: model structure and model soil-foundation. The part of model structure has 10 stories and 5 by 2 frame with raft foundation, which is made of polypropylene resin. The area of each store is 0.580×1.0 m and its geometry similarity ratio is 1:30. In the tests, the model structure was placed in the middle of the model soil- foundation, and the raft foundation was adopted idealized surface foundation. The model soil-foundation is composed of two common types of soft soils in Shanghai. The top layer is grey clayey slit with thickness of 0.55m and yellow-brown silty clay with thickness of 0.65m at the bottom. The physical and mechanical properties of the two types of soils are shown in tables 1 and 2.

TABLE I
PHYSICAL AND MECHANICAL PROPERTIES OF TOP-SOIL

ω /%	ρ (g·cm^{-3})	e	S_r /%	d_s	ω_L /%	ω_q /%	I_q	I_L
26.3	1.90	0.82	88.1	2.73	37.3	21.3	16.0	0.64

TABLE II
PHYSICAL AND MECHANICAL PROPERTIES OF SUB-SOIL

ω /%	ρ (g·cm^{-3})	e	Sr /%	d_s	clay content smaller than 0.5mm /%
31.9	1.86	0.92	93.8	2.71	13

The geometry of modal soil-foundation box is cylindrical

This work is sponsored by State Key Laboratory for Disaster Reduction of China.

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with diameter of 3 m and depth of 2 m [10]. The box is composed of steel bottom plate, steel pillars, mobile steel roof frame and rubber membrane walls.

Considering dynamic interaction between the tested soil-foundation and the infinite soil domain outside the tested part, the enough thin rubber membrane (0.005m) is chosen as the box's wall to approximate simulation the interaction. In order to supply sufficient radial stiffness and not to interfere with the shear displacement of soil during vibrating, a Φ4@60 reinforcing steel bar is used on external membrane surface to reinforce circumferential directions forces. The wall of the box is fixed in the steel bottom plate at the bottom and hinged with the mobile steel roof frame at the top. The mobile roof frame is supported by four steel pillars around the outside of box wall. There is a universal joint on the top of each steel pillar so that to eliminate the influence of horizontal restraint while the horizontal shearing displacement of soil layer occurs.

In order to test the dynamic changing characteristics of the excess pore water pressure in different soil layers during the test, six piezoresistive sensors for pore water pressure are embedded in both soil layers at different radial distances. The sensors used in the test are type YZ-20, which have small volume (Φ0.02×0.115m), high sensitivity (resolution ratio:≤ 1mm water column; precision: ≤0.1%ES; linearity: ≤0.05%ES) and rapid dynamic response (response time: 1ms (1~1kHz)). Fig. 1 shows the profile schematic drawing of the test model as well as the layout of sensors.

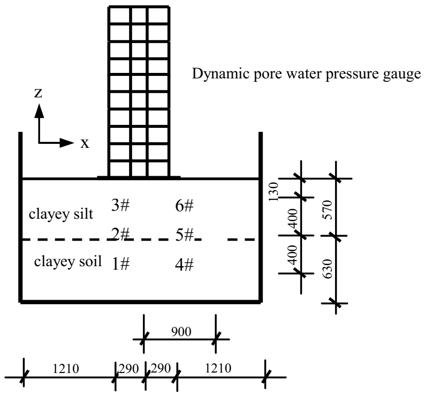

Fig. 1 The test model and distribution of pore pressure gauges

B. Test equipment and loading schedule

The dynamic experiment was carried out by a 4.0×4.0m^2 and three-dimensional shaking test table in the State Key Laboratory of Disaster Prevention in Civil Engineering at Tongji University. In the tests, both movements along X- and Y-axis are considered, among which X-direction corresponds to the principal vibration. Only influences of small dynamic intensities that simulate minor earthquake are studied in this test. Table 3 shows the corresponding intensity levels of input peak acceleration. Except for the levels 1(6) and 5(10) whose inputs were white noise along both directions, the input simulated seismic waves of each other level in sequence is: El Centro Wave along both directions (duration: 9.94s), Taft Wave along both directions (duration: 10.11s), Nanjing artificial Wave along X-axis (duration: 4.81s), Nanjing artificial Wave along Y-axis (duration: 4.81s).

TABLE III
INPUT LEVELS OF PEAK ACCELERATIONS OF SHAKING TABLE /g

Loading direction	Intensity level				
	1(6)	2(7)	3(8)	4(9)	5(10)
X	0.07	0.1	0.2	0.3	0.07
Y	0.07	0.08	0.16	0.24	0.07
Duration (s)	100	29.67	29.67	29.67	100

The different intensity levels are numbered as 1 to 5. The loading and unloading process is repeated in the test. In the second same process, the corresponding intensity levels are named 6 to 10. Of the both processes, 1(6) and 5(10) are white noise inputs.

III. EXPERIMENT RESULTS

A. Variation characteristics of excess pore water pressure

Suppose that the intensity levels indexed by 1-5 in table 3 is called the first cycle loading process, and the second repeated loading process is associate with those indexed by 6-10. Under the loading process of two cycles, the variation of excess pore water pressure in different layers of the soil-foundation is shown in Figs. 2 and 3. Fig. 2 measured by sensors #1 and #4 illustrates the variation of excess pore water pressure with different intensities in the silty clay layer. Fig. 3 measured by sensors #2 and #5 illustrates the variation in the clayey silt layer.

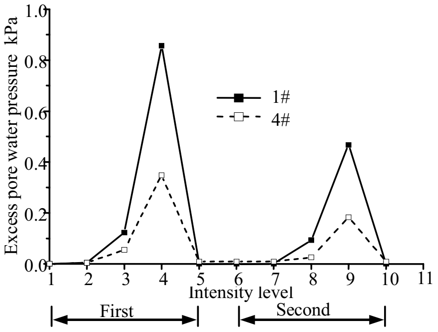

Fig. 2 Excess pore water pressure in silty clay

Residual pore pressure of different soils

Fig. 2 indicates that the residual pore pressure produced in silty clay became negligible when the simulation of earthquake ceases. When 0.07g white noise scanning test is conducted just after the first cycle excitation, it is observed that the excess pore water pressure decreases to its initial value and almost no residual pore pressure is remained. But the top soil layer of clayey silt is found larger residual pore pressure after the first cycled loading, as shown in Fig. 3.

Increase amplitude of excess pore water pressure in two loading cycles

In order to investigate the influence of a seismic aftershock, the same loading process was repeated after first loading cycle. The results show that the relative increase amplitude of excess pore water pressure in the repeated loading cycle is obviously smaller than that of the first cycle. This characteristic can be observed from both soil layers shown in Fig. 2 and 3.

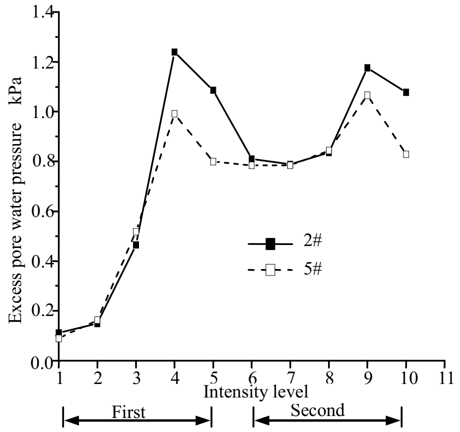

Fig. 3 Excess pore water pressure in clayey silt

Threshold of excess pore water pressure

Previous study reveals the excess pore water pressure beneath the covered layer of clayey soil rise with increasing shock intensities. The pressure, however, is limited by a maximum. This fact indicates the excess pore water pressure cannot indefinitely rise with increasing seismic intensity [11]. In this study the limit of the pressure refers to the threshold during cyclic loading process. In other words, the excess pore water pressure in the layer of clayey silt will increase with the intensity in second cycle. However, its maximum during the repeated loading cycle is found close to but no beyond the maximum pressure of the first cycle.

B. Analysis

About residual pore pressure of different soils

The reason for the difference of residual pore pressures between the two layers should attribute to their different physical and mechanical properties. Seed [12] indicates that the shear strength of plastic clay is mainly contributed by the attraction force among clayey particles. A higher of soil's liquid limit corresponds to higher shear strength.

The lower soil layer is the plastic clay whose clay content and liquid limit are relatively high. Under a small dynamic load, this soil will generate a small deformation. Since its shear strength is relatively high, most of the deformation is considered corres- ponding to elastic shear strain of the soil. After unloading, the elastic part of the shear deformation is recovered immediately, so as to reduce the excess pore water pressure. Even though in the case that a small amount of soil elements moves with irreversible deformation or moment, the residual pore pressure can also be eliminated since the compressible gas in the incomplete saturated soils is easier to dissipate through the pore during dynamic loadings.

The upper soil layer is the soft soil which has lower clay content, larger void ratio and higher water content as well as the degree of saturation. Thus the attraction force among soil particles is smaller and the soil structure is relatively sensitive. Since the physical and mechanical properties, the shear strength of the soil is rather low. The shearing strain of the soil is mainly presented as plastic strain even under small dynamic loading. After unloading, due to a certain amount of particles of the soil has moved with irreversible dislocation and rearrangement, it causes that the excess pore water pressure cannot return to its original state immediately. Further, there still exists considerable amount of clay particles in the soil (13% content with diameter smaller than 0.005mm) so that the permeability coefficient is rather small, which leads to the excess pore water pressure induced by plastic deformation cannot immediately dissipate and therefore appearing residual pore pressure shown in Fig. 3.

About increase amplitude of pore pressure in repeated loading cycle

The experimental phenomena of different relative increase amplitude in two loading cycles can be explained from the generation of dissipation condition of excess pore water pressure as well as its growth conditions. The excess pore water pressure in soil generates due to the application of dynamic loading and rises with increasing intensity and duration of the loads. It occurs simultaneously, in a microscopic view, the generation and growth of micro-drainage conditions in soil. In other words, the micro capillary drainage channels, similar to excess pore water pressure, are simultaneously generated due to the vibration occurring and developing with intensity increased.

The micro drainage channels are caused by some factors. For example, the heterogeneous density of soil particles brings the different vibration characteristics (amplitude, frequency and phase) among the soil particles under dynamic loads, and there exists the different amplitude-frequency characteristic between the sensors, wires and the soils. These factors are contributed to induce the complete or incomplete micro-cracks inside the soils during dynamic loading. Moreover, the difference in dynamic response due to the different stiffness of the two layers also causes the generation of micro-cracks near the boundary surface between the layers. These micro-cracks supply the paths along which the excess pore pressure can be dissipated. The development degree of micro-drainage conditions, such as the number of micro-cracks, connectivity and the splitting effect, grow with the dynamic energy. When the loading in the first cycle reaches a threshold, the micro-drainage conditions in soil already grow to a corresponding level. So in the repeated loading cycle, the pore pressure cannot accumulate like as one in the first cycle based on the developed micro-drainage condition. Instead, the relative increase amplitude of excess pore water pressure is obviously smaller than that of the first cycle.

About threshold of excess pore water pressure

The main factors affecting excess pore water pressure are vibration energy, micro-drainage conditions and soil consolidation deformation etc. Because the dynamic inputs are the same in the two loading cycles, the micro-drainage conditions, as well as the soil consolidation deformation, do not present obvious changes between the two cycles. Thus the maximums of the excess pore water pressure are approximated to the same in both cycles.

IV. EXCESS PORE WATER PRESSURE CAUSED BY UPPER STRUCTURE

Fig. 4 plots the variation of the excess pore water pressure detected by sensors #3 and #6. Sensor #3 is located below the center line of the foundation and sensor #6 is located at outside the foundation. The result of sensor #6 indicates the excess pore water pressure cannot accumulate to a high level if there is a thin cover thickness of soil layer and without additional loads. But the pressure detected by sensor #3 is observed to fluctuate greatly around a high value. The pressure by sensor #3 is mainly composed of loading potential. The loading potential [13] is defined as the excess pore water pressure which is caused either by additional stress for normally consolidated soils or by gravity stress for unconsolidated soils.

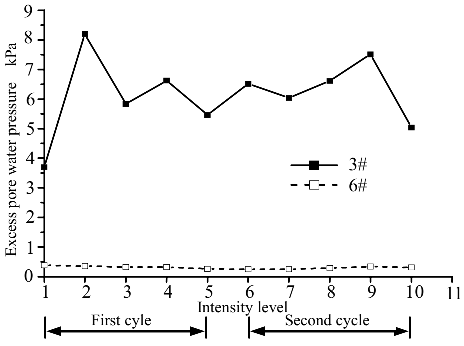

Fig. 4 Loading potential

In this test, the raft foundation of the model structure is as a surface foundation. The static load of the upper structure leads to plastic deformation of the soil-foundation beneath the raft foundation. As a result, a relatively high additional excess pore water pressure generates. Because the plastic deformation of the saturated soft soil is not steady when its foundation is vibrating, the excess pore water pressure presents fluctuation phenomenon.

V. CONCLUSION

Under minor shock, the shear strain of soil-foundation with high clay content and high liquid limit is mainly related to elastic strain. Its excess pore water pressure falls back soon after shock stopping and with negligible residual pore pressure. On the contrary, those with the larger void ratio, the higher water content as well as the saturation degree mainly be related to plastic strain even under very small dynamic effects, and to appear residual pore pressure after unloading.

The micro-drainage condition in soils generates and develops with the rising of excess pore water pressure. The micro-drainage conditions will restrains the relative increase amplitude of excess pore water pressure in the repeated loading process. For soft soil with the larger void ratio, the higher water content and higher the saturation degree, the peak of excess pore water pressure during the repeated loading process will not be significantly higher than that of the previous cycle. The implied meaning of the experimental result is that if the level of aftershock is less than the level of main shock, the excess pore water pressure during aftershock is probably larger than the residual pore pressure caused by main shock. But the relatively increase amplitude significantly decreases and the maximum pressure is not much larger than the threshold of the maximum value in main shock.

ACKNOWLEDGMENT

This work was supported by State Key Laboratory for Disaster Reduction of China and Inha University of Korea. The authors would like to thank Prof. Longgen Zhu in Key Laboratory of Geotechnical and Underground Engineering, Tongji University, P. R. China, for his helpful suggestions and advices.

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