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# 6. *Seismic Force of Incompletely Liquefied Sand on Underground Structures.*

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## 1. Introduction

It is generally known that seismic force shaking can liquefy a sand stratum and that, in consequence, considerable damage to structures may be caused. It is important to determine what kind of forces a liquefied sand stratum applies upon structures in sand, and to understand the dynamic behavior of structures buried in liquefied sand, when considering the aseismic design of underground structures.

As to the influence of liquefaction of sand on buried structures, the following two properties have already been established.

*1) Decreasing and vanishing of bearing capacity*

When sand is liquefied, the ground is unable to bear the weight of structures, or structures may be unable to bear the buoyant force due to liquefaction. In this case, however, the situation from the viewpoint of the design of structures is not as serious as would be expected. The reason is that, if the density of the structure is designed to be roughly equal to that of the surrounding ground, there would be no serious damage even though the bearing capacity vanishes. Thus in the aseismic design of the pile foundation of a structure, the horizontal bearing capacity of the ground during an earthquake has commonly been regarded as zero in a stratum which has a potential for liquefaction.

*2) Influence of floating force*

This force has already been mentioned in 1). Earthquake damage owing to the influence of buoyancy was reported, for example, in the rising of manholes in the Niigata Earthquake of 1964.

Accompanying the liquefaction of ground in an earthquake, buried pipes are torn off or broken into pieces and piles are broken under the ground.

The authors doubt if such severe damage can be explained only from the two influences mentioned above. Thus a vibration experiment was carried out using a sand box and some studies were made to investigate whether an incompletely liquefied sand stratum may exert another force, besides buoyance, upon underground structures.

## 2. Seismic force upon a buried model

*1) Arrangement of experiment*

Figure 1a shows the sand box on the shaking table.

The experiment was made up of an electromagnetic vibration table, a sand box, buried models and measuring apparatus. The model is made of wood. A sand box was placed on a shaking table and was vibrated.

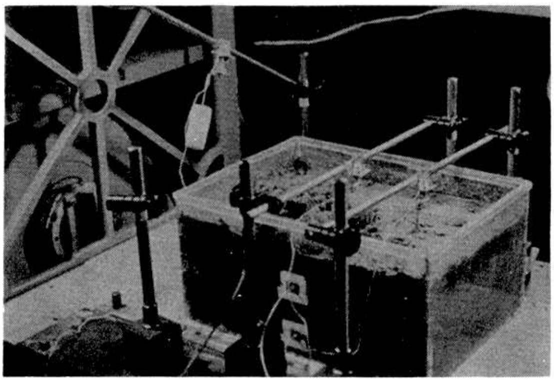

Fig. 1. a: Experiments with a sand box on a shaking table.

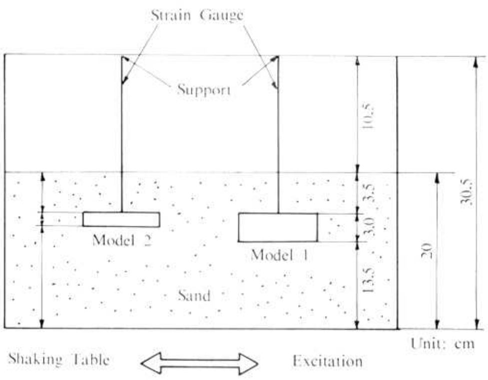


Fig. 1. b: Dimensions of buried models and a sand box.

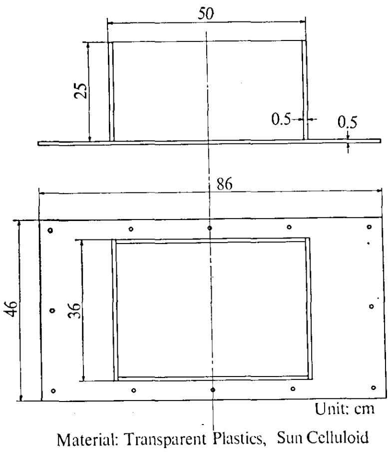


Fig. 2. Sand box for this vibration experiment.

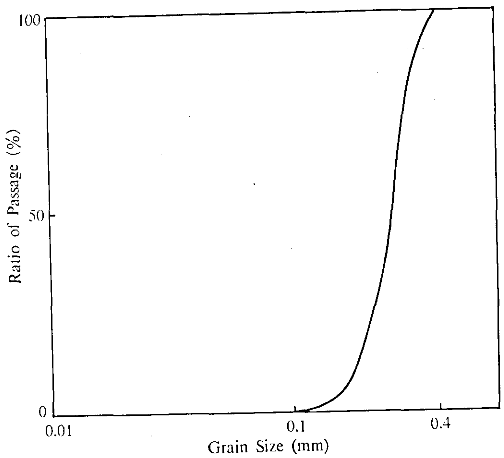


Fig. 3. Grain size accumulation curve of Toyoura sand which was used in the experiment.

Accelerometers and a porewater pressure gauge were buried in the sand box. The vibration table was also equipped with an accelerometer and a differential transform-displacement meter. Figure 1b shows the dimensions of the buried models and the sand box.

The seismic force acting upon a buried model in the horizontal direction was measured by a gauge attached to the elastic arm jutting out from the model buried in sand.

Figure 2 shows the dimensions of the sand box used in the experiment. Its material is transparent sun-celluloid, so that one could observe the behavior of sand strata during the experiment. Its size is 36 cm in width, 30 cm in length and 25 cm in height.

It should be mentioned that an infinite ground model can never be made in a laboratory experiment. The existence of side walls of the sand box causes the boundary conditions to differ from actual ones. The experiment would overestimate the force acting upon structures more strongly than the actual sand, because the walls push the sand stratum. Furthermore, the actual ground is never completely homogeneous.

Therefore, the authors think that the results from this experiment can be discussed only on a qualitative basis, not on a quantitative basis.

Toyoura standard sand was used for the model ground. The grain-size accumulation curve of this sand is shown in Fig. 3. It is fine sand of uniform grain-size with uniformity coefficient 1.5.

The vibration table used in the experiment is of an electromagnetic type made by Akashi-Seisakujo, 500 kg in maximum output.

Table 1. Wave forms of external force

| Wave form | Frequency (Hz) |
|---|---|
| Sine wave of one period | 3, 5, 7, 10 |
| Stationary sine waves | 5, 7, 8, 10 |
| Stationary random waves | 1~6 |
| Transient random waves | 1~6 |

*2) Method and procedure of experiment*

As is well known, it is quite difficult to pack sand in a box uniformly. Thus a great deal of care is paid to this matter.

Before starting the experiment, the authors measured the water content of a sample taken from the surface of the sand stratum. Values of water content per cent ranged from 20 to 30%. The sand stratum was about 20 cm thick.

Every time an experiment was over, the authors took the sand out of the sand box and dried it. They used it again for the next experiment with the water content less than 1%.

As shown in Table 1, the wave forms of the force applied to the vibration table were sine waves (only a single period), stationary sine waves, stationary random waves and transient random waves.

In this case a random wave is white noise whose frequency components above 6 Hz are filtered out. It is thought that the characteristics of the vibration table also help to filter out the high frequencies. A "transient" wave can be obtained by multiplying a stationary wave form by a transient envelope function.

The authors set up an accelerometer and a porewater pressure meter 10 cm below the surface of the sand stratum. The beginning of liquefaction was judged by this porewater pressure meter, change of acceleration of the sand stratum and rising of water in the sand stratum.

*3) Results of the experiment*

a) The liquefaction of the sand stratum

It is observed that liquefaction begins in the deeper part and that water comes up to the surface. Settlement of sand particles begins with the liquefaction. But near the surface of the sand stratum, settlement of sand particles may not occur because the water content of the sand increases, and then the sand becomes muddy.

b) The behavior of the buried model (in case of stationary random waves)

In Figs. 4 and 5 the authors show the behavior of a buried model when stationary random waves were applied as the acceleration of the

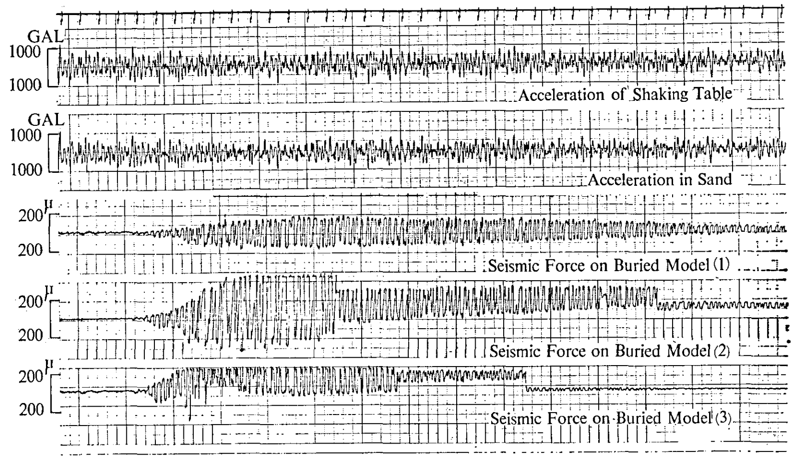


Fig. 4. Seismic force acting on buried model (Stationary random wave).

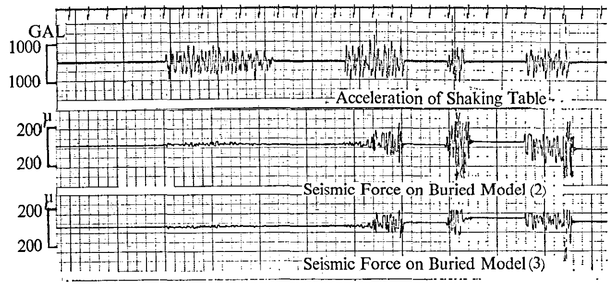


Fig. 5. Seismic force acting on buried model (Stationary random wave in short duration).

vibration table. The values of the water content per cent dry weight of the sand were 0.269 (Fig. 4) and 0.224 (Fig. 5).

In the experiment of Fig. 4, the acceleration amplitude of the vibration table was increased gradually, and the acceleration in the sand was the same value as that of the vibration table. In spite of the stationary vibration of the table, the buried models suddenly began to vibrate at a certain instant. The maximum value of strain could not be obtained because of over-loading. Although the amplitude of vibration of the shaking table remained almost the same, the amplitude of vibration of the buried model diminished gradually after the sand liquefied completely. The value of strain varies with the shape of the model. But after a certain time interval of vibration, the vibration of all the models were of almost the same shape. As for the form of the strain, the peaks are sharp, and afterward they become obtuse. While the vibration of the table is stationary, the seismic force upon the buried objects magnifies suddenly then diminishes gradually.

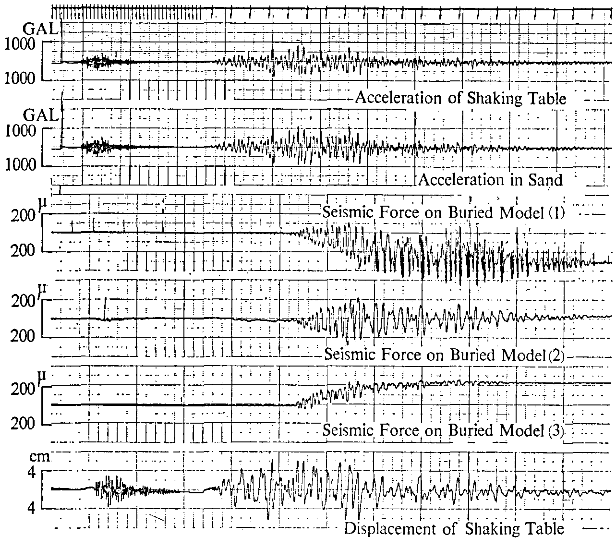


Fig. 6. Seismic force acting on buried model (Earthquake wave).

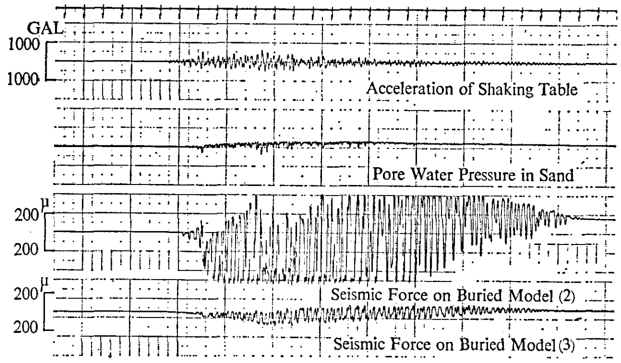


Fig. 7. Seismic force acting on buried model (Earthquake wave).

In the experiment of Fig. 5, the vibration table which had been vibrated in a stationary random wave was made to stop suddenly. The buried models came to a stop rest at the same time as the external force was stopped.

From these results, it can be said that the model in the liquefied sand stratum does not resonate but is vibrated forcibly by the surrounding liquefied sand.

c) The behavior of the buried model (in case of transient random waves)

In Figs. 6, 7, 8, and 9 the authors show the patterns of behavior of a buried model excited by an external force of transient random waves.

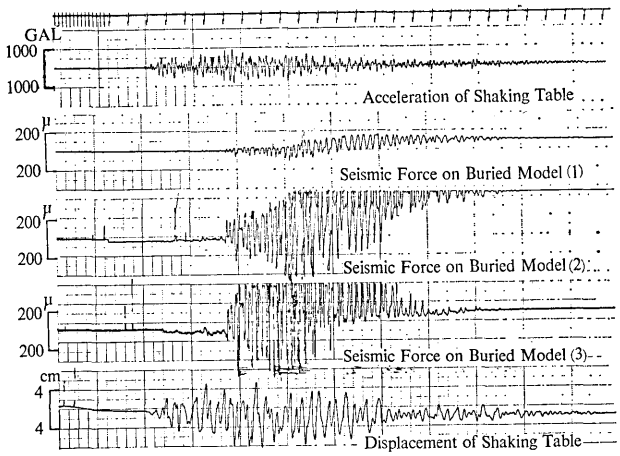


Fig. 8. Seismic force acting on buried model (Earthquake wave).

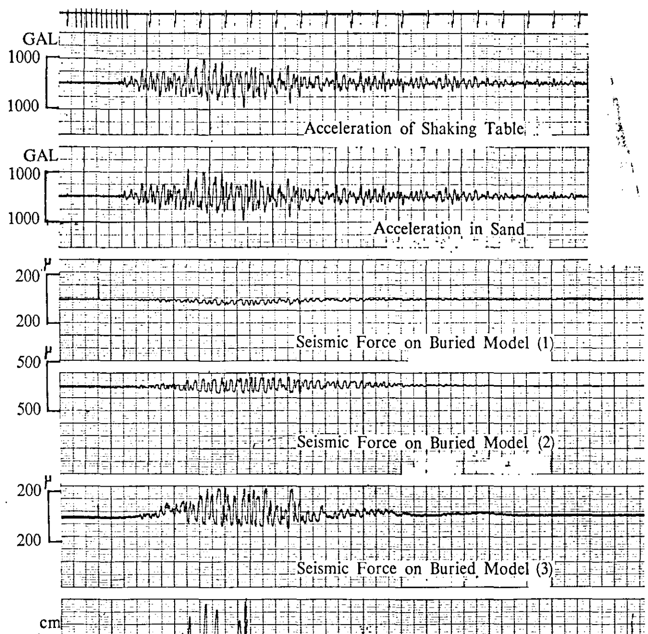


Fig. 9. Seismic force acting on buried model (Earthquake wave).

In these figures, one can observe that the buried models are suddenly subjected to a fairly large seismic force which is not in proportion to the magnitude of the input vibration.

The seismic force on a buried model takes the maximum value at the sand liquefaction due to the first earthquake shock.

Even if transient waves are applied over and over again after the first wave, the seismic force on the buried model is smaller. This may indicate that once a sand stratum liquefies in an earthquake, the separation of sand and water occurs, and that at the end of an earthquake, the lower part of the sand stratum gets more dense than before, so that it may not liquefy so easily in future earthquakes.

In Fig. 7, the porewater pressure measured by a porewater manometer, which is buried 10 cm below the surface of the sand stratum, begins to rise almost at the same time as the buried models begin to vibrate. Also in this case both of the models vibrate in the same phase.

### 3. Seismic force of liquefied sand upon pile foundations

The author used the following model to measure the magnitude of force exerted on pile foundations.

As shown in Fig. 10, a model pile, the lower end of which is fixed at the bottom of the sand box, may correspond to a pile which penetrates a weak sand stratum and is supported by its end in a stiff bearing stratum.

The sand box, the vibration table and other equipment, used in this experiment, are the same as used in the buried model experiment. The model pile is a round pipe made of vinyl chloride, 1.9 cm in outside diameter, 0.6 cm in thickness.

The experiments were performed, without changing the sand in the sand box, and the box was vibrated repeatedly by the acceleration of transient random waves (pseudo seismic waves).

Figure 11 shows the strain at the middle part and the bottom of a pile when it is vibrated at the maximum acceleration of 600 gal.

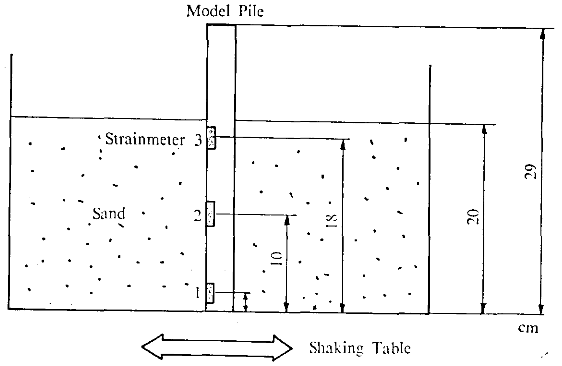


Fig. 10. Experiment for pile foundation.

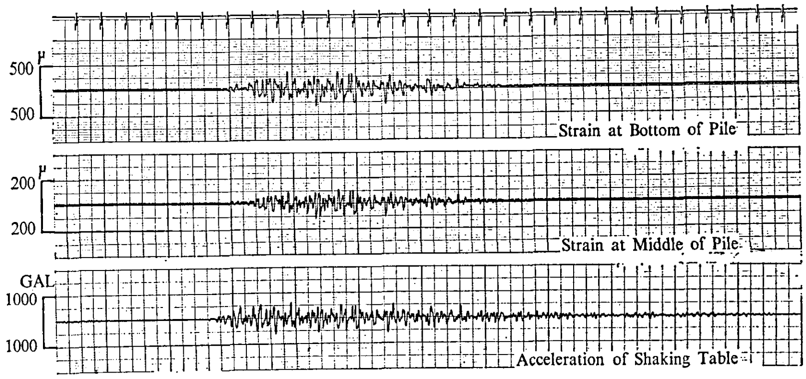


Fig. 11. Strain at pile foundation produced by liquefied sand (Input: Earthquake wave).

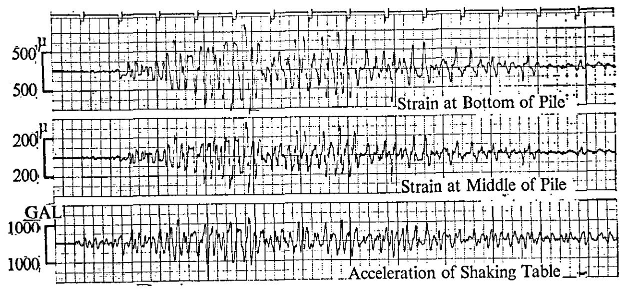


Fig. 12. Strain at pile foundation produced by liquefied sand (Input: Large amplitude of earthquake wave).

It is noticed that the wave form of the strain record is almost the same as that of the applied acceleration except during the first stage of vibration. At the first stage, though the vibration table shakes, only a very small strain of the pile is visible on the record. From this, the authors suppose that the sand surrounding the pile is not yet fractured at this moment, so that the seismic force scarcely acts upon the pile; however after the sand liquefies to some extent, a large strain is seen on the record.

Figure 12 is the result when the maximum acceleration of the vibration table is 2.2 times larger than the input used in the former experiment. Although the result is almost the same as that of Fig. 11, the peak of the strain in the large amplitude is sharper than the wave form of the applied acceleration, and this is a kind of non-linear vibration. The strain has a tendency to decay earlier than the acceleration of the vibration at the tail end of the vibration. Further, if we compare the maximum value of the strain in Fig. 12 with that of Fig. 11, the former is 3.6 times larger than the latter in the middle part of the pile and 3.5

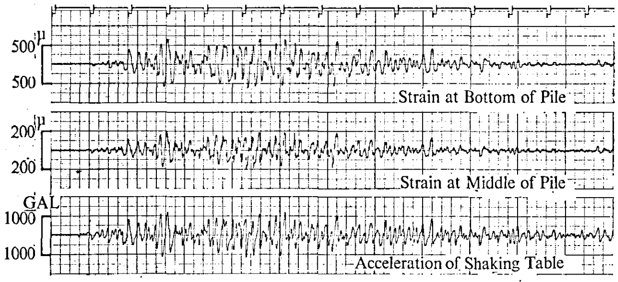


Fig. 13. Strain at pile foundation produced by liquefied sand (Input: Large earthquake, the second time to the same pile).

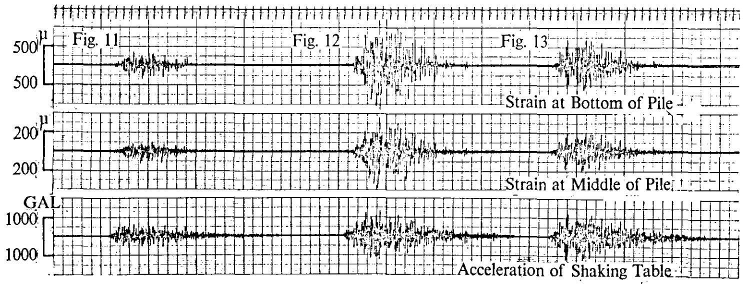


Fig. 14. Strain at pile foundation produced by liquefied sand during repeated earthquake excitation.

times at the bottom. It is understood, consequently, that the seismic force upon the pile is not proportional to the seismic acceleration, and that if the acceleration is larger, a force, which is more than that corresponding to the applied acceleration, is exerted upon the pile from the surrounding sand strata. Of course, this seems to be influenced by the liquefaction of sand.

Figure 13 is the results of applying almost the same amplitude of acceleration as that of Fig. 12 directly after the experiment shown by Fig. 12. It can be noticed that in spite of almost the same amplitude of seismic acceleration as that of Fig. 12, the strain of the pile becomes considerably smaller than the results in Fig. 12. In this case, both the amplitude of the acceleration and the strain are twice as large as those of Fig. 11.

It seems to us that this is because the sand was liquefied considerably by the experiment of Fig. 12 and the sand and water were separated by that experiment. Therefore, the sand at the bottom of the sand box became more dense than before. In consequence the sand did not liquefy easily even if the sand was given almost the same acceleration later. Consequently the force upon the pile diminished.

The authors combined Figs. 11, 12 and 13 into a single figure, Fig. 14, to make the relation mentioned above easier to recognize.

## 4. Conclusions

From the above-mentioned experiments using a buried model and a model pile, the following conclusions were obtained.

(1) When sandy ground liquefies incompletely due to an earthquake, a new force other than buoyancy acts upon underground structures. The force is considerably larger than the force acting on underground structures where sandy ground has not liquefied, and is also considerably larger than the force which acts after the sand has liquefied completely and the separation of sand and water has occurred.

(2) The cause of the new force is considered to be due to the considerable softening of the sandy ground. It is easily deformed while the frame of sand particles changes from a stiff condition to a condition of complete liquefacting in which the friction between the sand particles is eliminated by the porewater pressure. However, it is reasonable to consider that there is still a transient condition from the stiff state to the liquid state in which the particles of sand make contact with each other to some extent, and so they can transmit force to the structure.

(3) Once the ground is completely liquefied, the sand exerts only a force like dynamic water pressure, and the sand particles sink down and compact at the same time. But if rough particles of sand sink down to the bottom, the remaining very fine particles cannot become very easily sink down and the liquefied state continues for a considerable time. Though the process time needed for the sand to become completely liquefied is comparatively short time (several seconds) in this experiment, in the case of actual ground on a large scale, the authors think the time needed would be longer and as a result the duration of incomplete liquefied, in which a strong force acts upon underground structures, would also be longer time than in the experiment.

(4) From these conclusions it can be supposed that even though ground does not liquefy completely in an earthquake, if it happens that the effective stress diminishes and the soil softens because of the increase of porewater pressure, then this phenomenon causes a strong force upon underground structures. With the present design procedures it is possible to build a buried structure even in soft mud at the sea bottom since this type of soil is not sand, and no liquefaction will occur. But even with such soil, porewater pressure may rise, and investigations and surveys will need to be made against the possibility of softening.

(5) The liquefaction of sand passes through the processes of (a) deformation within the elastic range, (b) the rise of porewater pressure

(softening), (c) the complete liquefaction (separation of sand particles), (d) the sink of the sand particles, stiffening, etc. To determine the seismic force working upon underground structures from liquefying ground, we have to consider the dynamic properties of the ground as a liquefying process that is changing at every moment.

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## 6. 不完全液化砂が地中構造物に及ぼす地震力に関する実験的研究

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地震時に砂地盤が如何にもろいものであるかは，新潟地震によっても，はっきりしているわけであるが，一方，東京などの大都市では，地下鉄，沈埋トンネル，地下街等の地中構造物が非常な勢いで建設されており，その建設地点は，必ずしも地盤の流動化の起らないような強固な地盤ばかりとは限らないのが実状である．したがって，地震によって流動化した地盤は，その中に埋まっている地中構造物に対してどのような力を加えるであろうか，ということは重要な問題である．

にも拘らず，現時点ではほとんど何も明らかにされていない．この点を明らかにするため振動台上に設置された箱に砂をつめ，これを砂地盤とみなし，その中に模型地中構造物を埋設し，振動台を種々の波形で振動させ，砂地盤を液化させて，その際模型に加わる液化砂からの力を測定した．

本文中の Fig. 7 は結果の一例を示すものであるが，振動台は地震波形で振動させており，砂地盤中に埋設した間隙水圧計により液化の程度も測定した．砂中の間隙圧が上昇（すなわち，砂の液化が発生）するとともに，地中構造物に大きな力が作用することが認められる．そして，その力は，砂が液化を開始する頃が大きく，その後，完全に液化してしまうと，地中構造物に対する作用が減少していくことも認められる．

この液化時の最大作用力は，液化しない弾性範囲内に留まっている時の作用力に比べて数倍の値であって，このことは，地中構造物にとって，地盤の液化とは，液体の中に浮かぶということではなく，大きな力を受けるということを示している．

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