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Centrifuge tests on improved ground for liquefaction

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ABSTRACT : As a countermeasure against liquefaction of loose sandy ground, Grid-shaped stabilized ground improved by Deep Cement Mixing method has been developed. The grid can prevent the loose sand enclosed from liquefaction by constricting shear deformation and pore water pressure rising of the loose sand. Centrifuge model shaking tests were performed in order to grasp its liquefaction-proof effect quantitatively. The test results illustrated the effectiveness of the grid-shaped, improved ground in protecting the loose sand from liquefaction.

1. INTRODUCTION

Structure-damages induced by liquefaction of loose sandy ground has been attracting the attention of engineers to development of a countermeasure against the damages since the 1964 Niigata earthquake. Recent Japan promotes some big construction projects in waterfront area such as Tokyo Port which has great earthquake experiences, and effective countermeasures against liquefaction are in great demand. This paper describes studies on a soil improvement method to prevent the loose sand from liquefaction. The method is called Deep Cement Mixing method, and based on soil solidification method using cement material to construct grid-shaped solidified part in the loose ground. The study is on verifying the effectiveness of the improved ground in preventing liquefaction by using centrifuge model shaking tests. An actual construction work of grid-shaped improved ground as a building foundation was done in 1988 at Kagoshima, Japan with background of these studies (Babasaki et al, 1990). The effectiveness has been also studied by the Public Work Research Institute, Ministry of Construction, Japan Government and four construction companies (Koga et al, 1988).

2. TEST APPARATUS

2.1 Geotechnical Centrifuge

The equipment, the University of Chuo 3.05m radius centrifuge (Fujii et al, 1988) was used for tests on liquefaction-proof behavior of the grid-shaped improved ground.

2.2 Shaking Apparatus

Figure 1 shows a shaking system employed (Suzuki et al, 1991). The system consisted of a laminar box, a pair of L-shaped leaf springs, a torque motor, a gearwheel, a lever, an accumulator, an electromagnetic valve, eight vibration-isolated rubber blocks and a base plate. Electrical signals from operation control box passed through slip rings and a relay box caused the electromagnetic valve open, oil pressure in the accumulator released, and rotation of the motor started. The rotation of the motor caused rotation of the gearwheel and a cog of the gearwheel hit a metal tip downward which was bolted at an end of the lever. Up and down movement of the hit tip of an end of the lever was converted to horizontal movement of the other end of the lever by a pin support. The horizontal movement of the lever end caused deflection of the leaf springs and horizontal displacement of the laminar box. The deflection of the springs resulted in free vibration of the leaf spring and of the laminar box until the next cog's hitting to the tip.

The shaking system was put on the platform of the centrifuge so as to have vertical shaking direction.

2.3 Laminar Box Container

Rectangular frames of the laminar box, inside dimensions were 352mm and 352mm, were made by aluminum with 24mm wide and 10mm thick and the 22 frame stacks had the height of 220mm. Surfaces of the frames were ground by sandpaper and oiled (silicone oil) so as to reduce friction resistance between them. An disposable

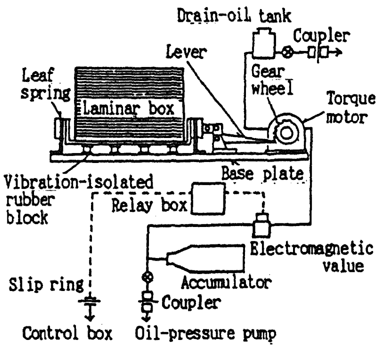

Figure 1. Shaking apparatus and laminer box

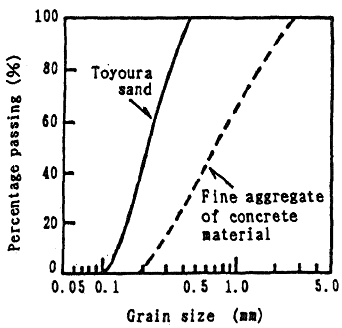

Figure 3. Grain size distribution

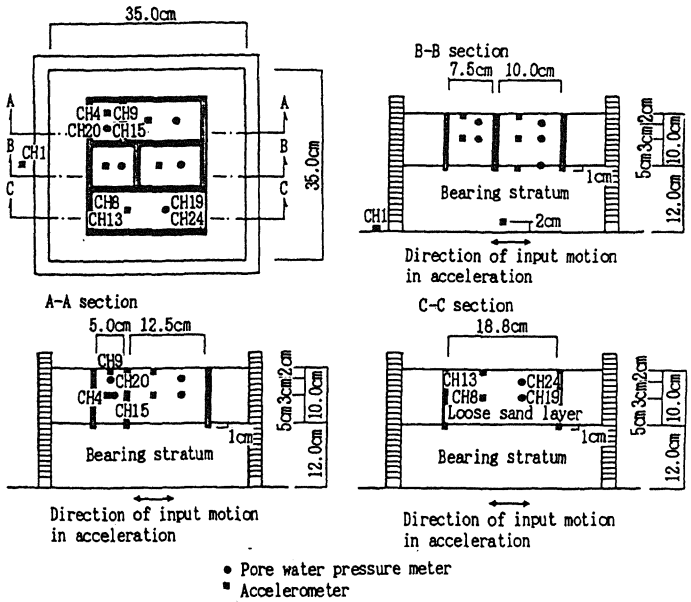

Figure 2. Improved ground model

Table 1. Specifications of model tests

Test No.	Model No.	Void ratio e	Relative demsity (%)	Groundwater level (cm)	γt (kN/m³)
1	STAC100G28	0.767	52	GL± 0	20.2
2	STAC100G30	0.767	52	GL± 0	20.2
3	STAC100G32	0.767	52	GL− 1	20.2
4	STAC100G34	0.767	52	GL− 1	20.2

neoprene rubber bag (2mm thick) were put in the box.

3. LIQUEFACTION TESTS

3.1 Test Models

Figure 2 shows model of ground scaled in 1/100 of prototype. The model was prepared as follows. Dry fine aggregate of concrete material (e_{max}= 0.853, e_{min}= 0.481) was placed in the box as a bottom, stiff soil layer of 12cm thick, compacted by a vibrator to be e= 0.572, Dr= 76%. Glycerin solution with a viscosity 100 times of water and a density of 12.2kN/m³ at 22℃ was used as pore fluid so as to obtain a comparable time scale between the model and a prototype in seepage characteristics. The bottom soil layer was saturated with the solution. The loose sand layer was prepared using Toyoura sand (e_{max}= 0.949, e_{min}= 0.601). The loose sand layer of 10cm thick (e= 0.767, Dr= 52%) was founded on the bottom stiff layer by dry-sand raining into the glycerin solution which kept 3cm thick above the surface of the loose sand. Grain size distribution curves of the aggregate and Toyoura sand are shown in Figure 3.

The grid-shaped ground was fabricated by light-weight precast concrete plate, unit volume weight of 19.0kN/m³ in surface-dry condition. Inside dimensions to the shaking direction of each grids were 5.0cm, 7.5cm, 10.0cm, 12.5cm and 18.8cm. The dimension to the direction at right angle to the shaking one was only 7.0cm. The grid-shaped ground was buried in the bearing stratum in 1cm depth. Two models of underground water table were prepared, 0cm and 1cm below the ground surface. Specifications of four models tested are shown in Table 1.

3.2 Shaking Conditions

The shaking tests were performed under 100g of centrifugal gravity. Figure 4 (a) shows prototype acceleration history of the bottom place. There can be seen sharp-peaked, high amplitude waves which were generated by hitting the metal tip of the lever by the six cogs of the gear wheel, as mentioned above. The sinusoidal-like waves between the sharp waves are free vibration of the springs and the box. The shaking system was adjusted to obtain

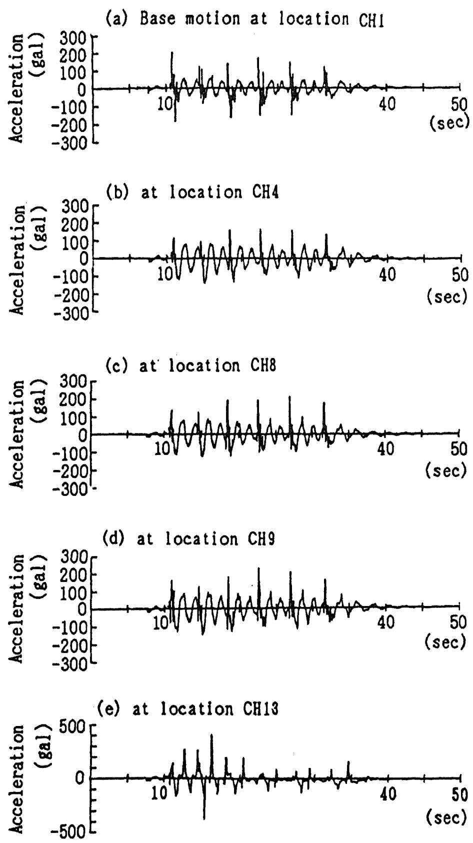

Figure 4. Prototype acceleration histories of Test 2

about 200 cm/sec² of the sharp-peak acceleration waves and about 60 cm/sec² of the free vibration.

4. TEST RESULTS

Prototype acceleration histories of accelerometers CH4 and CH9 (see Figure 2) embedded in the grounds enclosed by the grid-shaped soil model with interval of 5.0cm (the smallest grid) and CH8 and CH13 enclosed by that with 18.8cm (the largest) of the Test 2 are shown in Figure 4. Prototype histories of excessive porewater pressure of CH15 and CH20 embedded in the ground enclosed by the smallest grid of 5.0cm interval and of CH19 and CH24 enclosed by the largest of 18.8cm interval are shown in Figure 5. With respect to the 18.8cm grid results, the excessive porewater pressure history of CH24, embedded at 2cm deep below the surface showed abrupt increase immediately after shaking and was completely liquefied. Acceleration CH13 located on the ground surface showed little response right after the liquefaction. CH19 of porewater pressure meter also showed large pressure.

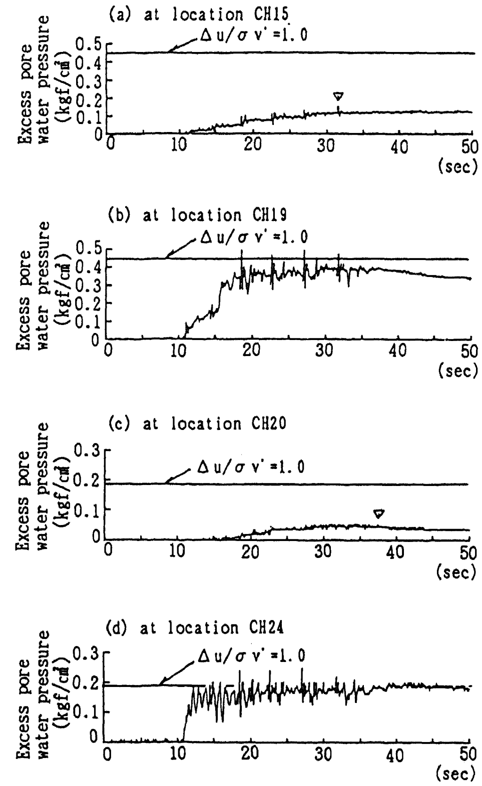

Figure 5. Prototype histories of excessive pore water pressure of Test 2

With respect to the 5.0cm-grid results, CH15 and CH20 of pore water pressure gauges showed small value and liquefaction-proof effect were clearly illustrated, compared with the results of the 18.8cm-grid.

Figure 6 shows the maximum acceleration of the free vibration part of Test 2, 4 and the unimproved ground model(Suzuki et al, 1991). All 5cm-grid models showed no-increment in the response whereas the 18cm-grid showed the same increment as the unimproved model at the ground surface. In Test 2 (water table= GL-0cm), the larger the grid space, the greater the maximum acceleration at the ground surface. In Test 4 (water table= GL-1cm), the acceleration of the ground surface of 12.5cm, 18.8cm-grid showed the same as the unimproved model while the others showed little increment. All accelerations below GL-5cm enclosed by the grids were smaller than those of the unimproved ground. These data shows the effectiveness of the grid-shaped improved ground in preventing the soft sandy ground from liquefaction.

Figure 7 (a) shows relationship between $\Delta u/\sigma_{v'}$ (maximum excessive porewater pressure ratio) and L/H of Test 1 and Test 2 (water table= 0cm): where Δu is maximum excessive porewater pressure, $\sigma_{v'}$ is initial effective overburden stress, L is shaking-direction

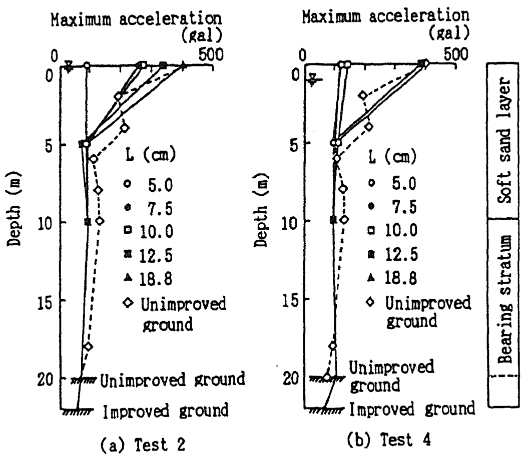

Figure 6. Relationship between prototype maximum acceleration of free vibration part and depth of Test 2 and 4

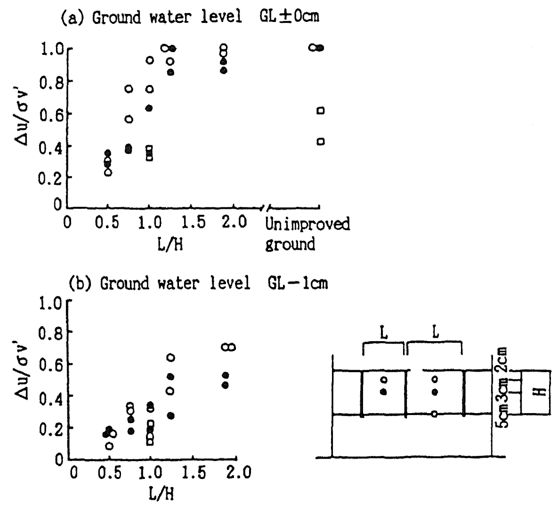

Figure 7. Relationship between maximum excessive pore water pressure ratio $\Delta u/\sigma_{v'}$ and L/H, where L is the space between grid walls and H the thickness of the layer prone to liquefaction

inside dimension of the grids and H is the thickness of the loose sand layer. In the Figure, the results of no-improved ground model are additionally shown (Suzuki et al, 1991). $\Delta u/\sigma_{v'}$ -values at 2cm deep below the surface, symboled by ○ , are close to 1.0, as L/H becomes larger than 1.0 and liquefaction occurs in the ground surface area. $\Delta u/\sigma_{v'}$ values at 5cm deep, symboled by ● , approach to 0.8 - 1.0 as L/H exceeds 1.0 and middle area of the loose soil thickness is also close to liquefaction. On the contrary, in the case that L/H is less than 1.0, $\Delta u/\sigma_{v'}$ becomes less than 1.0 as L/H decreases. At L/H = 0.5 both $\Delta u/\sigma_{v'}$ of ○ and ● are about 0.3.

Figure 7 (b) shows a relationship between $\Delta u/\sigma_{v'}$ and L/H of Test 3 and Test 4 (water table = -1cm, Total unit volume weight of the soil above the ground water table was assumed 18.0kN/m³). Increase in effective overburden load by decreasing in the ground water table leads to smaller $\Delta u/\sigma_{v'}$ than that of Test 1 and Test 2 and to no liquefaction even in the case of L/H > 1.0. However, the $\Delta u/\sigma_{v'}$ becomes larger as it is closer to the surface of the ground. At 0.5 of L/H, $\Delta u/\sigma_{v'}$ is 0.1 - 0.2 at any depth.

5. CONCLUSIONS

The grid-shaped ground solidified by Deep Cement Mixing method is effective to prevent the loose sandy ground from liquefaction induced by the earthquake. The inside dimension to vibration direction is important to make sure of the liquefaction-proof effect. Increase in effective overburden stress such as lowering the ground water table results in promotion of the liquefaction-proof effect.

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REFERENCES

Babasaki R., Suzuki K., Saitoh S., Suzuki Y. and Tokitoh K. 1990. Construction and testing of deep cement foundation improvement using the deep cement mixing method: Deep Foundation Improvements, Design, Construction and Testing. ASTM STP 1089.

Fujii N., Kusakabe O., Kato H. and Maeda Y. 1988. Bearing capacity of a footing with an uneven base on slope, Direct comparison of prototype and centrifuge model behavior: Centrifuge 88. Paris

Koga Y., Matuda O., Koseki J., Endokida M., Matuo T. and Suzuki K. 1988. Experimental study on the deep mixing method as a countermeasure against liquefaction: US-JAPAN Joint Work Shop on Remedial Treatment of Liquefiable Soils.

Suzuki K., Babasaki R. and Suzuki Y. 1991. Liquefaction tests by a laminar box in a centrifuge: Second International Conference on Geotechnical Earthquake Engineering and Soil Dynamics.

Suzuki K., Babasaki R. and Suzuki Y. 1991. Centrifuge Tests on Liquefaction-Proof Foundation: Centrifuge 91. Colorado.