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Effectiveness of top-shaped concrete blocks in reducing settlement in ground liquefied by an earthquake

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ABSTRACT: Shaking table tests were performed to clarify the settlement in liquefied loose sand of a new foundation incorporating top-shaped concrete blocks. Shaking table tests were also performed on foundations with two differently shaped concrete blocks to investigate the effectiveness of the three foundations in controlling settlement.
FEM elastic analyses were performed to compute the stress distributions in the models and in in-situ ground when the top-shaped concrete blocks were applied. Moreover, the factor of safety against liquefaction, F_L was evaluated in in-situ ground. For the liquefaction analyses, shear stress in the ground during an earthquake was estimated by dynamic analyses using the SHAKE computer program.

INTRODUCTION

Recently, a new foundation made of top-shaped concrete blocks has been applied in Japan for small structures, such as houses, built on soft clayey ground. Arai et al.(1987) and Arai et al.(1988) have demonstrated that this method eliminates the settlement of structures and increases the bearing capacity of soft clayey ground in static condition. According to them, a combination of top-shaped concrete blocks and gravel fill disperses the surface load like a flexible foundation.

However, no research has been performed on the effectiveness of top-shaped concrete blocks in preventing the settlement of small structures on loose sandy ground in seismic condition. In view of this, several shaking table tests were conducted to study the effectiveness of the foundation in controlling settlement. Furthermore, FEM elastic analyses were performed to clarify the mechanism of effectiveness.

2 TEST APPARATUS

The shaking table used for the tests was 1m in length and 1m in width in plane. The soil container was 1m in length, 70cm in depth and 60cm in width, as shown in Fig.1, and its front wall was made of glass, through which the deformation of the soil could be observed. Foam rubber of 5cm in thickness was inserted inside both walls, as

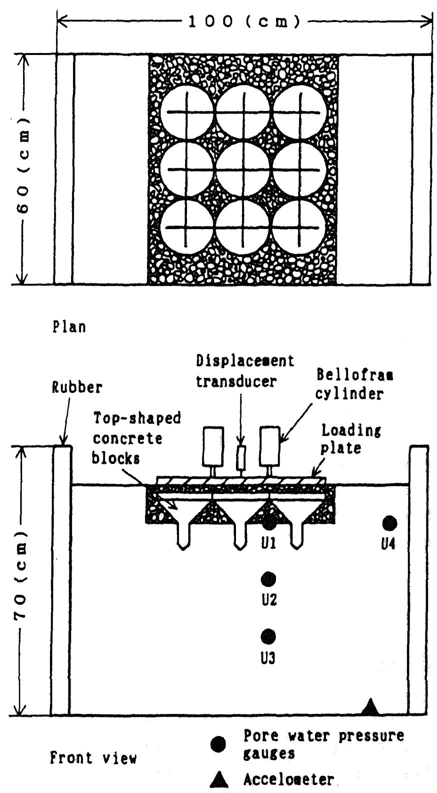

Fig. 1 Diagram of Apparatus for Shaking Table Tests

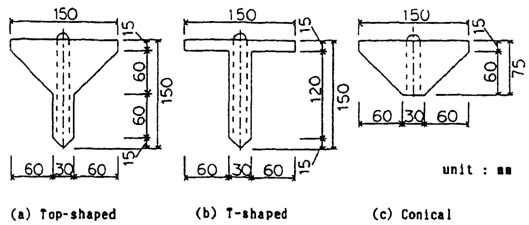

Fig. 2 Shapes of Concrete Blocks

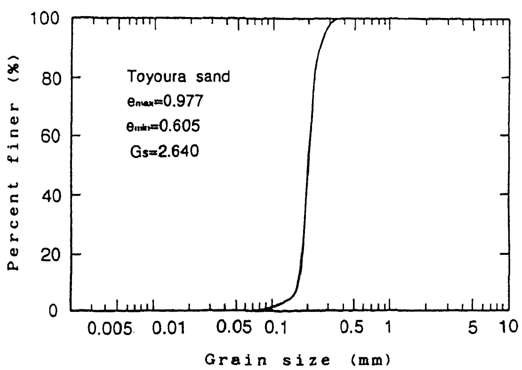

Fig. 3 Grain Size Distribution Curve of Toyoura Sand Used in the Tests

shown in Fig.1, to induce uniform cyclic shear strain in a soil model during shaking. Test material was poured into the container to a depth of 55cm. Half scale top-shaped concrete blocks, as shown in Fig.2, were set on the surface of the model ground, in which four pore pressure gauges and one accelometer were installed. Fig.2 also shows a schematic illustration of two differently shaped concrete blocks used in this study. One is a T-shaped concrete block or a disk-shaped concrete plate with a leg, and the other is a conical concrete block without a leg.

Toyoura sand taken from a beach in Yamaguchi Prefecture was used as the test material. The grain size distribution curve is shown in Fig.3. This sand has subangular grain shape and has a specific gravity of 2.640. The maximum and minimum void ratio were measured at 0.977 and 0.605, respectively.

3 TEST PROCEDURES

A soil model with a relative density of 50% was made by pluviation under water. A lattice of iron rods was placed on the surface of the soil to determine the position of the concrete blocks and fix their legs. Then, concrete blocks were installed at the specific positions, and the

Table 1 Conditions of Shaking Table Tests Using Top-Shaped Concrete Blocks

Test No.	Installation conditions of top-shaped concrete blocks			Crusher-run		Lattice of iron rods and iron bars		Width of loading plate (cm)		Load (kgf)	
	Two rows	Three rows	None	In-stall-ed	None	In-stall-ed	None	30	45	75	150
A 1			○		○		○	○			○
A 2			○		○		○	○		○	
A 3			○		○		○		○		○
A 4			○		○		○		○	○	
A 5	○			○		○		○			○
A 6	○			○		○		○		○	
A 7	○			○			○	○			○
A 8	○				○	○		○			○
A 9	○				○		○	○			○
A10		○		○		○			○		○
A11		○		○		○			○	○	
A12		○		○			○		○		○
A13		○			○	○			○		○
A14		○			○		○		○		○

Table 2 Conditions of Shaking Table Tests in the Use of Each Kind of Concrete Block

Shapes of concrete blocks	Installation conditions of concrete blocks		Crusher-run		Lattice of iron rods and iron bars	
	Three rows	None	In-stall-ed	None	In-stall-ed	None
Without countermeasure		○		○		○
Top-shaped	○		○		○	
T-shaped	○		○		○	
Conical	○		○		○	

Width for loading : 45(cm) Load : 150(kgf)

tops of the blocks were connected using iron bars. A crusher-run was put into the spaces between the concrete blocks and on the upper part of the blocks. A loading plate was set on the crusher-run and a pressure equal to the weight of a typical house, $0.074 kgf/cm^2$, was exerted on the plate by means of four bellofram cylinders. At the same time, the model ground water level was raised to a depth of 1cm from the ground surface. Before shaking, the model ground was allowed to sit for thirty minutes.

In the shaking table tests, two types of tests, described as follows, were performed.

(1) The test conditions were changed as shown in Table 1 ; without concrete blocks, using two or three rows of top-shaped concrete blocks, with or without crusher-run, with or without a lattice of iron rods and iron bars, and changing the width for loading and the overburden pressure.

(2) The tests were conducted without concrete blocks and with three rows of three differently shaped blocks, as summarized in Table 2.

Shaking motion was applied at a frequency of 3Hz and with an acceleration of 250 gal, appropriate to induce liquefaction after

Table 3 Properties of Materials Used in FEM Analysis

	Young's modulus (kgf/cm²)	Poisson's ratio	Unit weight (tf/m³)
Concrete	140000.0	0.300	2.40
Sand	350.0*	0.350	1.90
Steel plate	2100000.0	0.300	7.90
Crusher-run	20.0	0.333	1.80

*** The value is obtained by triaxial test in the condition of confining pressure of 1 kgf/cm².**

several cycles of shaking. Acceleration and excess pore water pressure during shaking were measured at five points and the loading plate's settlement up to 10cm was measured by a displacement transducer, as shown in Fig.1. Settlement of more than 10cm was measured by a vernier caliper after shaking. Whether or not liquefaction occurred in the model ground was judged from the value of the pore water pressure gauge at point U4 in Fig.1.

4 METHOD OF ANALYSIS

In order to study the initial stress distribution in the model ground and in in-situ ground, on which the top-shaped concrete blocks were installed, FEM elastic analyses were performed in the plane strain condition. In in-situ ground, ten rows of top-shaped blocks were set under the right side of a house with a width of 5m. Table 3 summarizes the properties of the materials used in this analysis. The Young's modulus of sand shown in Table 3 is the value obtained in an effective confining pressure of 1 kgf/cm^2, and the Young's modulus of each element used was corrected by adjusting the effective confining pressure in that element. The overburden pressure used was 0.074 kgf/cm^2, and the ground water level was at the ground surface for the model ground and at a depth of 2m from the ground surface for the in-situ ground.

After conducting the initial stress analysis, the SHAKE computer program was used for the dynamic analysis of total stress to estimate liquefaction in in-situ ground to a depth of 10m under the center of the house. Fig.4 is a soil boring log with SPT N-values, values of unit weight γ_t and mean diameter of soil D_{50} employed in the analysis. The N-values to a depth of 10m were evaluated by the method described hereafter. The unit weight γ_t and the mean diameter of soil D_{50} used for the dynamic

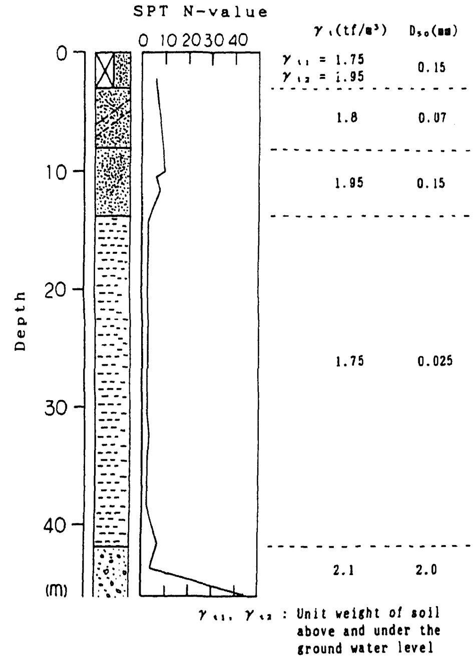

Fig.4 Soil Boring Log with SPT N-values, Values of Unit Weight and Mean Diameter of Soil Used in the Liquefaction Analysis

analysis were the values shown in the specification for highway bridges(1980), in which these two soil properties are evaluated by soil classification. Similarly, the shear wave velocity Vs used was evaluated from the following special modified formulae mentioned in that specification.

$$Vs = 80N^{0.333} \text{ for sandy soil} \quad \cdots\cdots (1)$$
$$Vs = 100N^{0.333} \text{ for clayey soil}$$

N denotes SPT N-value, and the shear wave velocity Vs to a depth of 10m was specially evaluated from Eq.(1) using the N-values obtained from formula (2), derived from Iwasaki et al.(1978), assuming that the liquefaction strength ratio was 0.2.

$$R_l = 0.0882\sqrt{N/(\sigma_v'+0.7)} \quad \cdots\cdots (2)$$

The relationships between dynamic shear modulus ratio, G/G_0 and shear strain, γ, and damping ratio, h and shear strain, γ, derived from Yasuda et al.(1985) were utilized for the dynamic analysis. These relationships are also mentioned in Yasuda et al.(1991). The effective overburden pressure, σ_v' was obtained from the initial stress analysis.

On the basis of the results of the analyses described above, the cyclic shear stress, τ_l was obtained from the liquefaction strength ratio R_l, and the maximum cyclic shear stress, τ_{max} was

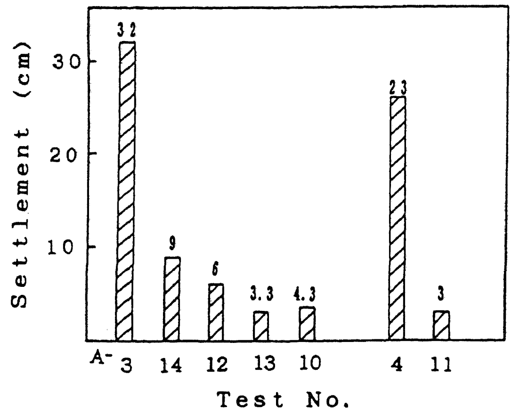

Fig. 5 Final Settlements Attained in the Use of Three Rows of Top-Shaped Concrete Blocks

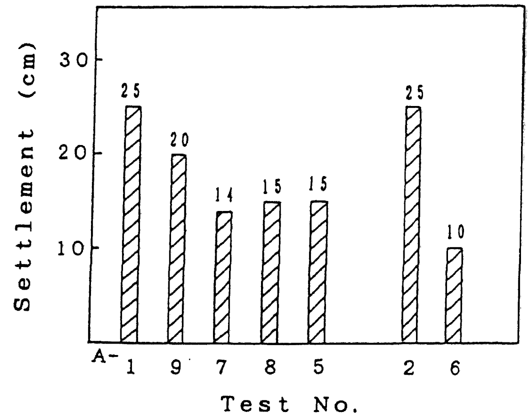

Fig. 6 Final Settlements Attained in the Use of Two Rows of Top-Shaped Concrete Blocks

evaluated from the dynamic analysis. The factor of safety against liquefaction, which is the ratio τ_l to $0.65\tau_{max}$, was estimated in succession.

The irregular time history employed in the dynamic analysis was a component horizontal acceleration recorded during an earthquake in Japan. It was the NS component recorded at the University of Tokyo in Chiba City during the Chibakentoho-oki Earthquake in 1987.

5 TEST RESULTS

Figs.5 and 6 indicate the final settlements of the foundations using three and two rows of top-shaped concrete blocks, respectively. In the tests on foundations with three rows of blocks, as shown in Fig.5, the settlement reached about 20cm to 30cm in tests [A-3] and [A-4], without a foundation. However, when three rows of top-shaped concrete blocks were installed, settlement was limited to less than 10cm. In test [A-10], with a foundation reinforced with crusher-run, a lattice of iron rods and iron bars, the settlement was only 4.3cm. The settlement of the foundation with two rows of top-shaped concrete blocks was larger than that with three rows, but the settlement was less than that when no foundation was used.

The final settlements in tests [A-14] and [A-9], without crusher-run and iron bars, were greater than in tests with their reinforcement. Settlement in test [A-10], with the use of crusher-run, was not so different from settlement in test [A-13], without crusher-run. Settlement in test [A-12], without iron bars, was greater than in tests [A-10] and [A-13], with them. Therefore, it can be concluded that

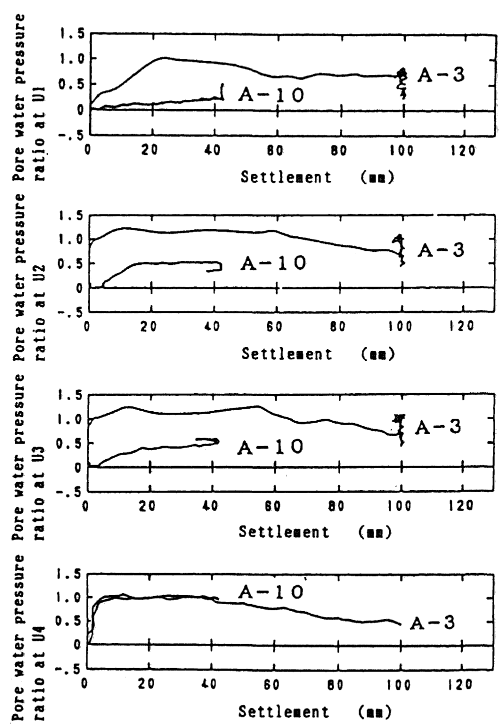

Fig. 7 Relationships between Excess Pore Water Pressure Ratio and Settlement

settlement is not decreased by the drainage effect of crusher-run, but it is reduced by the iron bars, which prevent the legs of the concrete blocks from spreading in the model ground.

The relationships between excess pore water pressure ratio and settlement are shown in Fig.7 for test [A-10], with three rows of top-shaped concrete blocks, crusher-run and iron bars, and for test [A-3],

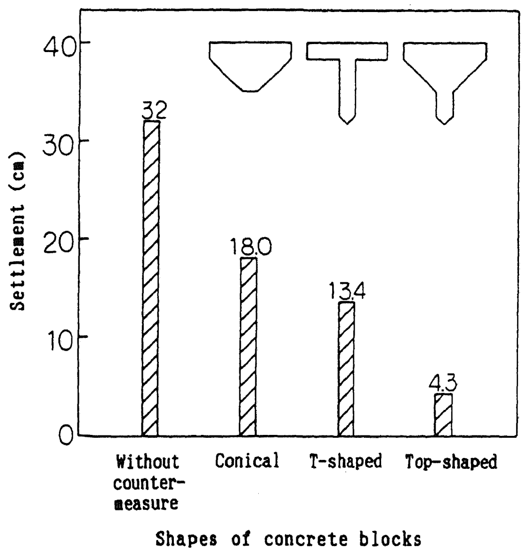

Fig. 8 Final Settlements Attained in the Use of Each Kind of Concrete Block

without a foundation. Liquefaction took place throughout the model ground in test [A-3], because all excess pore water pressure ratios became equal to 1.0. On the contrary, in test [A-10], with countermeasures, liquefaction occurred only at point U4, the excess pore water pressure ratio was less than 0.5 and liquefaction did not take place in the model ground below the foundation. These trends were seen in other tests. The lateral flow of the ground under the foundation was restrained and settlement was reduced, because it is difficult for liquefaction to occur in ground below a top-shaped foundation. Therefore, it may be stated that the top-shaped foundation is effective in controlling settlement in loose sand deposit during an earthquake.

Fig.8 shows the final settlement obtained by the tests in which three rows of differently shaped concrete blocks were utilized, as shown in Fig.2. In the test without countermeasures, settlement exceeded 30cm, but when T-shaped and conical concrete blocks were used, settlement decreased to 13.4cm and 18.0cm, respectively. Furthermore, the settlement of the foundation using top-shaped blocks was no more than 4.3cm. The settlement of a foundation incorporating top-shaped concrete blocks is much smaller than that without countermeasures, because a top-shaped foundation has an effect due to its leg and an effect due to its conical shape. A T-shaped foundation restricts settlement more than a conical foundation.

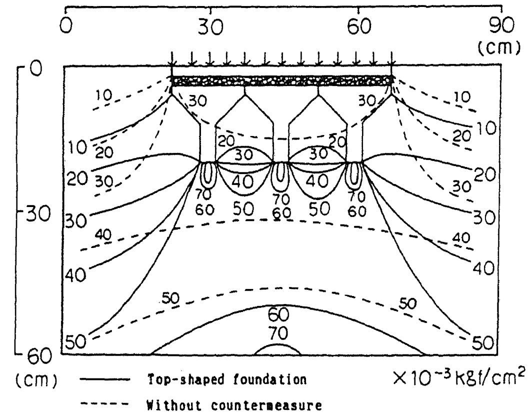

Fig. 9 Distribution of Mean Effective Principal Stress in the Model Ground

6 RESULTS OF ANALYSIS

The distributions of mean effective principal stress in the model ground without countermeasures and with a foundation of three rows of top-shaped concrete blocks are shown in Fig.9, respectively, in which an overburden pressure of 0.074 kgf/cm^2 was loaded on the surface of the ground. In the shaking table test without countermeasures, the mean effective principal stress concentrated in the ground just under the loading plate. However, when a top-shaped foundation was installed in the model ground, the effective stress became large at the tips of legs and small near the conical portions of the blocks. Furthermore, the effective stress in the sphere deeper the block tips was larger with the foundation than that without it.

Thus, confining stress increases throughout a larger ground area under a top-shaped foundation than without a countermeasure, because stress is relatively widely dispersed by the foundation. Therefore, it is difficult for liquefaction to occur under a top-shaped foundation and settlement is reduced.

The distributions of mean effective principal stress are shown in Fig.10 for the analysis in in-situ ground without countermeasures and with a top-shaped foundation. Using a top-shaped foundation, the effective stress apparently increases owing to stress dispersion.

Fig.11 shows the factor of safety against liquefaction, F_L evaluated from the liquefaction analysis in in-situ ground, applying the irregular time history of the Chibakentoho-oki Earthquake with a maximum acceleration of 225 gal, where $\Delta p'$ means

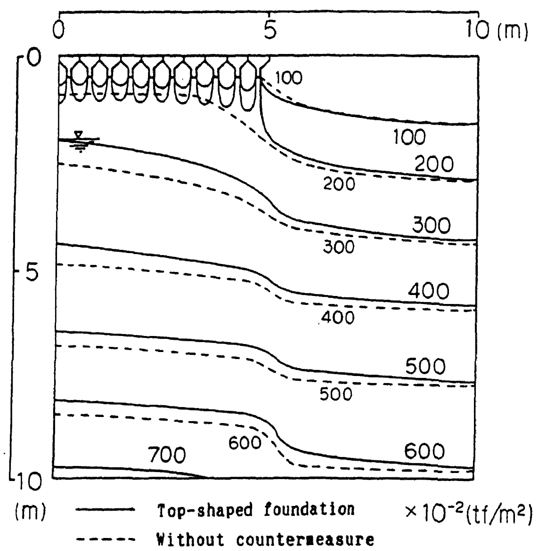

Fig. 10 Distribution of Mean Effective Principal Stress in In-situ Ground

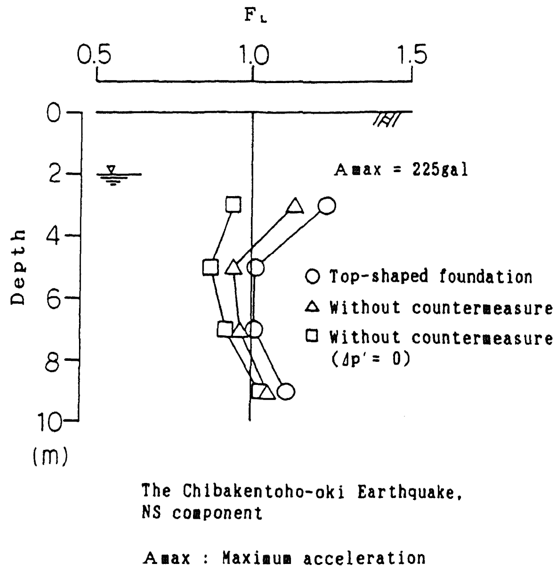

Fig. 11 Results of Liquefaction Analysis in In-situ Ground

overburden pressure on the surface of the ground. Liquefaction does not occur in the whole layer of the ground below the top-shaped foundation, because the factor of safety, F_L does not get smaller than 1.0. Therefore, it can be concluded that liquefaction resistance is increased in the ground under a top-shaped foundation.

7 CONCLUSIONS

Based on shaking table tests and analyses, the following conclusions were derived.

(1) The final settlement of a foundation using top-shaped concrete blocks was only 4.3cm, the smallest settlement observed when three types of foundation were tested. Therefore, this kind of blocks the most effective in controlling settlement in loose sand during an earthquake. The settlement resulting from the use of T-shaped and the conical concrete blocks was smaller than that without a countermeasure. Consequently, a top-shaped foundation has an effect due to its leg and due to its conical shape.

(2) According to the distribution of mean effective principal stress obtained by the FEM elastic analysis, confining stress increases within a larger ground area under the top-shaped foundation than without a countermeasure. Stress is relatively widely dispersed by a top-shaped foundation and liquefaction resistance is increased in the ground under the foundation.

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