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Shaking table test on reinforced sand

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ABSTRACT: Shaking table tests were conducted on saturated sand layer reinforced with wires in order to study the effectiveness of the reinforced earth method as a countermeasure for liquefaction. In this paper, the effects of arranging direction, spacing and area of reinforcement and rigidity of reinforcing materials on the liquefaction resistance are investigated.

1 INTRODUCTION

Liquefaction characteristics of reinforced sand has so far been studied by the laboratory element tests (cyclic triaxial compression test and cyclic torsional simple shear test)[1)2)3)]. As a result, it has been found that: If the reinforcing materials are arranged in the direction of minimal principal stress, ample reinforcement effect can be obtained regardless of the rigidity of the materials, even with material like nonwoven fabric, and that if the reinforcement is arranged in the different direction of the principal stress, the reinforcement effect is affected by the rigidity of the materials.

During this study, the liquefaction phenomenon of actual ground (dissipation of pore water pressure from the upper layer), which is difficult to reproduce by the laboratory element tests, has been successfully reproduced using a small shaking table. The study has examined if wire, used as a model reinforcing material, will increase the ability of reinforced sand to resist liquefaction, and how the direction of reinforcement material arrangement and its rigidity affect the reinforcement effect.

2 TEST PROCEDURES

Figure 1 shows a small pneumatic type shaking table used for the test. The sand box dimensions were 110cm long, 30cm wide, and 60cm high. The walls in the direction of vibration were jointed to the bottom plate by hinges to allow free shearing deformation of the model ground. The sand box was designed to be small since the purpose of the test was to examine the effect of reinforcement materials under various conditions.

The pneumatic cyclic loading system of this testing device was the same as a pneumatic type cyclic triaxial compression test[4)]. Giant boosters were used so that the pressure could follow as in high frequency as possible.

The saturated sand layer was formed by pluviating dry Toyoura sand (Gs=2.64) into the water from the hopper (with 5mm wide opening) keeping the height of fall constant (50cm above the surface of the water). The water depth is 25cm from the bottom of the sand box. The void ratio was e=0.88. The side walls were hammered at 12 locations each for 10 times equally with a mallet to produce a state of void

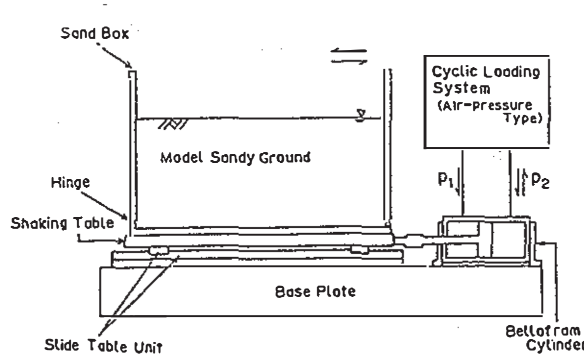

Figure 1. Small type shaking table

ratio of 0.80. Tests were made on two samples, void ratio of e=0.88 and 0.80. The water level was set at the ground level, and the sample was saturated for 12hours (this, although not perfect, was considered to raise the degree of saturation). The depth of the sand layer was arranged for 40cm. Figure 2 shows the arrangement of measuring equipment (such as pore water pressure gauge, accelerometer, and displacement gauge).

In this experiment, the sand layer having no reinforcement was subjected to vibration at several levels of acceleration. The number of loading cycles up to liquefaction (where the pore water pressure Δu equals to the initial effective earth pressure σ'_v) was arranged, and the mean curve of acceleration versus the number of loading cycles was obtained. A similar test was conducted with reinforced sand and the results were likewise arranged. The effect of reinforcement was examined by comparing the number of loading cycles up to the liquefaction under the same density. The reinforcement materials used for this experiment were based on the wire of 20cm long and 1.2mm diameter (wire length and diameter varied by the test). Sand was applied to the wire surface using Araldite and such wires were mainly arranged vertically in the area as shown in Figure 2.

The stress condition in the ground of this test was close to the case of torsional simple shear test. The direction of the reinforcement (vertical direction) under this test was inclined away from the direction of the principal stress, it failed to serve as a perfect tensile and compressive reinforcement. However, the arrangement of the reinforcements was based on vertical direction for the ease of actual construction work. The reinforced area in the model ground was limited to I =40cm and was located in the center of the sand box, this test was made different from the element test in that the entire specimen was reinforced at regular intervals. The reinforcement materials were arranged at regular intervals to one another (standard is $\Delta l=\Delta w=2.5$cm). If actual ground is assumed by applying only geometric scale, disregarding the law of similarity, the model ground of $\Delta l=\Delta w=2.5$cm, $h_R=20$cm will be equivalent at a scale of 1 to 25 to the case where the reinforcement materials of 5m long are arranged at intervals of $I_R=10$m, $\Delta l=\Delta w=62.5$cm to the sand ground of 10m deep.

Furthermore, in this test, the supply air pressure of the bellofrom cylinder for generating the specific table acceleration was checked by a gauge before application, and a testing frequency of 1.5HZ was applied.

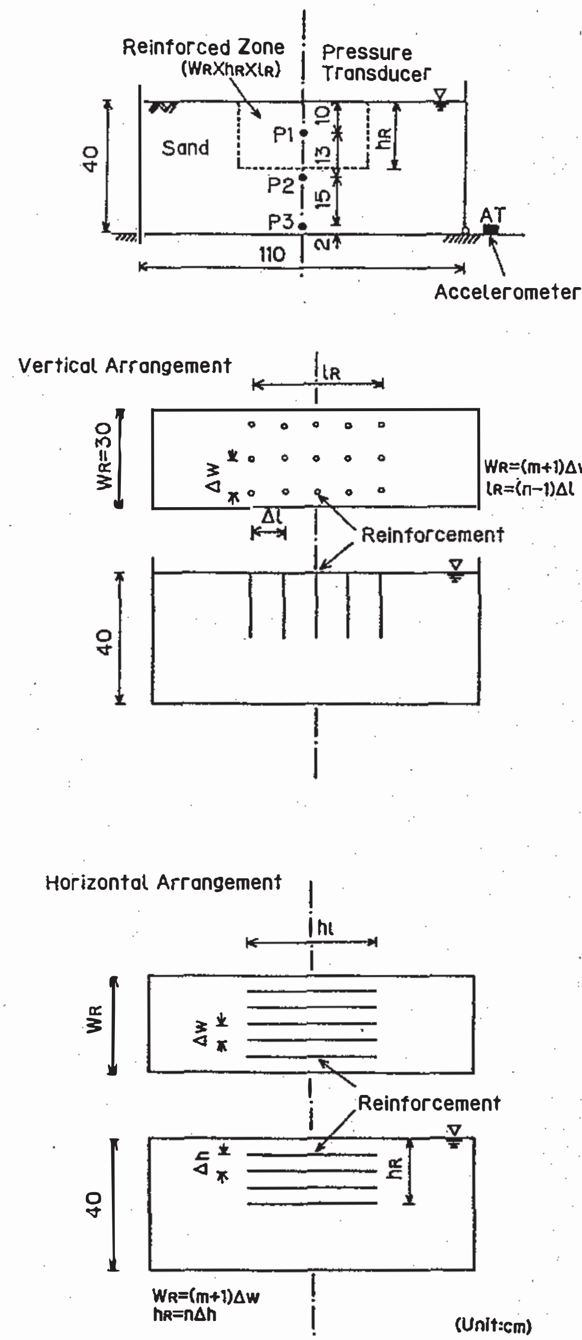

Figure 2. Measuring equipment and the arrangement of reinforcement

3 TESTING RESULTS

Figure 3 shows the record of table acceleration and pore water pressure (Pl) when the sand layer was vibrated with the void ratio e=0.80 and at a table acceleration of 156 gal. This figure shows that a specific acceleration was generated in the early stage, being kept almost at a constant value until liquefaction is reached.

Figure 4 shows the relationship between the acceleration and the number of loading cycles until the model ground reinforced by wire (d=1.2mm, l=20cm, m=11, n=17, Δl= Δw=2.5cm) reached liquefaction (e=0.88). Here, the number of loading cycles required till the liquefaction was measured at the location Pl inside the reinforced area. The solid line in the figure shows the relation between the acceleration and the number of loading cycles for unreinforced sand only. The curve of reinforced sand is located to the right of the one for the unreinforced sand. The figure shows that the reinforced sand required more loading cycles than the unreinforced sand at the same acceleration,hence the effect of reinforcement. Noting the acceleration that caused liquefaction at N=2, the scale of the reinforcing effect is an increase of about 20 gal.

The test was conducted by pluviating sand from 50cm above the surface into the water to keep constant density, but the sand was packed rather loosely, it was either liquefied immediately after the application of vibration or not liquefied at all. Therefore the test is considered imperfect for evaluating the effect of reinforcement.

Figure 5 shows the results of test with e=0.80 using the forementioned testing method. In this figure, α/g, $\sigma_d/2\sigma'_c$, and τ/σ'_c are commonly represented by the axis of ordinates and the number of loading cycles up to liquefaction by the axis of abscissas to make comparison with previously described element test (cyclic triaxial compression test: e=0.83, d=0.9mm, 8layers of wire, torsional simple shear test: e=0.77, d=0.9mm, arranged in vertical direction at intervals of =1.26cm)[5]. The small shaking table test and element test cannot be simply compared because of the difference in drainage condition, saturation, confining pressure, preparing method of specimen, position of reinforcement insertion and spacing, and other conditions. However, as the trends of reinforcement effect, these two tests share a point that the smaller the acceleration ratio and stress ratio, the greater the reinforcing effect. Noting the acceleration that produces liquefaction at N=10, the scale of the effect of the shaking table is an increase of about 40 gal. Supposing that the acceleration ratio and stress ratio are equal, the shaking table has the greatest effect. The following subsections describe the results of studies on various factors that affect the reinforcing effect of a small shaking table.

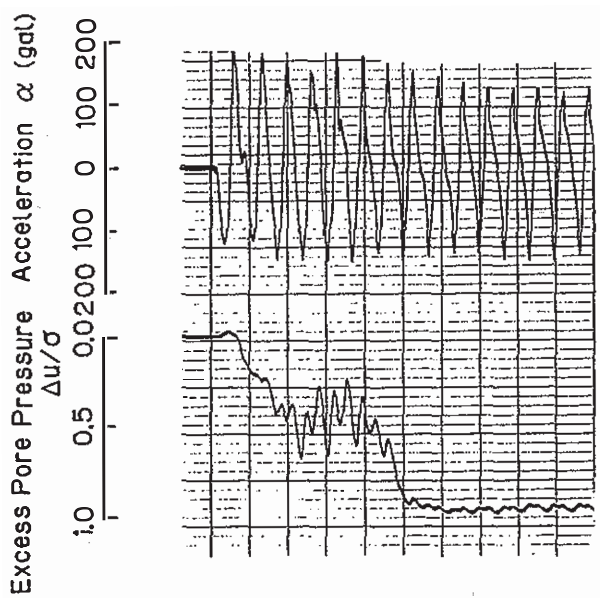

Figure 3. Record of table acceleration and pore water pressure

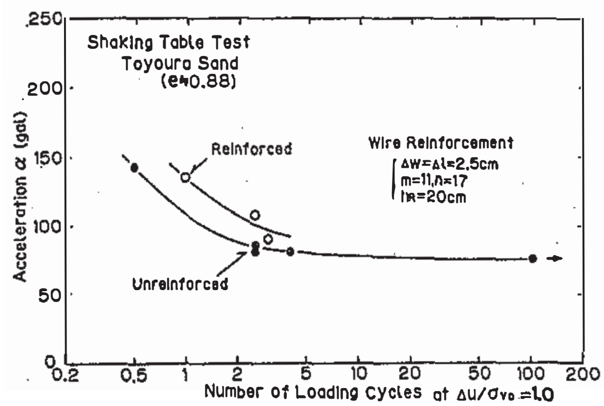

Figure 4. Acceleration versus number of loading cycles

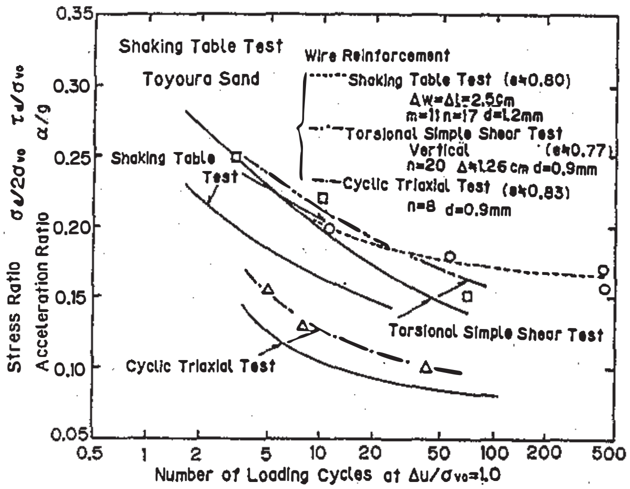

Figure 5. Comparison between shaking table test and element test

3.1 Effect of diameter (rigidity) of reinforcement

From the results of torsional simple shear tests of specimen reinforced with wires of different diameters or materials of different rigidity, it was found that the scale of reinforcing effect depended on the flexural rigidity of reinforcement material, and that the greater the rigidity, the greater the reinforcing effect, if the reinforcement was arranged in deviation from the direction of principal stress.

The state of stress of actual ground under the cyclic shearing stress during earthquake is close to that of the torsional simple shear test, where the direction of the minimum principal stress is inclined against the horizontal plane. Considering the actual construction method or the underground state, construction in the vertical direction is easier, and in this case, the reinforce-ment is arranged in deviation from the direction of the principal stress. Figure 6 shows the difference in the effect of reinforcement when two types of wires having different diameters (d=1.2mm and 2.0mm) were arranged vertically to model ground (m=11, n=17, Δl=Δw=2.5cm). The figure shows that the reinforcement by the wires of greater diameter had a greater effect than the wires of smaller diameter. Since the two types of wires were of the same material, their rigidity E were equal. With regard to the geometrical moment of inertia I ($\pi d^4/64$), the ratio between the two types of wires was about 1:8 or the wire of greater diameter had approximately eight times as great flexural rigidity (EI) as the wire of a smaller diameter. The tendency that the greater the diameter and flexural rigidity, the greater the reinforcing effect is same as the results of the torsional simple shear test. The degree of the reinforcing effect is remarkably greater than that shown by the latter, however.

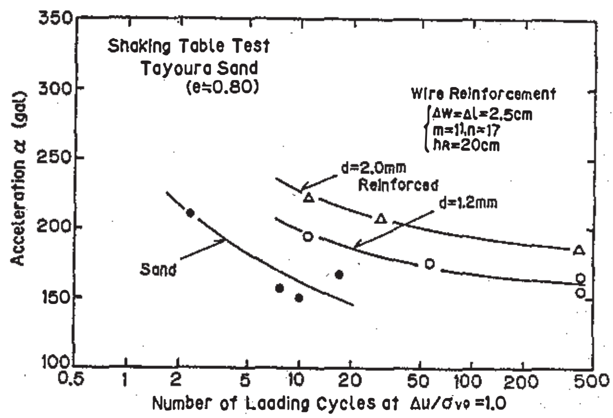

Figure 6. Effect of diameter (rigidity) of reinforcement

3.2 Effect of direction of reinforcement arrangement

As stated in Subsection 3.1, reinforcement materials cannot always be arranged in the direction of principal stress. Therefore, the reinforcement must be arranged at the most effective location within the range feasible for construction. To study the effect of the direction of reinforcement arrangement, a comparison of the effect of reinforcement was made, as shown in Figure 7, between the reinforcement material arranged in horizontal direction (d=1.2mm, Δh= w=2.5cm, h_I=40cm) and in vertical direction (d=1.2mm, Δl=Δw=2.5cm, h_R=20cm). The figure shows that the reinforcement arranged horizontally had a greater effect than the one arranged in vertically. This trend coincides with the results of the torsional simple shear test. Furthermore, strictly speaking, in the case of model ground the shearing stress is applied horizontally in the Ko state, different from the state of stress in the torsional simple shear test. Therefore, the direction of minimum principal stress during vibration is closer to horizontal than to vertical, confirming the tendency of the test results.

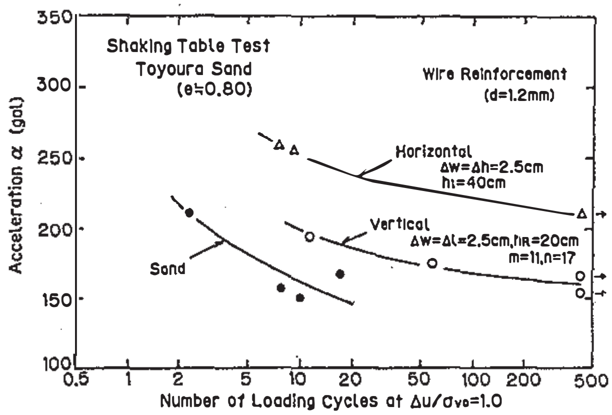

Figure 7. Effect of direction of reinforcement arrangement

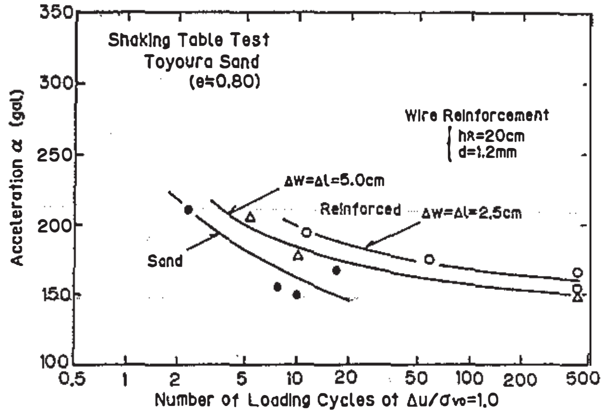

Figure 8. Effect of reinforcement intervals

3.3 Effect of reinforcement intervals and area

The most important thing for actual construction work is the volume of materials and the depth they are buried to. Figure 8 (▲l=Δw=2.5cm, Δl=Δw=5.0cm) and Figure 9 (h_R=20cm, h_R=35cm) show the effect of reinforcement intervals and area. As previously stated, disregarding the law of similarity and noting only geometric scale, the reinforcement intervals of Δl=Δw=2.5cm are equivalent to 62.5cm in the ground, and Δl=Δw=5.0cm to 1.25m. Reinforcement depth of h_R=20cm is equivalent to 5m, and h_R=35cm to 8.75m, and both values are reasonable. Both figures show that the narrower the reinforcement interval, or deeper the area, the reinforcing effect becomes greater.

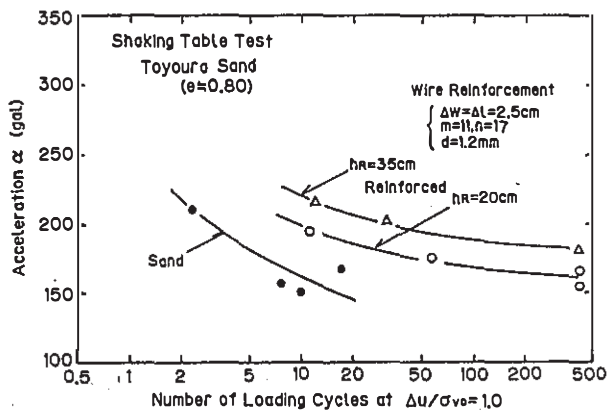

Figure 9. Effect of reinforcement area

4 CONCLUSION

The results of the shaking table experiments of saturated sand layer reinforced with wires are summarized as follows:

1) The ground will have much greater liquefaction resistance if the saturated sand layer is reinforced.

2) Similar to the cyclic triaxial compression test or torsional simple shear test, the reinfocing effect is great when the acceleration of shaking table is small.

3) The greater the rigidity of reinforement material, the narrower the reinforcement intervals, and the wider the reinforcement area becomes, the greater reinforcing effect becomes.

Furthermore, in comparison between horizontal and vertical reinforcements, the former has a greater effect of reinforcement. Judging from the results thus far described, the reinforced earth method is considered as an effective and inexpensive measure to prevent liquefaction during earthquakes.

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