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DYNAMIC PROPERTIES OF SOFT CLAY DIRECTLY OBTAINED FROM CENTRIFUGE SHAKING TABLE TEST

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ABSTRACT

A number of strong motion records over 0.5g of peak ground acceleration have been observed in recent years. According to these records, it is well known that acceleration response at a site on soft surface ground is relatively small when it is compared with the response at a site on stiff ground. In order to confirm this, the authors have performed centrifuge dynamic model tests under 25g centrifugal field. The model ground consists of a soft clay sandwiched between two sand layers at mid-depth. Its depth corresponds to about 9m in prototype scale. First, the changes of the earthquake response with input acceleration amplitude were studied. Amplification of peak acceleration response of surface ground compared to base acceleration reduced with increasing input amplitude because of the softening of clay layer. However, no reduction of peak velocity response of the surface ground compared to the input velocity occurred. Next, we focused on the nonlinear behavior of the soft clay layer and successfilly obtained the stress-strain relationships from vibration data using a direct evaluation technique. From stress-strain relationships obtained, we studied shear modulus dependency on a loading frequency. Comparing shear moduli at the same strain level, we found that the lower the loading frequency was, the smaller the average shear modulus was.

KEYWORDS

Centrifuge test; shaking table test; dynamic properties; stress strain relationship; soft clay; nonlinear behavior; earthquake response; frequency dependency.

INTRODUCTION

Research concerning the earthquake ground response has been an important subject in earthquake engineering. In recent years, a number of strong motion records over 0.5g peak ground acceleration (PGA) have been observed. Examples include the 1994 Northridge Earthquake in California, the 1994 Sanriku Haruka-oki Earthquake and the 1995 Hyogo-ken Nanbu Earthquake in Japan. Under these present conditions, the nonlinear properties of ground associated with ground response amplification during earthquake become increasingly important.

According to vertical borehole array records and earthquake response analyses so far, it is well known that the PGA at a site on soft ground, in the case of significant strong motion, is relatively small compared with that at a site on stiff ground. The reason for this is explained by the softening of the surface ground with large strain amplitude or liquefaction of sandy material. On the other hand, in general, we have considered that damages on a soft ground would be much larger than those on a stiff ground. If these are true, it implicitly leads us to the following two conclusions: (1) It is not appropriate to explain the earthquake damage by acceleration or PGA , and (2) Acceleration response of the soft ground subjected to strong motion is much larger in fact. To clarify which result is correct, we have studied the dynamic response of ground with a soft clay layer using centrifuge dynamic model testing.

CENTRIFUGE SHAKING TABLE TEST

Centrifuge shaking table testing has been undertaken to study the dynamic response of horizontal layers subjected to one-dimensional shear motion. The centrifuge used in the study is located at the Port and Harbor Research Institute (PHRI). Its effective radius is 3.8m. Other details of the PHRI centrifuge were introduced previously (Terashi, 1985). The research group, including the first author, developed the earthquake simulator accommodated in the centrifuge and has been working extensively in centrifuge dynamic model testing (Kazama *et al.,* 1993).

Test Condition

Figure 1 shows the details of models stacked rings and the cross section of the model ground and sensor layout. Dimensions of the ring are 300mm in diameter, 10mm in thickness and 6mm in width. The container consists

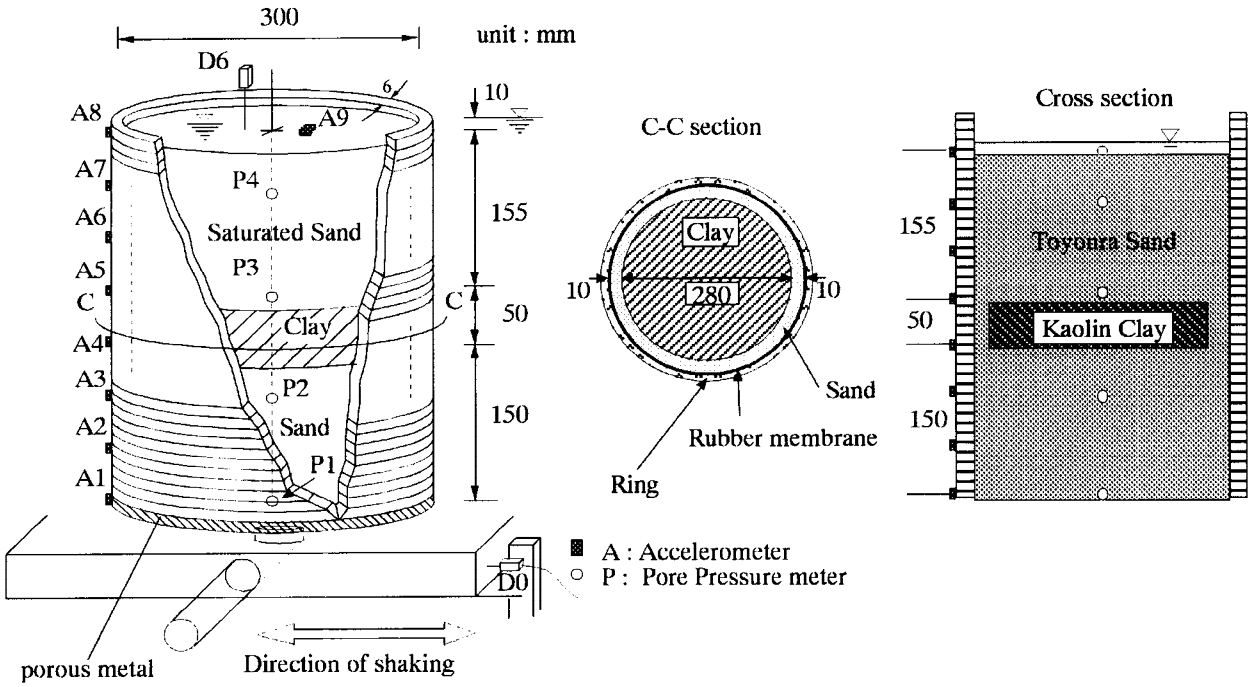

Figure 1 Cross section of models and transdusor layout.

Table 1 Physical properties of model ground

Item	Sand Layer	Clay Layer
Unit Weight (gf/cm^3)	1.989	1.534
Density of soil grain	2.65	2.692
Relative Density	75%	----
Water Content	----	80.1%

Table 2 Input earthquake motions

Test No.	Input Earthquake motion	Max. Acc. (Gal) in prototype scale
1	Ohfunato	74
2	Hachinohe	39
3	Ohfunato	245
4	Hachinohe	147
5	Ohfunato	498
6	Hachinohe	281

of about forty rings coated with Teflon. A thin rubber membrane separates the soil from the rings. Acceleration transducers and pore water pressure meters are installed in the vertical direction. We confirmed the agreement of the accelerometer records attached to the rings with that at the model ground. We also examined ring performance with regard to ring friction in advance (Kazama *et al.*, 1996).

The model ground involves a soft clay layer sandwiched between two sand layers at mid-depth. The construction procedure of the model ground is as follows. First, the lower sand layer is constructed by raining sand in air through several sheaves, and pore fluid is added through a porous metal placed at the bottom of the container with vacuum. Next, Kaolin clay, which was previously mixed with water, was placed as a soft layer. Finally, the upper sand layer was constructed in the same way as the lower sand layer. The pore fluid material used in the experiment is ordinary water. The physical properties of the model ground are shown in Table 1.

We conducted the model test under a 25g centrifugal field. According to a scaling relationship for the centrifuge dynamic testing, the depth of the model ground corresponds to about 9m in prototype scale. In the following section, we will plot graphs in the prototype scale. Table 2 shows the input earthquake motions used in the experiment. In this Table, we show the maximum acceleration at a base in prototype scale. "Ohfunato" and "Hachinohe" represent the scaled strong motions recorded at Ohfunato port in the 1978 Miyagiken-oki Earthquake and at Hachinohe port in the 1968 Tokachi-oki Earthquake, respectively.

THE DYNAMIC RESPONSE OF THE MODEL GROUND

Figure 2 shows the distribution of the peak ground acceleration response for all tests. Even if the input acceleration became larger, the acceleration response of surface ground became only slightly larger. In particular, from the mid-depth placed the soft clay layer, the response of upper sand layer was considerably reduced. Furthermore, when the base motion becomes more than 250gals, the reduction of the acceleration response was also observed in the lower sand layer. In addition, the upper sand layer responses of Test-5 and Test-6 were almost the same levels. It can be fairly certain that the soft clay layer yielded in Test-5 and Test-6.

Figure 3 shows the distribution of the maximum excess pore water pressure built-up in the model ground. The ratio of excess pore water pressure to initial effective vertical stress was over 50% only in Test-6. This is the evidence of the loss of effective confining pressure. Thus, the reduction of acceleration response during large input motion would be explained by the nonlinear behavior of soft clay layer and the softening of lower sand layer due to the loss of effective confining pressure.

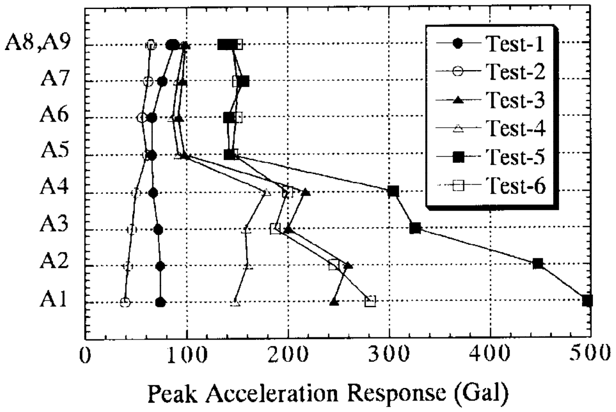

Figure 2 Distribution of peak acceleration response

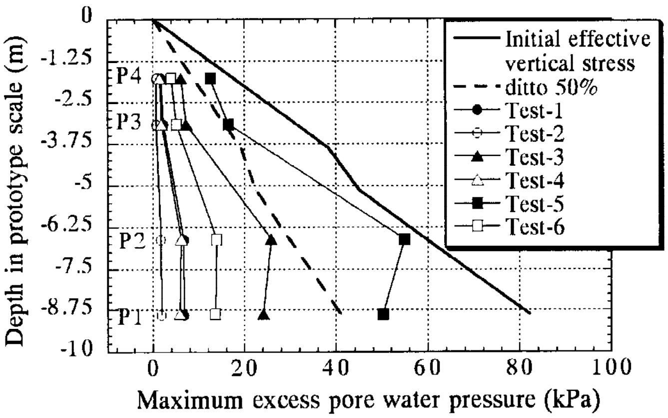

Figure 3 Distribution of maximum excess pore water pressure response

Let us, for a moment, consider the peak velocity response by integratiing the acceleration records as shown in Figure 4. No obvious response reduction is found. It may indicate that the main frequency contents of the

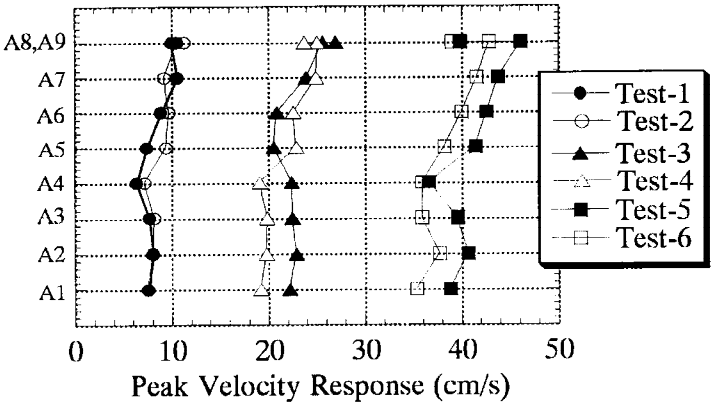

Figure 4 Distributions of peak velocity response

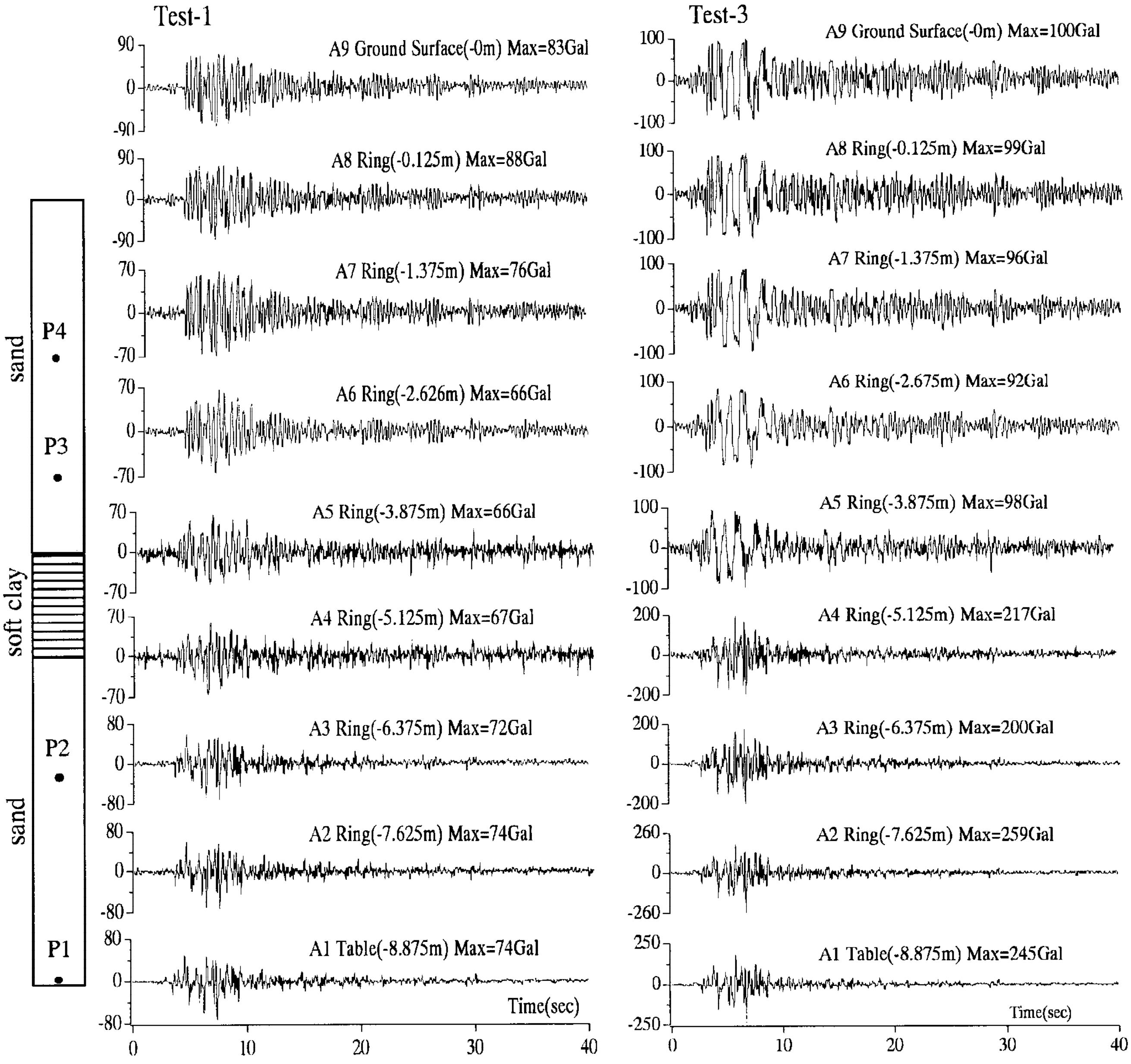

Figure 5 Time histories of acceleration response in depth direction (Test-1,3)

response move to a lower frequency range at high input motions. It can be seen from acceleration time histories in Figure 5 that the period characteristic changes considerably from the soft clay layer when input acceleration is increased. This is the evidence that the softening of soft clay layer significantly affects on the response of the upper layer.

Returning now to the earthquake damage on the ground, there is no doubt that the stronger earthquake causes the more severe damage, in case of their frequency contents being consistent. Consequently, it is considered that the velocity response is more appropriate than the acceleration response to explain earthquake damages to the ground.

STRESS STRAIN RELATIONSHIP OBTAINED FROM VIBRATION DATA

When studying the ground response, the estimation of the dynamic properties of soils is very important. In general so far, dynamic properties of soils are obtained from laboratory tests or in-situ investigation. On the other hand, the back-analyses have been used to evaluate the dynamic properties from vibration data (Matsuda *et al.*, 1986, Suetomi *et al.*, 1990, Kamiyama *et al.*, 1993, Tokimatsu *et al.*, 1994, Kokusho *et al.*, 1995 and Yoshida *et al.*, 1995). However, the back-analysis has the disadvantage being dependent on system idealization. Accordingly, the properties were determined as the most suitable properties to be able to explain the data, not determined from the stress-strain relationship as the same way of the laboratory tests. Recently, a few attempts had been made to evaluate the stress-strain of soils from seismic data directly (Koga *et al.*, 1990, Zeghal *et al.*, 1994, 1995 and Kazama *et al.*, 1995). Here, we called it "direct evaluation technique". An advantage of this technique is that stress-strain relationships are directly obtained from actual vibration data. It is independent of the system idealization. Using this technique, we have evaluated the dynamic properties of the model ground. As space is limited in this paper, we focus on the behavior of the soft clay layer.

Shear Stress and Strain Evaluation

Figure 6 explains how to evaluate shear stresses and shear strains from vibration data. As shown in Figure 6, we calculated shear stress at depth z by integrating the shear force from surface to depth z. We also calculated average shear strain by dividing a relative displacement between adjacent measure points by its distance H. Here, the displacement was obtained by double integration of an acceleration record. We have used 0.25Hz (in prototype scale) low-cut filter to avoid a drift when integrating. Details of the technique were introduced by (Elgamal *et al.*, 1995, Kazama *et al.*, 1996). Accuracy of the technique was also examined by (Kazama *et al.*, 1996).

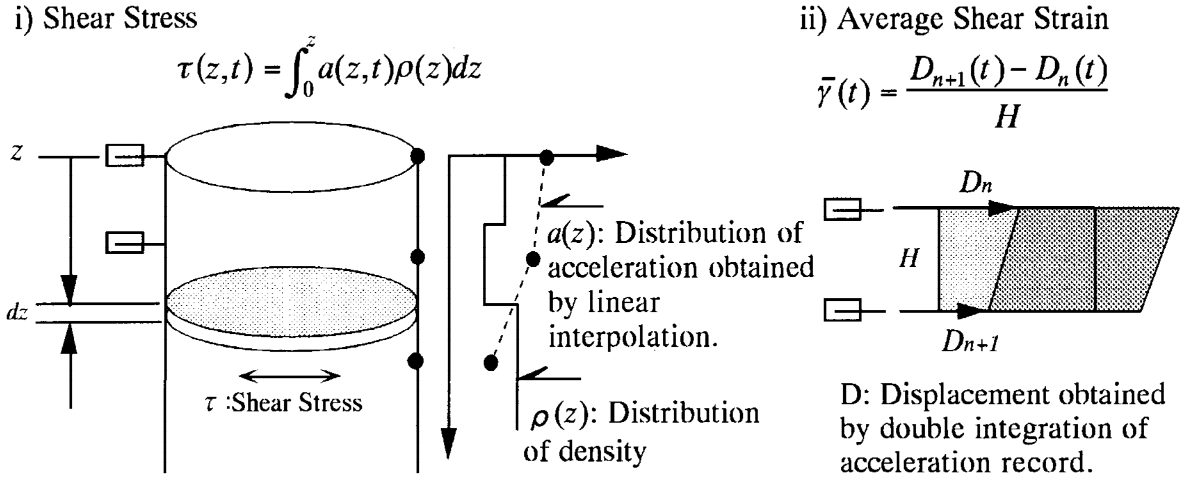

Figure 6 Evaluation of the shear stress and shear strain

Shear stress and strain obtained

Figure 7 shows the shear stress-strain relationships of the clay layer obtained by the technique explained above. The technique caught the nonlinear behavior of soft clay layer successfully. It is found in Figure 7 that the shear strain became easily larger with the increasing of input acceleration level. On the contrary, the shear stress did not increase substabcially with the increasing of input acceleration level. This is one of the aspects of the nonlinear behavior. In addition to this, it is likely that the maximum stress ratio of the Test-5 and Test-6 reached an upper limit (as indicated by dashed line). Reading its strength from Figure 7, it was about 0.12 a stress ratio. As previously mentioned, this is why the peak acceleration response of upper sand layer was the same between Test-5 and Test-6.

Defining an average shear modulus during the shaking as a $(\tau_{max.}-\tau_{min})/(\gamma_{max.}-\gamma_{min.})$, we obtained the average shear modulus as shown in Figure 8 for each test. The average shear modulus reduction pattern with strain amplitude is similar between the two earthquake motions.

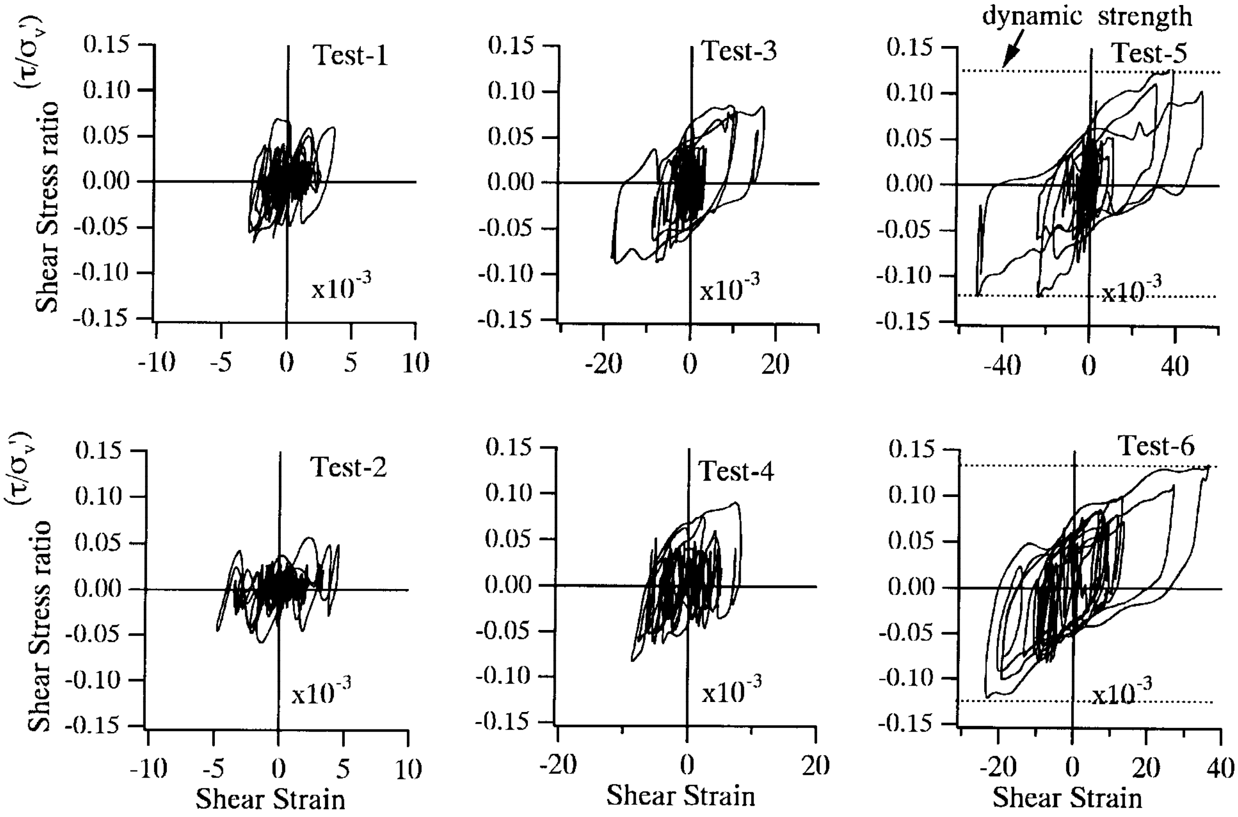

Figure 7 Shear stress and strain relationships of soft clay layer obtained from direct evaluation technique

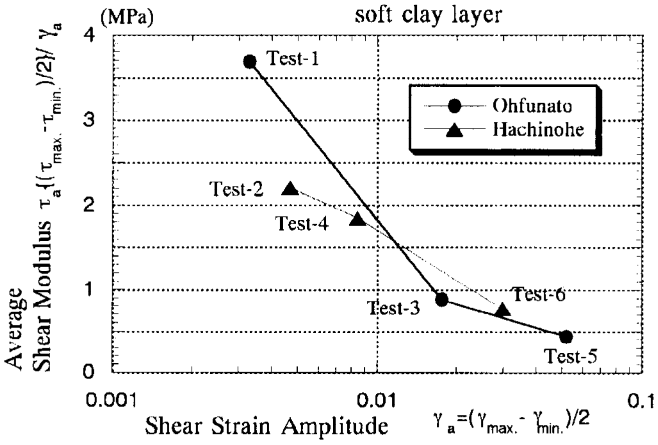

Figure 8 Average shear modulus reduction pattern with strain amplitude

Figure 9 shows the stress and strain time histories and the change of their relationships with time in Test-3. First of all, a nonstationary behavior of clay is found. Stiffness gradually reduces starting from 4 seconds and the largest loop is recorded after 6 to 8 seconds. Secondary, the frequency content of the stress ratio is found to be rather higher than that of the shear strain. This indicates that the effect of the high frequency component of shear stress on shear strain was relatively small compared to that of the low frequency component. Hence, we divided the stress and strain time histories into three parts using band-pass filter. Figure 10 shows the dependency of average shear modulus on shear strain amplitude for all tests. If the shear modulus depends only on the maximum subjected shear strain, the shear modulus will be independent of frequency. However, the frequency dependency of shear modulus can be seen in the figure. Comparing the average shear moduli at the same strain amplitude, we found that the lower the loading frequency was, the smaller the average shear modulus was.

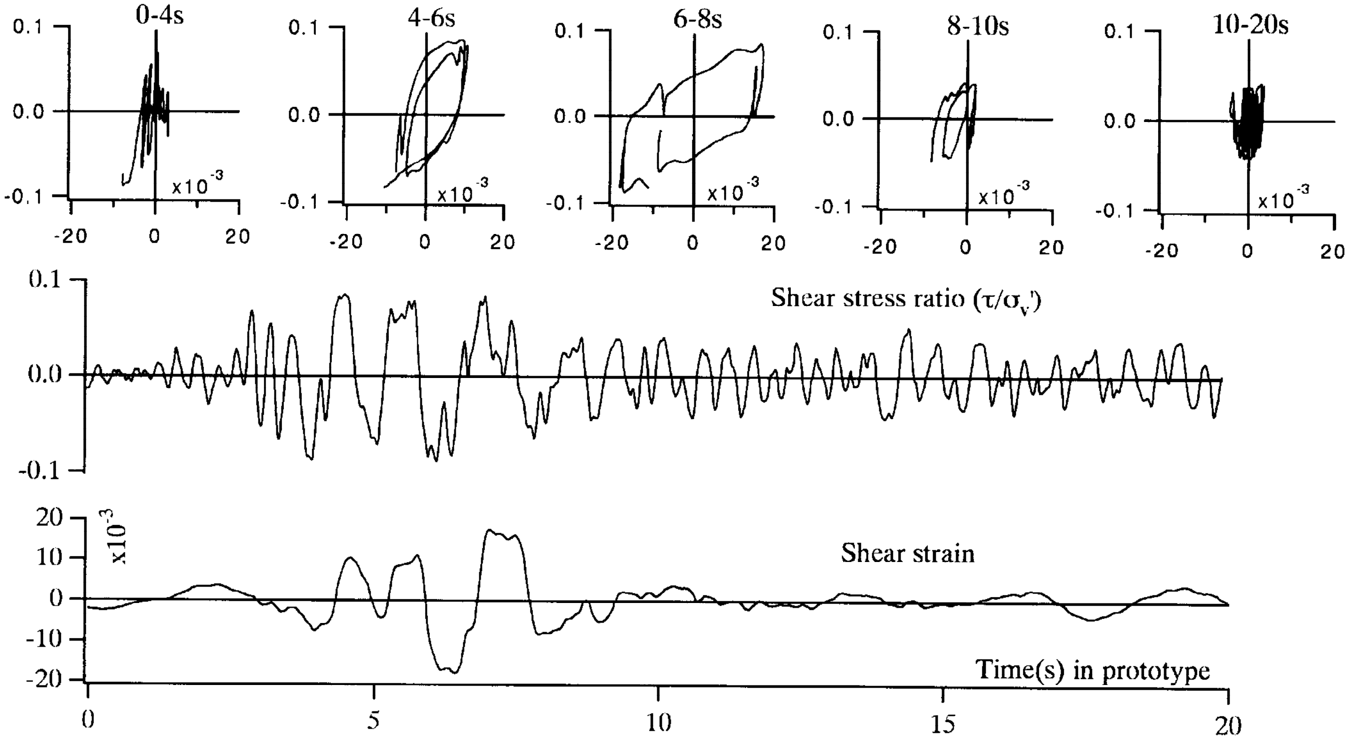

Figure 9 Stress strain time histories and the change of the its relationship with time

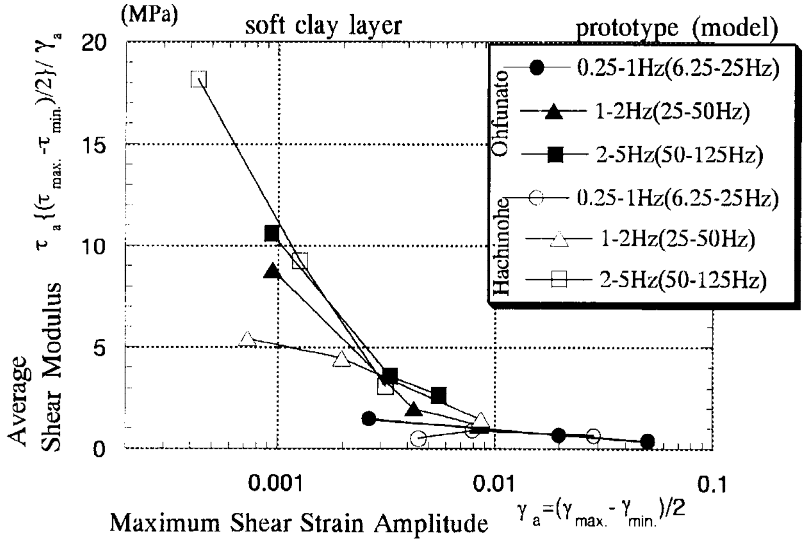

Figure 10 Average shear modulus dependency on frequency content.

CONCLUSION

In this paper, we have reported the results of centrifuge dynamic model test concerning the dynamic ground response. The model ground consists of a soft clay layer sandwiched between two sand layers. We focused on the nonlinear dynamic behavior of the soft clay layer and examined the dynamic ground response. The results obtained from this study are summarized as follows:

(1) The reduction of the peak acceleration response of upper sand layer compared to base acceleration was due to the softening of the soft clay layer.

(2) No reduction of the peak velocity response of upper sand layer compared to base velocity appeared.

(3) From (1) and (2), it is considered that the velocity response is more appropriate than the acceleration response to explain the earthquake damage on the ground.

(4) Using the direct evaluation technique, we successfully obtained the stress-strain relationships of soft clay layer. The nonlinear behavior of soft clay layer gave the most likely explanation for the dynamic response of the model ground.

(5) Comparing shear modulus of clay at the same strain amplitude, we found that the lower the loading frequency was, the smaller the average shear modulus was.

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