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DEVELOPMENT OF EARTHQUAKE SIMULATOR IN PHRI CENTRIFUGE AND ITS APPLICATION

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SUMMARY

The authors have developed an earthquake simulator which can be accommodated in the centrifuge of the Port and Harbour Research Institute (PHRI). The earthquake simulator is of electrohydraulic type and can generate scaled large earthquake motions of which frequency contents range up to 300Hz and a peak acceleration up to 10G in a 50G centrifugal field. This paper introduces and illustrates the outline of the earthquake simulator and its application.

INTRODUCTION

Soil structures and foundations in Japan have often suffered from great earthquakes. Studies in the dynamic geotechnical field are very important in Japan. In general, use of a centrifuge is effective for both static and dynamic model tests. So far, only static model tests have been carried out in the centrifuge of the Port and Harbour Research Institute(Ref.1).

The use of the PHRI centrifuge for dynamic tests had to wait until recently when the authors decided to start developing the earthquake simulator which can be accommodated in the existing PHRI centrifuge. Obviously a centrifuge model test satisfies the similitude for models made of geotechnical materials and is, at present, the most promising method for testing model grounds and structures. However, many difficulties had to be overcome for developing the earthquake simulator in the centrifuge. The purpose of this paper is to introduce the outline of the earthquake simulator and to show some results of application.

DESIGN OF THE EARTHQUAKE SIMULATOR

The general scaling relationship for the dynamic model tests is shown in Table 1 (Ref. 2). The scaling law for a centrifuge dynamic model test is, also given in Table.1, obtained by substituting n_ℓ, n_ρ, n_ε, n_g for 1/n, 1, 1, n in the general scaling law, respectively. A small-scale model and a full-scale structure are related through this relationship. Thus, if a model is constructed at a 1/50 scale, it is subjected to a 50G centrifugal acceleration to simulate the prototype structure. In the dynamic test, the frequency of the input motion applied to the model is 50 times higher, and the acceleration is 50 times larger. For example, in order to simulate a real earthquake motion, which has a peak acceleration of 0.2G, a duration of 60s and a frequency content up to 6Hz in the scaled model, the model is subjected to an excitation which has a peak acceleration of 10G, a duration of

1.2s and a frequency content up to 300Hz. If the mass of the model container and specimen is about 100kg, the capacity of the shaking force must be about 10kN.

Table.1 Scaling relationship for a dynamic model test.

Quantity (Model/Prototype)	General scaling law	Scaling law in the centrifugal field
Length	n_ℓ	$1/n$
Mass density	n_ρ	1
Strain	n_ε	1
Acceleration	n_g	n
Time	$(n_\varepsilon n_\ell/n_g)^{1/2}$	$1/n$
Frequency	$(n_\varepsilon n_\ell/n_g)^{-1/2}$	n
Displacement	$n_\varepsilon n_\ell$	$1/n$
Stress	$n_\rho n_g n_\ell$	1
Stiffness matrix	$n_\rho n_g n_\ell/n$	1
Pore water pressure	$n_\rho n_g n_\ell$	1
Coefficient of permeability matrix	$(n_\varepsilon n_\ell/n_g)^{1/2}/n_\rho$	$1/n$
Bending stiffness of pile	$n_\rho n_g n_\ell^{5}/n_\varepsilon$	$1/n^4$

In order to design a centrifuge earthquake simulator, we had to consider advantages and disadvantages of various shaking systems. The authors examined various approaches such as the 'bumpy road' of Cambridge University, electromagnetic devices, electro hydraulic equipments, explosive firing and piezoelectric actuator(Ref.3-7). With the bumpy load, we will have to make a great deal of effort to change the input motion and to modify the PHRI centrifuge. The electromagnetic devices are too heavy and large to mount on the swing platform, and explosive firing seemed difficult to control the input motion. Moreover the authors could not find a large piezoelectric actuator in Japan. Consequently, it was decided to attempt to design an electrohydraulic type of shaker. Though this system is a little complex, we need no improvement on the PHRI centrifuge. This system satisfies the required capacities for shaking and the required reliability. Moreover, the authors could find an accumulator, a servo valve and shut off valves which can be mounted on the swing platform. The reliability of the servo valve and of the shut off valves and the safety of the accumulator in a 60G centrifugal field were confirmed by the authors before making up the whole system.

OUTLINE OF THE EARTHQUAKE SIMULATOR

The earthquake simulator consists of an oil pressure supply unit, an actuator and a shaking box unit, a control unit and an oil tank. Fig.1 illustrates the arrangement with all units on the swing platform.

The oil supply unit consists of an accumulator to supply oil pressure to the servo valve and shut off valves. Fig.2 shows the layout of the oil flow circuit of the simulator. The A-shut off valve reduces oil leakage from the servo valve. The B-shut off valve is used in case of emergency. The C-shut off valve with flow control valve is used to avoid an impulse liquid flow to the servo valve. Once we accumulate oil pressure, we can experiment several times during one flight.

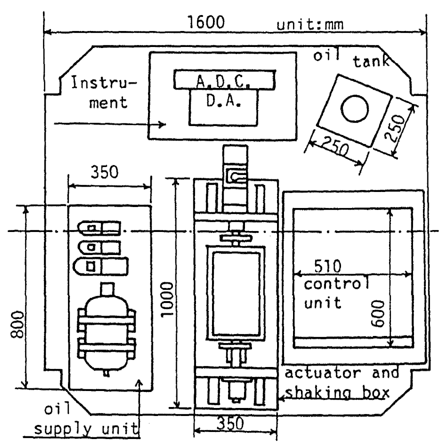

Fig.1 A plane view of the system.

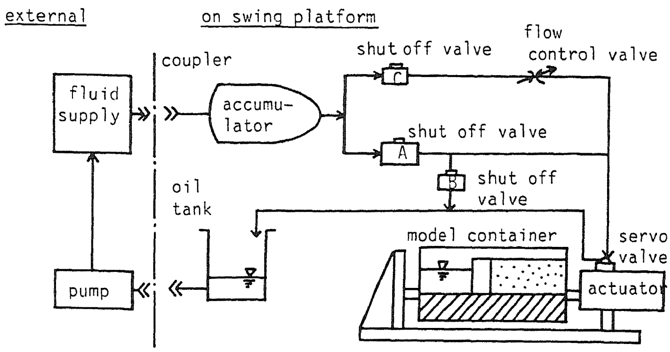

Fig.2 Oil flow circuit

The actuator and the shaking box unit are the main unit shown in Fig. 3. The dimensions of the shaking box are 400mm(L)X180mm(D)X270mm(H). It is supported by eight arms from four beams. The shaking box is made of titanium to save the total shaking mass. The major specifications of the actuator are:

Shaking force ± 12kN
Maximum displacement ± 3mm
Maximum velocity ± 30cm/s
Maximum usable oil pressure 30MPa
(ordinary use 21MPa)
Volume of the accumulator 4 liter
Frequency content up to 300Hz
Payload 92kg
The servo valve is controlled by LVDT displacement feed back system.

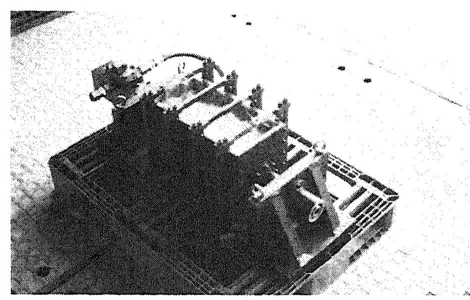

Fig.3 Photograph of the actuator and the shaking box

The system controller is composed of two control boxes. One is mounted on the swing platform as shown in Fig.1. The other is located in the control room. They are connected by eight lines through slip rings. The controller has a sequence circuit to control the experiment from start to end. That is to say, if an operator presets the experimental conditions such as input wave, duration of shaking, amplitude and frequency, the only thing the operator needs to do during the flight is to press one button. The servo valve receives electrical signals from a function generator or Read Only Memory (ROM) and an actuator generates the input motion. Typical earthquake motions are memorized in the four ROMs. Each ROM has a length of 8192 words and we can select the time interval of the input motion from 0.001msec to 10msec.

Fig.4 shows a current data acquisition system. We use a dynamic amplifier on the swing platform to save the slip ring channel and to improve the SN ratio. In the case of centrifuge dynamic model test, as an object is a very fast phenomena, we operate the analogue data recorder from a few seconds before the experiment starts to avoid failure in collecting the data.

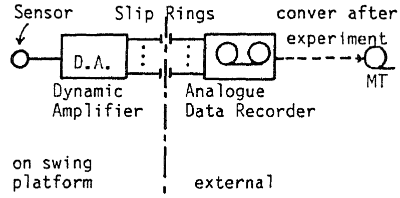

Fig.4 Data acquisition system

This system has also some disadvantages. For example, we can not see the phenomena in visual because the control box hinders the soil container. We can select only one input motion during one flight because we have to set the input motion conditions before the centrifuge operation. Those minor drawbacks in the existing system will be easily improved in the near future.

Permanent deformation of the gravity type caisson during earthquake The authors discussed about sliding deformation of the gravity type caisson during earthquake by using the model as shown in Fig.5. The input motion was the integrated displacement of the acceleration observed at Hachinohe Port in the 1968 Tokachi-oki earthquake, M=7.9. The sand used in the model was Toyoura sand which had wet density of 1.89 g/cm^3 and relative density of 38%. The model ground was constructed by pouring the dry sand naturally from 20cm above the water surface into water. We used water as a pore fluid material to avoid liquefaction. Because the sliding behavior not liquefied is different from that with liquefaction. Fig.6 shows the time-histories measured in the No.4 experiment. The permanent deformation at the top of the caisson and the maximum response acceleration of the caisson are shown in Fig.7,8 with the maximum input acceleration in prototype scale.

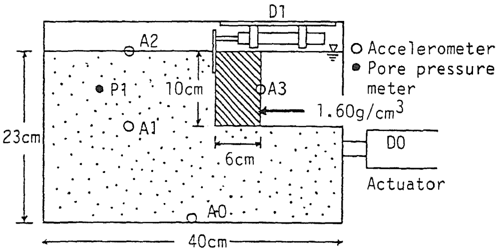

Fig.5 Cross section of the model

Table 2 Test condition

Test No.	Centrifugal Acc. at 3.62m	Model Amax(G)	prototype Amax(Gals)
1	50.3	2.41	47.0
2	50.2	5.59	109.1
3	50.2	10.11	197.3
4	49.9	12.83	251.9

Amax: Max. Acc. of the input motion

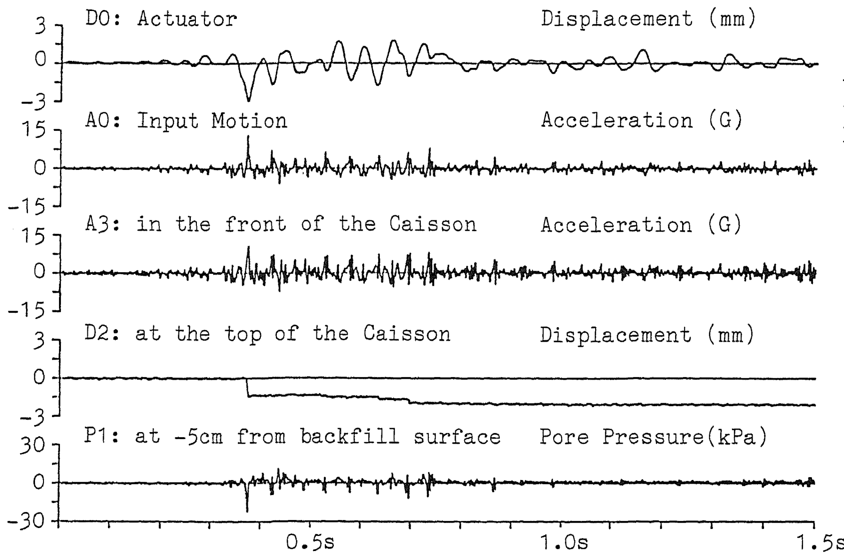

Fig.6 The time histories measured in the No.4 experiment.

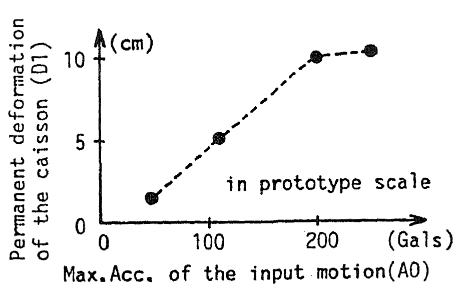

Fig.7 The permanent deformation at the top of the caisson.

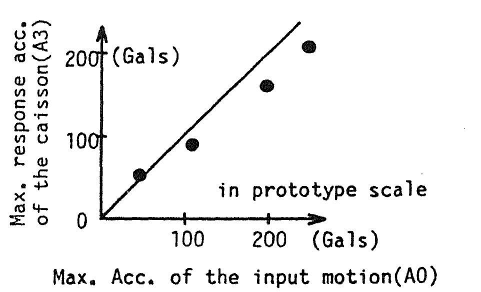

Fig.8 The maximum response acceleration of the caisson foundation.

The following trends about the sliding behavior are found in those figure.
1. The permanent deformation increase with increasing the input acceleration. The caisson subjected to input acceleration of 200Gals slides 10cm in prototype scale.
2. The pore water pressure did not rise remarkably, because the model fluid material was water. This result is predicted by the scaling law about the permeability of the fluid material.
3. The pore water pressure decrease when the caisson is sliding.
4. The maximum response acceleration of the caisson did not so much increase with increasing the input acceleration because of caisson sliding.

Confined pressure effects on the shear wave velocity of the sandy layers It is well known that a shear modulus of the sand is in proportion to square root of confined pressure σv. From elastic wave theory, it is also known that the shear modulus is equal to ρVs^2. Thus, the shear wave velocity is in proportion to $\sigma v^{0.25}$. This effect is important for the construction of the centrifuge model ground. The authors studied on this point with the saturated sandy layers.

Fig.9 shows the cross section of the model and equivalent prototype ground depth by using the scaling law. Table 3 lists the model and the equivalent prototype test condition for each case. The input motion is a white noise, which frequency content of the acceleration is constant with frequency, which is generated by the authors in considering the response characteristics of the servo valve. The sand and the pore fluid material used in the model and the model construction method are the same as those of the caisson sliding experiment described above. According to the pore water pressure meter, it is confirmed that the pore pressure dissipated rapidly and large value did not appear during excitation.

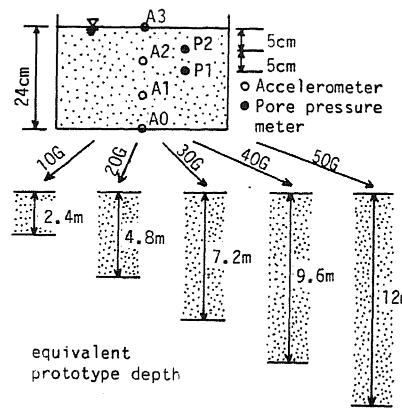

Fig.9 Cross section of the model and the equivalent prototype depth.

In all cases the authors calculated the transfer function between the input acceleration and the acceleration response of the sand layers and searched for the first natural frequency of the layer(f_1). Typical transfer function is shown in Fig.10. If it can be assumed that the model ground is characterized by average shear wave velocity Vs, Vs can be identified by multiplying f1 by 4H, in which H represents layer thickness. The average shear wave velocity of each case were

Table 3 The model and equivalent prototype test condition.

	Target Acceleration unit: G	Actual Acceleration at 3.62m. (Maximum Acceleration of the input motion unit: G)				The first natural frequency of the sandy layers in the model, unit: Hz (Max.Acc.in prototype scale unit:Gal)			
	Flight No.	1	2	3	4	1	2	3	4
CASE-I	50G	-	-	48.7 (2.99, 3.01)	-	-	-	417 (60.2) 428 (60.6)	-
CASE-I	30G	-	29.3 (2.54, 2.52)	-	-	-	375 (85.0) 375 (84.3)	-	-
CASE-I	10G	11.3 (1.28, 1.26)	-	-	-	257 (110.7) 257 (109.5)	-	-	-
CASE-II	50G	49.0 (1.45)	49.1 (2.67)	48.7 (3.93)	49.7 (4.18)	425 (28.9)	413 (53.3)	410 (79.1)	430 (82.4)
CASE-II	40G	42.2 (1.48)	42.0 (2.62)	42.8 (3.49)	42.2 (3.84)	420 (34.4)	405 (61.2)	425 (79.8)	427 (89.2)
CASE-II	30G	27.3 (1.19)	26.8 (2.24)	27.4 (3.53)	27.8 (4.91)	390 (42.8)	383 (81.9)	390 (126.2)	392 (172.9)
CASE-II	20G	17.3 (1.16)	17.3 (2.19)	16.6 (3.55)	16.9 (4.75)	356 (65.7)	355 (123.9)	366 (209.3)	366 (275.5)
CASE-II	10G	10.4 (1.14)	-	-	-	263 (107.4)	-	-	-

obtained as shown in Fig.11. In this case the average shear wave velocity did not strongly depend on strain level because the model ground had high stiffness. The solid line described in this figure incline 0.25 power of the centrifugal acceleration. The result obtained from the centrifuge experiment is explained by confined pressure effect. This indicates that the confined pressure affects on the dynamic properties of the sand even if its depth is less than 12m. And it looks like difficult to construct loose sand in the centrifuge model ground.

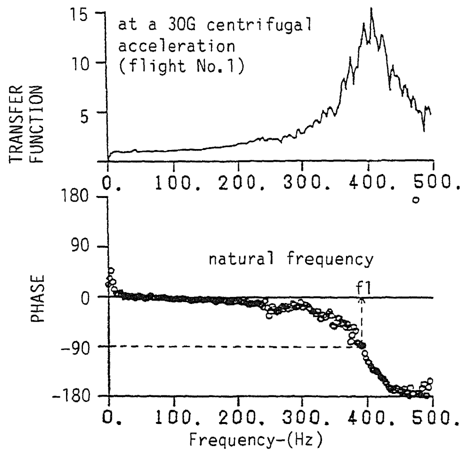

Fig.10 Typical transfer function at a 30G centrifugal field.

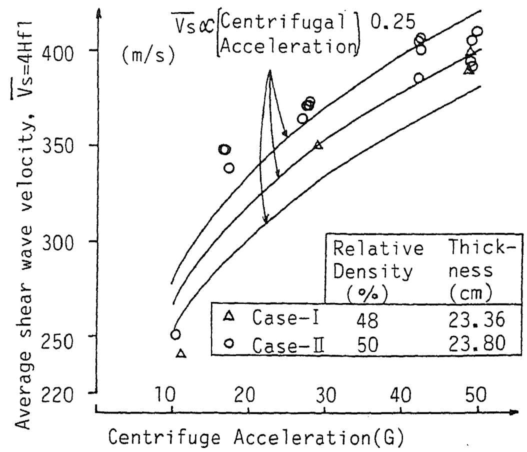

Fig.11 Relation between the average shear wave velocity and centrifugal acceleration

CONCLUSIONS

The earthquake simulator developed by the authors shows satisfactory performances for testing ground and structure models in the centrifuge. Obviously, the earthquake simulator in the centrifuge has a wide applicability to geotechnical problems such as soil-structure interaction. But there are many problems had to be overcome for application to the dynamic geotechnical testing. The examples are a model construction method, an effects of side friction and rigid end wall, a choice of the fluid material and an effect of strain rate with cyclic loading and so on. The technical progress of the dynamic centrifuge testing and the so-called 'modeling of models' analysis will solve these problems, and fruitful results are expected from the model tests in the coming few years.

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