VIBRATION TEST OF A STRUCTURE

SUPPORTED BY PILE FOUNDATION

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Abstracts; To make clear such problems as soil-structure interaction problem, it is an important point to make use large size shaking table, because, similarity law between model and prototype is hardly satisfied in experimental studies with small size shaking table. For the reason mentioned above, the writer planned and completed the large size shaking table in co-operation with Prof. S. Okamoto.

The size of the sand box on the shaking table is 10 m in length, 4 m in depth, and 2 m in width. The shaking table is moved in a horizontal direction with electro hydraulic servo system, which is driven by two oil pumps of 100 HP for each.

Using the shaking table, model test of liquid gas tank of pile foundation was performed. The model of soft ground is made of the mixture of both cinder sand and oil. As for strength of soil, bending stress of piles, and time, the similitude between the model and the prototype is fully satisfied. The experiment was done by changing the frequency as well as the amplitude of the shaking table, step by step. The main results obtained are as follows;

1) Maximum bending stress occurs at the period of about 1.3 sec, in prototype.
2) As the frequency of the table increases, ground movement becomes larger and larger, and at this time, it is recognized that the surrounding soil pushes the piles horizontally.

1) Large size shaking table.

It is well-known that small size vibration table does not give us satisfactory results for the experimental studies on earthquake resistant properties of such soil structures as embankment and fill-type dam and on soil-structure interaction problems, which will occur in case of surveying stability of foundations and analyzing the behavior of underground structures and so on, because in vibration tests of small size, the similarity law between model and real system is not perfectly satisfied. Due to the reason mentioned above, the mammoth shaking table was planned and installed in Chiba Experiment Station of the Institute of Industrial Science, the University of Tokyo, in 1967.

In order to investigate vibrational characteristics of soil structures, foundations in soft ground and underground pipeline and so on, the big sand box was equipped and it is 10 m long, 4 m deep, and 2 m wide. The minimum width of the sand box is decided by taking into account that depth of sand

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layer influenced by the friction between the wall and sand is about 50 cm, as well as the appropriate weight and size of the shaking table. The large size shaking table in the Port and Harbour Technical Research Institute, Ministry of Transportation is 2 m wide, and it seems that 2 m is enough width to eliminate friction influence.

The depth of the sand box is also decided under consideration that the lowest point of slip circle is above the sand layer influenced by friction. As the depth of the sand box is 4 m, the vibration test of prototype soil layer(15 m deep)may be done with good satisfaction as to similitude. As middle parts of both side-walls, parallel to the direction of exciting, are able to be removed, such a long size model as that of bridge can be put to vibration transeversely.

The shaking table is moved in one horizontal direction with electro hydraulic servo system, which is driven by two oil pumps of 100 HP for each. The power of oil pump is not enough to move the sand box of 170 tons weight with desirable amplitude or acceleration. Then to get the enough amplitude of the table for testing the non-linearity of soil layer and to get an accurate sinusoidal waves in the vibration of the table, resonating phenomenon of the table and detachable spring system is utilized. The number of the detachable spring is 9. In order to minimize the friction between shaking table and its support, floating device by oil pressure is used. The mechanism of driving is illustrated in Fig. 2, and the main properties of the shaking table are as follows.

Period; 0.1 sec ~ 1.0 sec
Maximum amplitude; ±100 mm
Maximum acceleration; 400 cm/sec/sec

Maximum acceleration is considered to be necessary to do tests of liquifaction of sand, and its effect upon the stability of structures on loose sand layer. Stability test and breaking test of structures are also possible using this large size shaking table.

Amplitude, period and shapes of waves areset as input data at function generator in Fig. 2, and whether the shaking table is moving just as the input data or not is checked by deflectometer installed at the middle point of the shaking table, and vibration characteristics detected by the deflectometer is fed-back to the function generator. The systems applied to the shaking table are 1) accelerating apparatus of electro servo mechanism, 2) amplifying by resonance of the springs, and 3) feed-back system by using deflectometer, and this system was checked by model test in the manifacturing shop at design stage We have the following conclusions, 1) the system mentioned above is seemed to be appropriate, but 2) to cut the small noise in the wave of the table, the spring should be installed between the actuator and the sand box.

Here, the writer wants to describe the base structure of the shaking table. The base structure consists of 3 parts, that is, 1200 t concrete block, 54 isolation rubber blocks reinforced by steel plates, and foundation concrete slab. By this, harmful tremor does not propagate out through the base foundation in operation and no one can feel any ground vibration outside the shaking table house.

The mammoth shaking table is made by HITACHI Ltd., under supervising of the Laboratory of Earthquake Resistant Structures, the Institute of Industrial Science. (see Photo. 1. and Fig. 1 and 2)

2) Model vibration tests of liquid gas tank

Liquid gas tanks will be constructed on southern part of Yokohama where the soft silty clay layer, 15 m in thickness, covers the little hard mud-stone layer, so-called Dotan in Japan. The 21,440 tons tank, including liquid gas weight, is designed to be supported by 349 steel piles, and the pile is 50 cm in diameter, and 12.7 mm in thickness, and the treatment works of soft silty clay layer are now under construction.

In this design, due to low temperature of natural liquid gas (about-160°C), the bed slab of the tank must be isolated up above the ground surface, and so the soil pressure can not at all be expected to resist the horizontal seismic force applied to the gas tank. In order to examine aseismicity of the liquid gas tanks, model vibration test was done.

As a fundamental concept, similarity about acceleration is decided to be one, because gravitational acceleration is invariable. To fully satisfy the similarity law, scale in length must be small. In this case, the scale of the model is 1:5, and the scale in weight is 1:123, and the other physical quantitites are automatically decided by above three factors, that is, acceleration, length and weight. Relations between physical properties of the model and those of the prototype are shown in Table-1.

The model of soft ground is made from the mixture of both cinder sand and isolation oil, whose mixing ratio is 8:2. The cohesion of the model ground is about one-fifth of that of the prototype which is measured by vane-test in the field, and the similarity about cohesion is satisfied by adoption of the mixing ratio mentioned above.
The experiment was done changing step by step the frequency as well as the amplitude of the shaking table, on the partial model with 9 alluminum piles. (see Fig. 3) Results obtained are shown in Fig. 4 and 5.

As the experimental research has not yet finished, here only tentative conclusions will be described as follows.

a) Fundamental period of the model is 0.6 sec, and that of the prototype is estimated to be 1.3 sec, which is a little longer than the theoretical one.

b) Acceleration measured at the center of the model tank, and bending stresses of the pile become very large near the resonance period, but rapidly drop down as the frequency changes from the resonance frequency.

c) Accelerations measured at each point near the surface (for example AG-3. and AG-4) are closely coincident independent of frequency.

d) Stresses due to bending moment occurred in each pile are almost the same value, corresponding to the positions,

e) When the ground is put into resonance condition, acceleration near the ground surface increases very larger than that of the underground and bending stresses in piles approaches closely to the same values. (see Fig. 5(b)) In Fig. 5, S-33, S-32, and S-31, mean the strain gages at the top, at the middle point, and the end of the pile respectively.
S-33 and S-31 have the same phase, which is faster than S-32 by 180

degrees, and this phenomenon is elucidated by the fact that the ground movement becomes more severe than that of the structure model at the frequency more than 9, and the surrounding soil is actively pushing the pile in this case.

f) Piles are sustained under bending stress as well as axial atress due to the rotational movement of the superstructure. Fig. 6 shows the relation between axial stress of a pile and frequency of the table.

In this case, outer two piles are subjected to high axial stress, but the stress of the center pile is not so high.

3) Static loading test

In general, the spring constant of soils is given as a function of contact area, mechanical properties of soils, and depth from the surface, and so on. The dynamic spring constant is not easily obtained, because it is a function of many factors mentioned above, and the additional mass of soil affects the period even when the spring constant is determined experimentally by vibration test of a mass excited by exciting machine.

Rigorously speaking, the dynamic spring constant may differ a little from the static one, but this value is necessary to get the period of the model supported by piles, so the static loading test was carried out, in order to make clear the mechanical properties of the artificial sand layer in the sand box of the shaking table.

The horizontal force was applied to the concrete block by jack apparatus, and displacement-loading curve was got as shown in Fig. 7. The displacement-load curve during loading has a different slope from unloading, and shows non-linear characteristics, and it is not clear whether this non-linearity reveals in dynamic test or not.

The dynamic spring constant in the following analysis is nearly equal to the mean value of the slopes of loading and unloading stages. It is also assumed to chang linearly with depth, and to be 0.7 kg/cm^3 at the bottom. Fig. 8 shows the resonance curve obtained theoretically using the above value of spring constant of the soil, and it is concluded that there is fairly good coincidence between experimental curve and theoretical one.

4) Additional mass of soil

Before analyzing dynamic response of a structure supported by piles, additional mass of soil must be investigated. Judging from the acceleration distribution under soil, theoretical curve shows some divergence from the experimental one, (see Fig. 9.) and this divergence is considered to come from the fact that the shear-wave transmission theory gives the acceleration distribution curve as shown by the curve (I) in Fig. 10, but the experimental results is shown in the curve (II). Therefore the acceleration distribution curve in steady state is assumed to be represented by the following equation, but not by shear wave theory

$$a_i(t) = 100\left\{1 + \frac{\omega^2}{p^2-\omega^2}\left(\frac{d_i}{d}\right)^2\right\}\sin\omega t \quad \cdots\cdots\cdots (1)$$

where ω is frequency of the shaking table, p frequency of sand layer, d the depth of sand layer, d_i the depth of point and $a_i(t)$ acceleration at point i.

After assuming acceleration distribution curve as mentioned above, the effect of additional mass upon bending moment of the pile was checked by comparing theoretical results with experimental ones. In calculation the value of spring constant is used just one as mentioned above, and additional mass ratio β (= additional mass divided by total mass of soil surrounded by 9 piles) is taken as variable. The acceleration distribution is given by Eq.(1) when frequency of the shaking table is low, difference between the experimental values of bending stress of piles and the theoretical ones is not so much. But as the frequency increases, the second mode of vibration of the piles becomes predominant, and the effect of the additional mass appears clearly. The experimental values are shown by circles in Fig. 9. and the theoretical values are shown by four folding lines. When β=100 % horizontal force (= additional mass of soil mutiplied by acceleration) becomes so much large, that bending stresses are extremely larger than the experimental result. β=10 % is thought to show the best solution.

5) Dynamic response of prototype

Model of theoretical analysis of dynamic response is shown in Fig. 11. Pile are assumed to be represented by the system of 3 degrees of freedom, and at each point, addional mass and springs of soil are applied to. The value of additional mass ratio adopted in calculation is 10 % as explained in 4), and spring constant of soil is assumed to change linearly with depth and the maximum value is put to be 2.0 kg/cm^3 at the bottom of soft surface layer, by refering data books and soil condition on the construction spot.

Input data supplied through foundation is not sure, so 2 earthquake records are used alike usual procedure made by many earthquake engineers; one is El Centro 1940, and the other Taft 1952. Earthquake energy is considered to supply to the structure through bottom hard rock as well as side sand layer.

Amplification of ground acceleration by incidence and reflection is given by the following equation(2), not by equation(1), because ground motion during an earthquake can not be taken as steady motion. Eq.(2) is induced by usual shear-wave transmission theory.

$$a_i(t) = \frac{2}{1+\alpha}\left(\phi\left(t-\frac{d_i}{V_1}\right)+\phi\left\{t-\frac{1}{V_1}(2d-d_i)\right\}\right]$$

$$-\frac{2(1-\alpha)}{(1+\alpha)^2}\left[\phi\left\{t-\frac{1}{V_1}(2d+d_i)\right\}+\phi\left\{t-\frac{1}{V_1}(4d-d_i)\right\}\right]+\cdots$$

$$+\frac{2(-1+\alpha)^K}{(1+\alpha)^{K+1}}\left(\phi\left\{t-\frac{1}{V_1}(2Kd+d_i)\right\}+\phi\left\{t-\frac{1}{V_1}(2Kd+2d-d_i)\right\}\right]+\cdots \quad \cdots\cdots(2)$$

where $\alpha = \rho_1 V_1 / \rho_2 V_2$, ρ_1 and ρ_2 are density of surface layer and foundation rock, V_1 and V_2 are shear-wave velocity of surface layer and foundation rock, $\phi(t)$ is input data of an earthquake, α and α_i are defineed in (4). $a_i(t)$ expressed by the above equation is acceleration pattern at point i ($i = 1,2$ and 3 in Fig. 11), and $a_i(t)$ is an input data, whose energy is supplied through spring of soil into piles and then into the liquid tank.

Calculation results are shown in Fig. 12.

6) Conclusions

Followings are concluded;

1) Dynamic response of piles due to an earthquake is investigated.

2) The results show that piles are pushed by surrounding soil during earthquake. This charactcristic is induced from the fact that bending stress is maximum at the top of pile, and decreases with depth, when static force is applied horizontally at the top, but the bending stress distribution due to earthquakes differs from the static features considerably.

3) Deflection of pile becomes larger than the value calculated by static force, owing to soil pressure acting on piles horizontally during earthquake. When there is no horizontal soil pressure, deflection of pile can be calculated by theory of beam on elastic foundation, and there is a fixed point at some depth from the surface. On the contrary, when soil aurrounding piles is pushing piles, there is no fixed point, and therefore we must pay attention on the large deflection of the head of pile.

4) As the usual design practise, horizontal reaction of piles is neglected, and horizontal seismic force must be resisted by bottom friction or battered piles, or earth pressure acting at the front face of footing foundation. Judging from the results obtained by the writer's research, the usual design practise is affirmative, because horizontal resistance of vertical piles must be estimated smaller than usual static calculation, otherwise, large deflection of the pile must be taken into account in design.

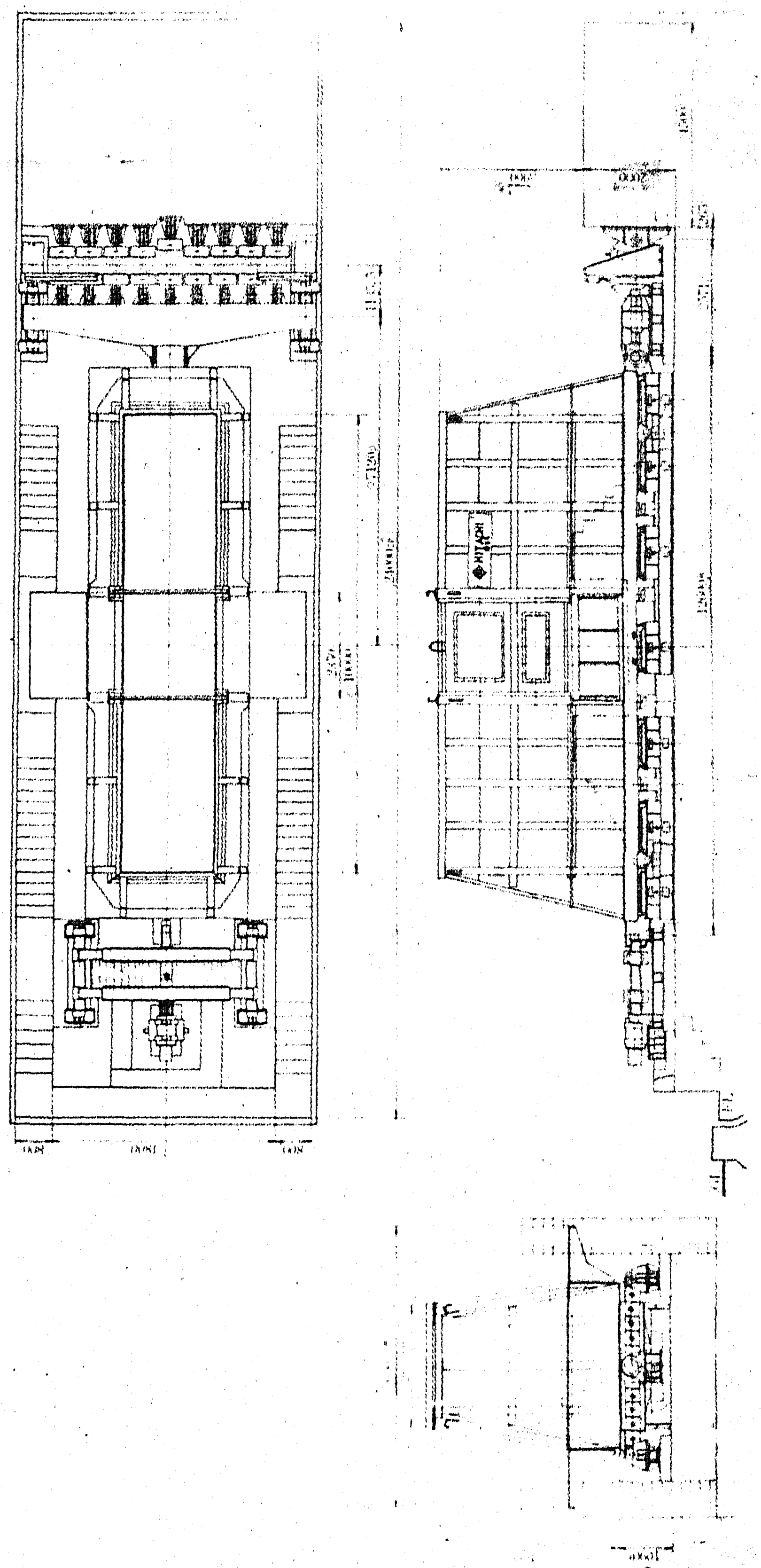


Fig. 1 Large size shaking table

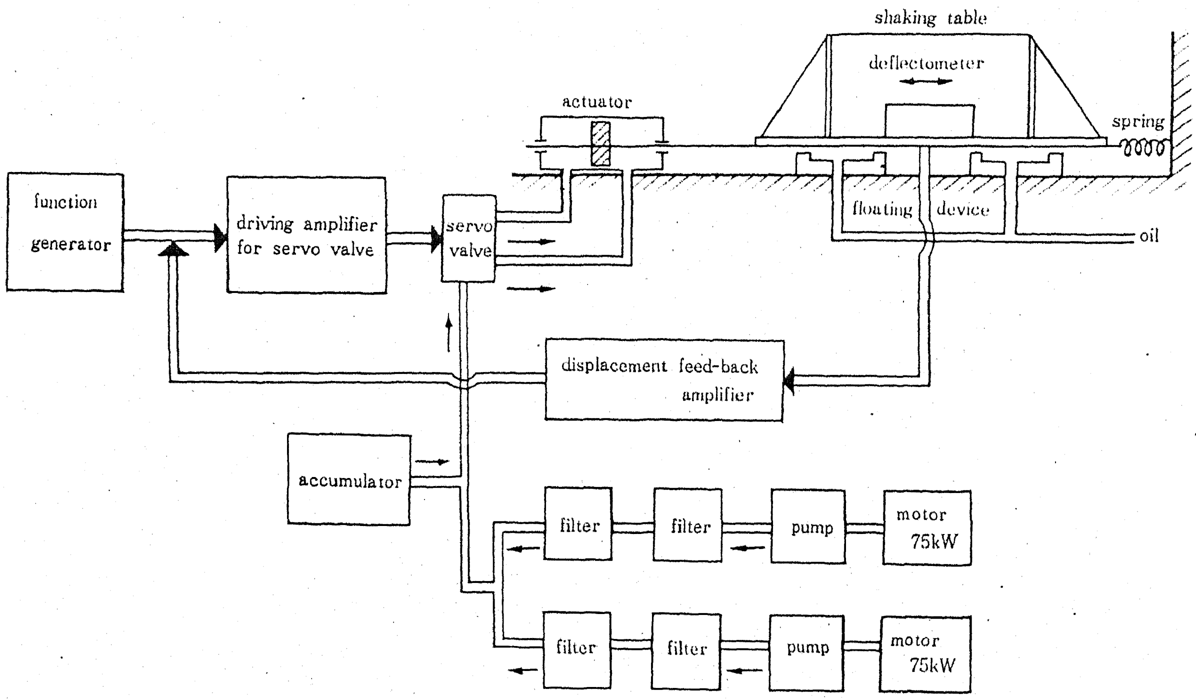
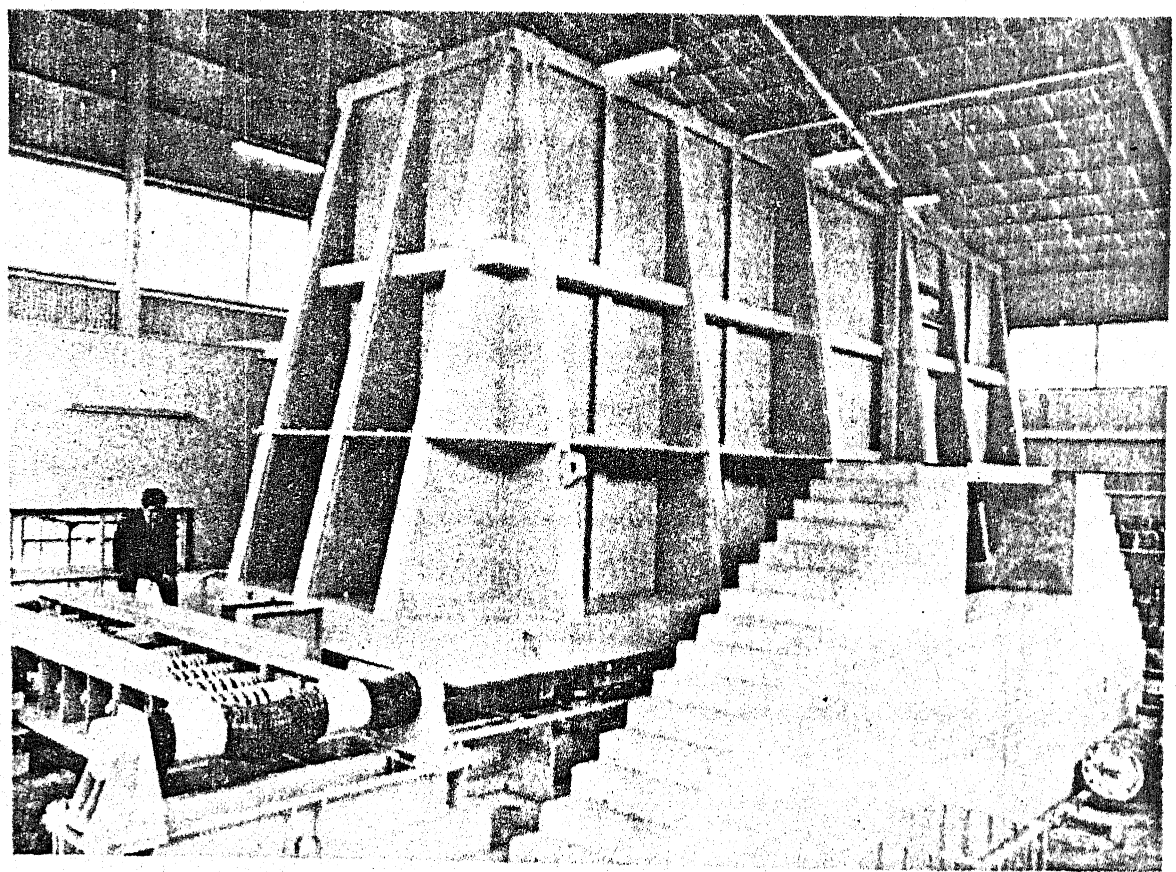


Fig. 2 Mechanism of driving



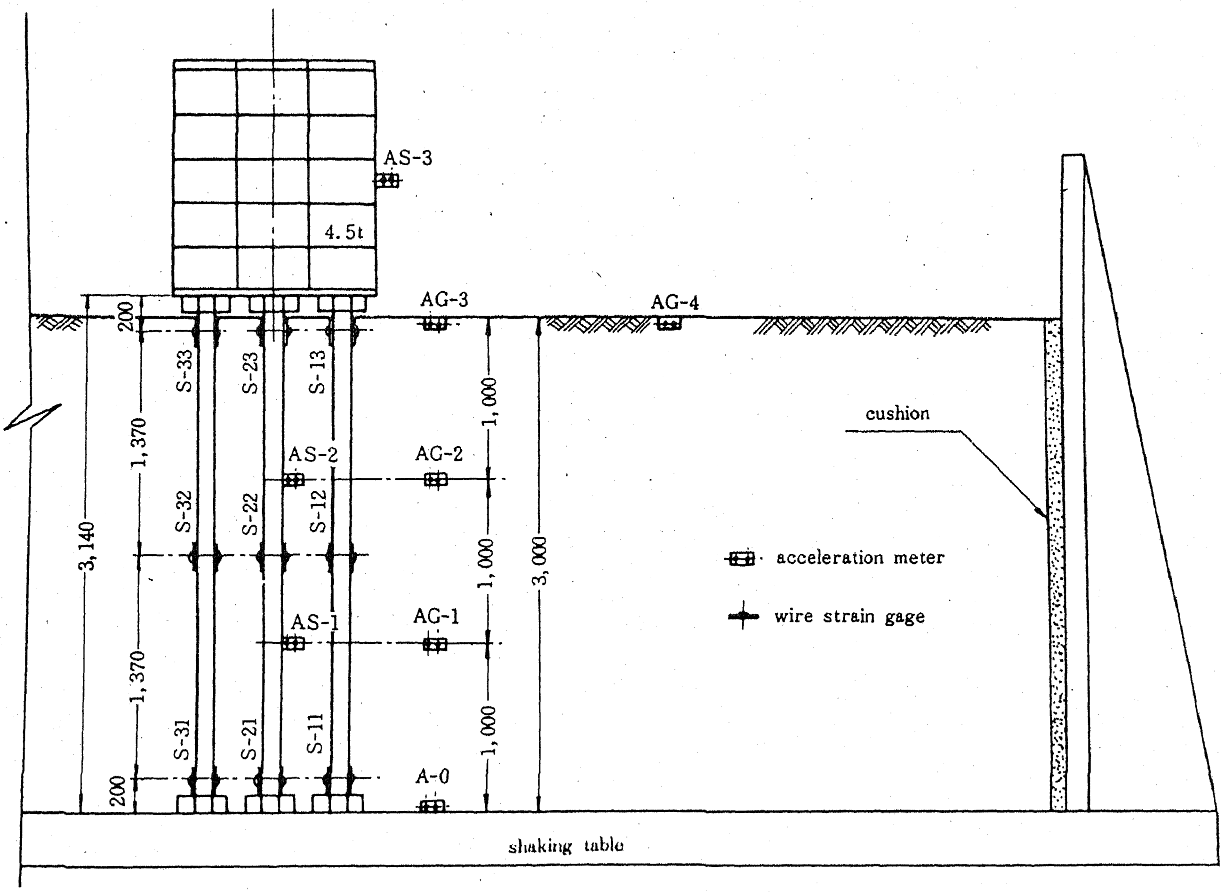


Fig. 3 Model of a structure supported by piles

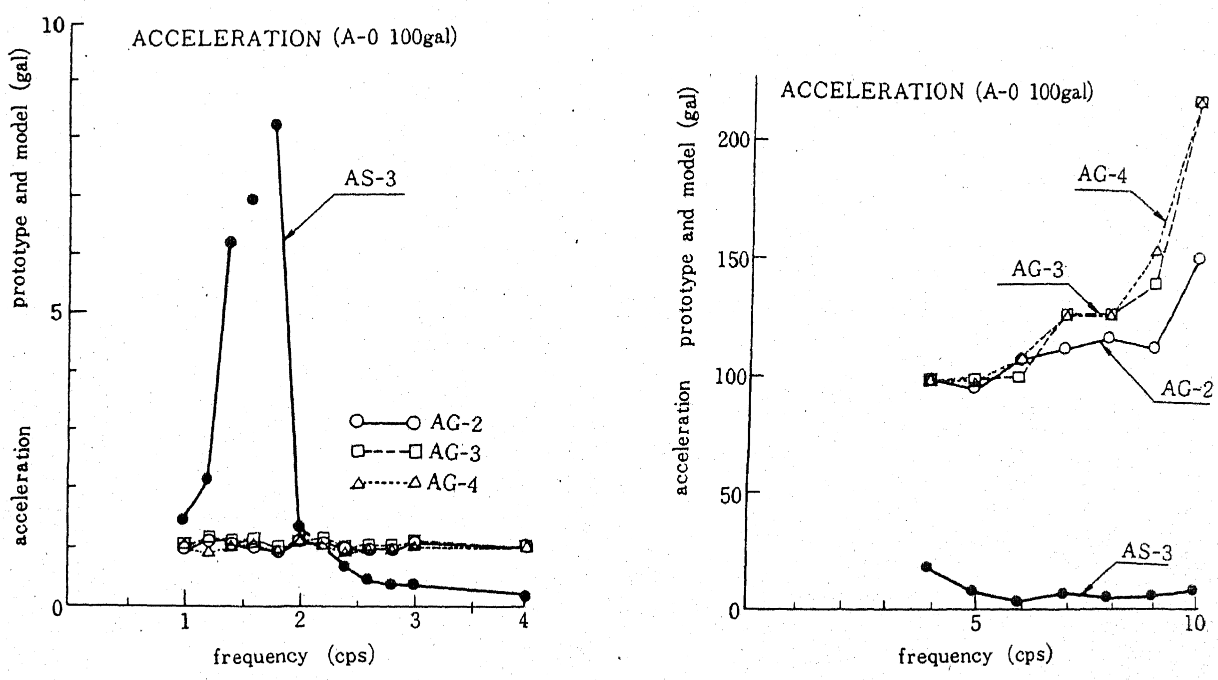
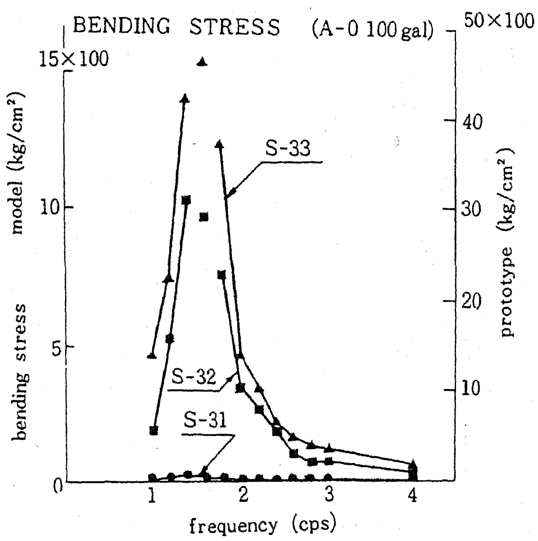


Fig. 4 Acceleration-frequency curve



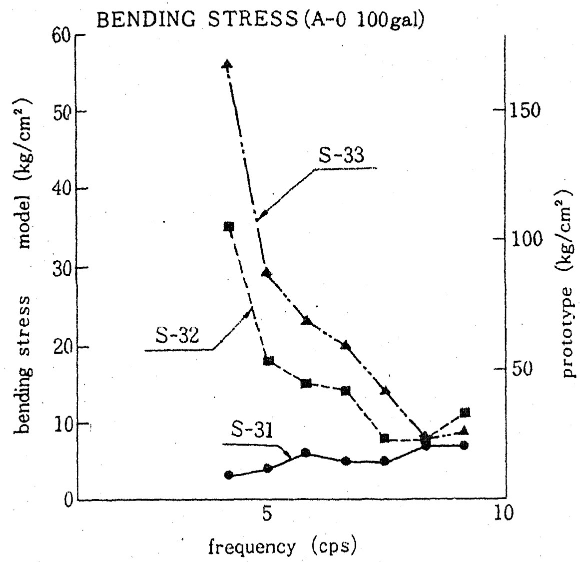


Fig. 5 Bending moment frequency curve

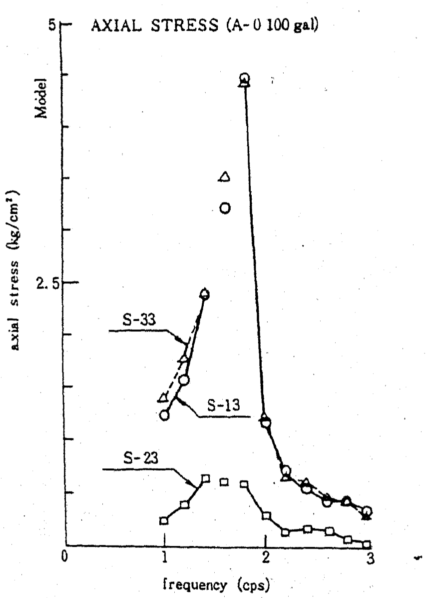


Fig. 6 Axial stress frequency curve

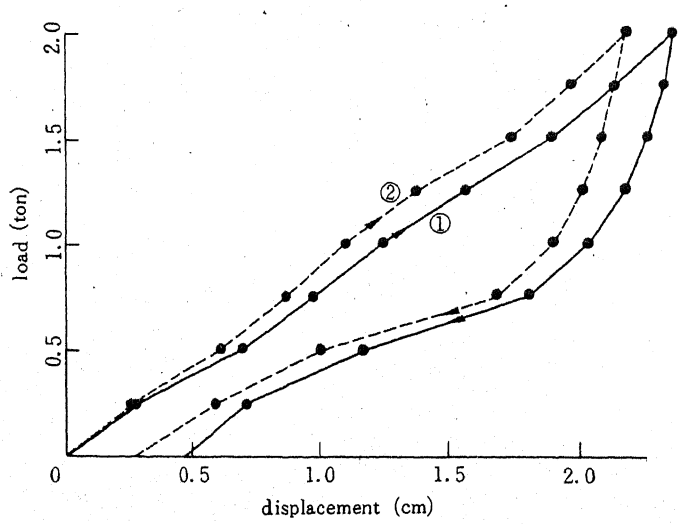


Fig. 7 Displacement load curve

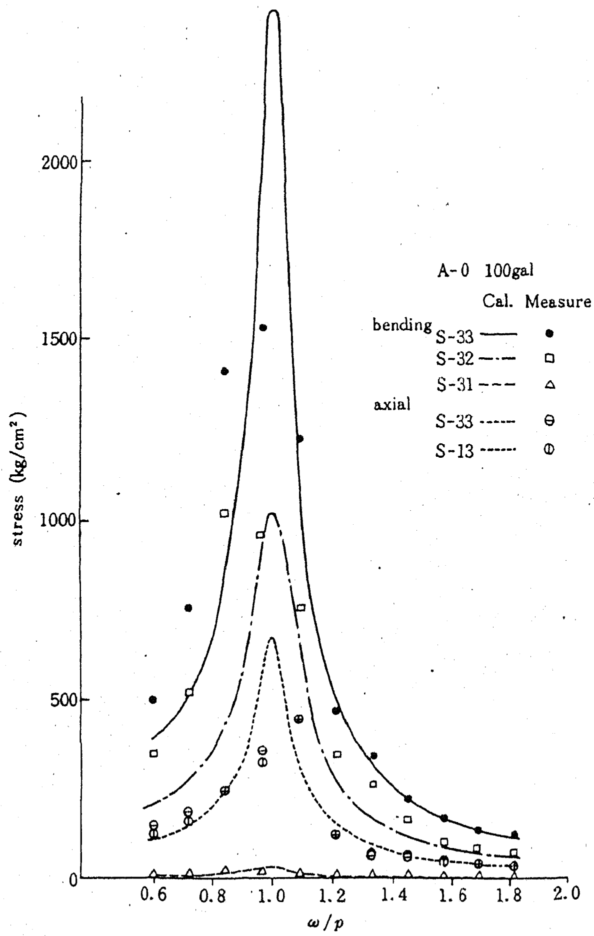


Fig. 8 Resonance curve

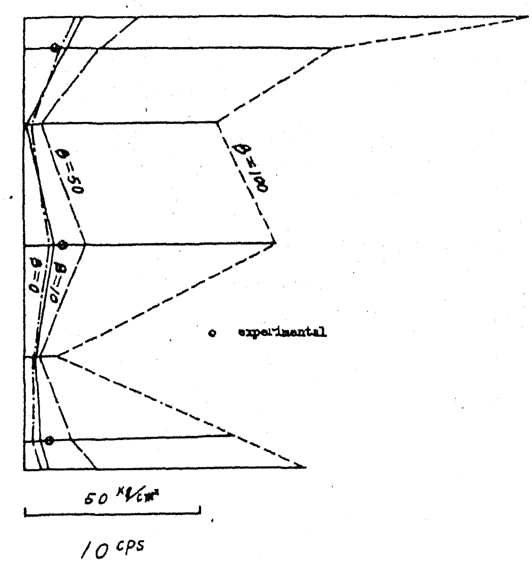


Fig. 9 Distribution of bending stress of the pile

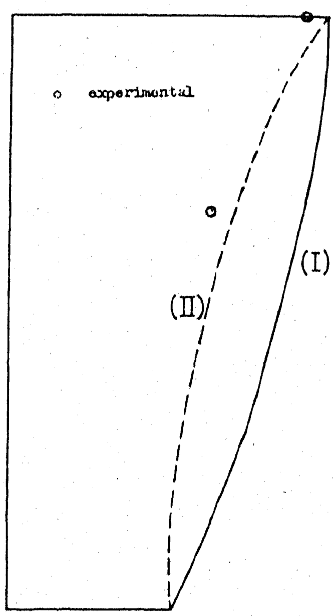


Fig.10 Acceleration distribution

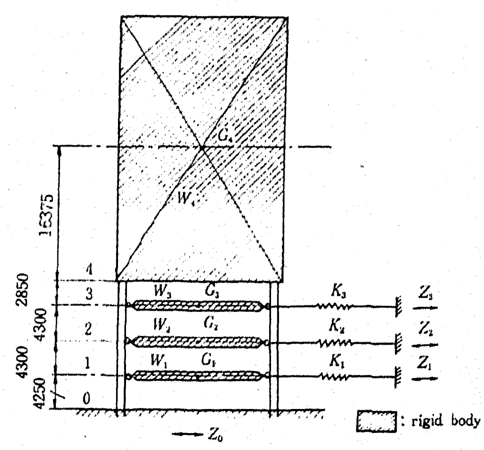
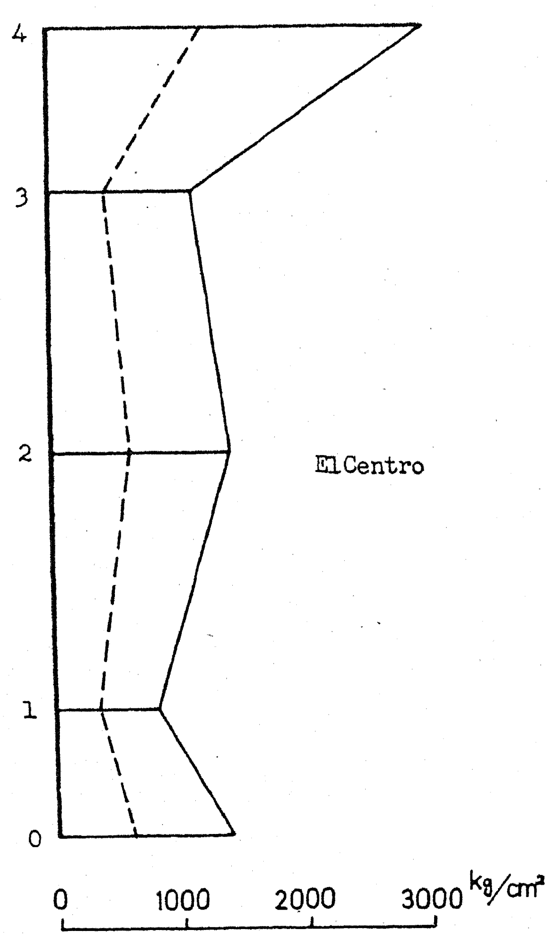


Fig.11 Model used in analysis



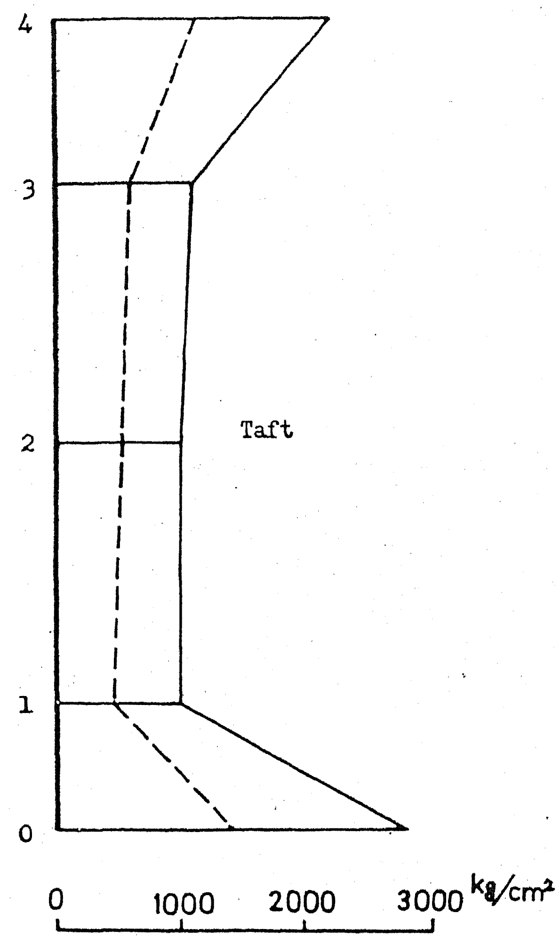


Fig.12 Dynamic response of bending stress due to earthquake

Table-1

Physical Property	Dimension	Scale
Acceleration	LT^{-2}	1
Length, Diameter	L	1/5
Weight, Force	MLT^{-2}	1/123
Stress, Cohesion	$ML^{-1}T^{-2}$	about 1/5
Flexural rigidity	$ML^{3}T^{-2}$	1/123 x 25
Angle of repose	none	1
Specific gravity	$ML^{-2}T^{-2}$	about 1
Time	T	$1/\sqrt{5}$