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EXPERIMENTAL AND ANALYTICAL STUDY ON THE EFFECT OF INPUT MOTION ON THE BEHAVIOR OF A CAISSON QUAYWALL

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SUMMARY

In Japan, we have a lot of caisson type quaywalls in port areas. In Japanese seismic code for port facilities, it is assumed that inertia force and dynamic earth pressure due to backfill soil act on caisson in the same direction at the same time during earthquakes. Therefore, bottom friction of caisson is to bears these two forces at any moment in the code. However, in actual, the phase characteristic of these three forces varies with some conditions such as stiffness of backfill soil and frequency of input motion and so on. In this study, in order to clarify the phase characteristics of the above three forces acting on the caisson during earthquakes, we carried out shaking table tests for caisson type quaywall modeled at a scale of 1/22 of the prototype. From the test results, it can be seen that the phases are varying with input acceleration level and large bottom friction is caused by caisson's rocking motion. To investigate a mechanism, which affects the phase characteristics of three forces acting on the caisson, a simple two mass-spring model simulation was introduced. Interaction spring between caisson and backfill soil was estimated by experimental results and Fourier analysis. The simulation correspond to the experimental results in the phase of the three forces, demonstrate that bottom friction of caisson is highly dependent upon the natural oscillation of backfill soil, the input seismic motion and interaction stiffness between caisson and backfill soil.

INTRODUCTION

For the seismic design of caisson type quaywalls in Japan, the Mononobe and Okabe equation [Mononobe and Matsuo, 1929 and Okabe, 1926] is used for estimating dynamic earth pressure of backfill soil. Its equation is based on a modification of the static Coulomb earth pressure theory with dynamic forces treated as additional static forces. Therefore, it is assumed that dynamic earth pressure and the inertia force have the same phase in the present code. In other words, the two forces are to act on caisson in the same direction at the same time. Using by this equation, Noda et al. (1975) have estimated the seismic coefficient corresponding to the severity of ground motions for a lot of damaged gravity quaywalls by earthquake and it is still used for level 2 seismic design.

However, it is reported that the phase between dynamic pressure and inertia force during earthquakes varies with some conditions such as stiffness of backfill soil and frequency of input motion and so on [Kazama, M. (1993), Miura, K. (1997)]. In addition, the distribution of lateral earth pressures is not given in Mononobe Okabe equation. Seed and Whitman, (1970), Ohara, S., (1970) and Ichihara, M. and Mastuzawa, H. (1973) have suggested the point of application of the total thrust or incremental dynamic thrust to be between 0.33H(triangular pressure distribution) or 0.67H(inverted triangle) from base. The distribution may influence in the rocking motion of caisson. Existing design methods may not adequately account for these issues, and verification of these methods is incomplete.

In this study, underwater shaking table tests were carried out to investigate the seismic response of a caisson type quaywall and ground motion behind a quaywall. The main aim is to clarify the relationship among incremental dynamic earth pressure acting on the back of the caisson, the bottom friction force on the caisson, and the inertia

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force of the caisson. This study uses experiments and simple two mass-spring model simulations to reveal the mechanism, which affects the phase of the inertia force of the caisson and dynamic earth pressure.

EXPERIMENTS

To investigate the phase characteristics of the bottom friction force, inertia force and the earth pressure, shaking table tests for caisson type quaywall were carried out. It was modeled at a scale of 1/22 of the prototype.

Experimental Model:

In this study, large underwater shaking table is used. It means that these tests were carried out in the water. Figure 1 shows a cross section and transducer layout of the model. The model consists of caisson, backfill soil, rubble mound and foundation soil. The base ground is made to be stiff with using sand and some cement. Rubble mound is made of crushed rocks. Backfill soil is compacted.

Figure 2 shows a model caisson used in the test. The caisson size is 750mm in height, and 855mm in width. It is equivalent to a quaywall of water depth 12.7m in the prototype scale (scale ratio is 1/22). Its seismic coefficient, which is defined by Japanese code for port facilities, is 0.25. A rubber sheet is set on the bottom plate of caisson in order to raise friction coefficient between caisson and rubble mound. In the actual design, the friction coefficient increases from 0.6 to 0.7 with using mat such as asphalt and rubber.

The model caisson can measure earth pressure and bottom friction force on caisson with using plate which is supported by 3 load cells. In addition, inertia force of caisson can be measured by accelerometers which are set on the caisson.

Experimental Condition:

Sinusoidal waves are used as input motion for the model to clarify the phase characteristics of the forces acting on the caisson. The waves have 10 Hertz in frequency and 20 times in cycle. These waves correspond to about 1 Hertz in the prototype scale (Iai, S. 1988). The input motion has only one horizontal component. The magnitude of the input motion is gradually increased as approximately 100Gal, 200Gal, 400Gal, 600Gal and 800Gal (five cases). Same model is used thorough all the tests.

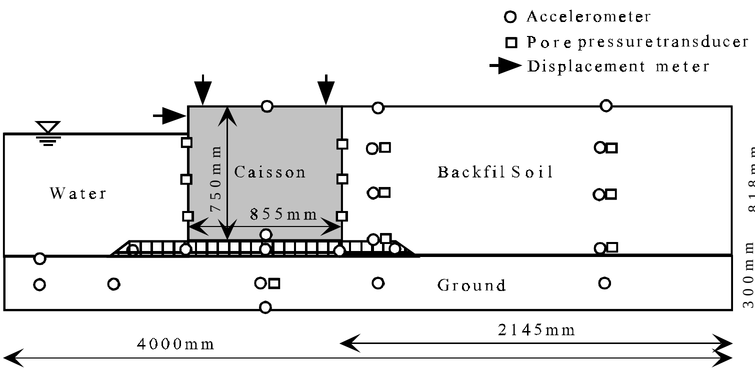


Figure 1: Cross Section of the Experimental Model

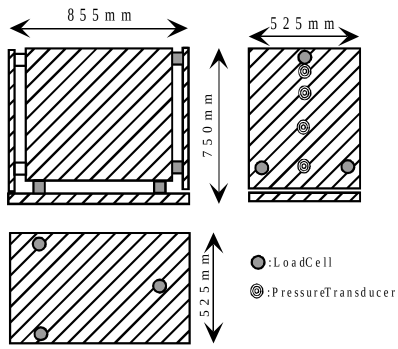


Figure 2: Details of Caisson Model

EXPERIMENTAL RESULTS AND ITS CONSIDERATION

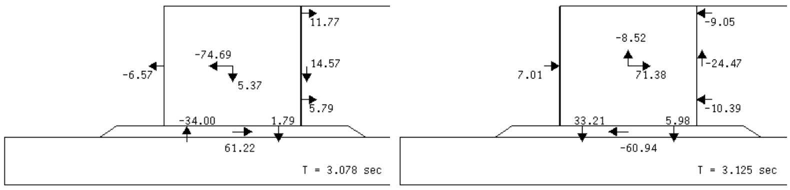
In this section, the load balance acting on the caisson, the shear stiffness of the ground, the earth pressure during earthquake and the bottom friction force are stated from experimental data.

Load Balance:

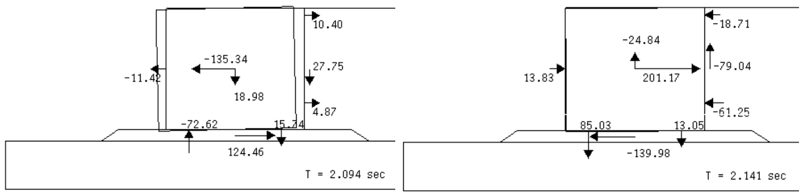
The loads acting on the caisson are examined by the load cell, accelerometer and pore pressure transducer. The load balances when the caisson is going to act toward sea side and toward land side are shown in figure 3 and table 1. Displacements are emphasized at these figures and these loads are incremental component between dynamic and static.

It can be seen that the incremental backfill earth pressure is acting in the opposite direction of the inertia force in case of 100 or 200 Gal input acceleration. However, these forces are acting in the same direction in case of more than 400 Gal input acceleration. It is stated in detail for this reason in chapter 4.

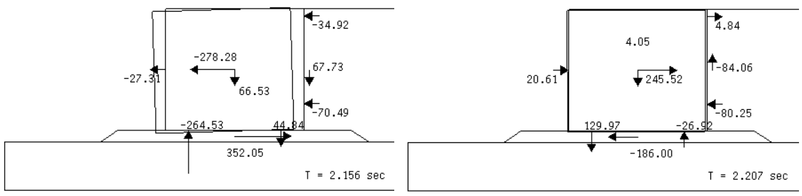
Phases between inertia force and incremental backfill earth pressure with the different input acceleration level are examined quantitatively by Fourier spectrum analysis shown in table 2, where F_P is incremental backfill earth force, F_I is inertia force of the caisson plus dynamic water force, F_F is incremental friction force on bottom of the caisson. The phase of the F_P / F_I is varying drastically from about 180 degree to about –35 degree between 200 Gal input and 400 Gal input in the same way as seen in figure 3. However, the phase of the F_F / F_I is not varying with all input levels and is about 180 degree which is opposite phase.



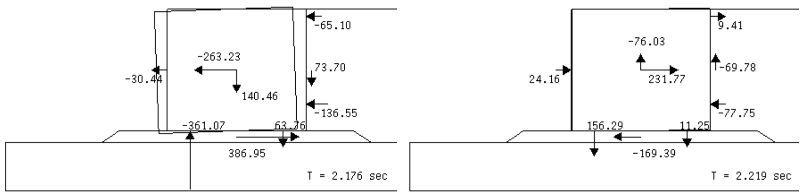
a) At 100 Gal (Displacement is magnified 100 times)



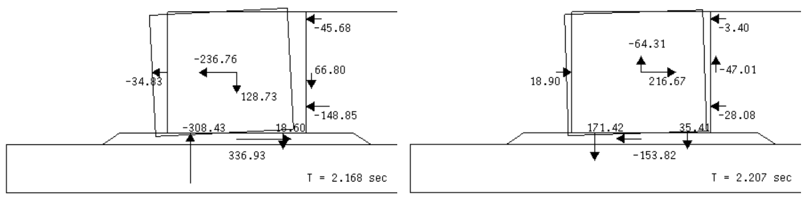
b) **At 200 Gal (Displacement is magnified 100 times)**



c) At 400 Gal (Displacement is magnified 20 times)



d) At 600 Gal (Displacement is magnified 20 times)



e) At 800 Gal (Displacement is magnified 20 times)

Figure 3: Load Balances among Inertia force, Dynamic Water Pressure and Dynamic Earth Pressure (Left: to the sea side, Right: to the land side)

In case of large input motion, large vertical load is obtained from the sea side load cell on the bottom of caisson. The vertical load is caused by rocking vibration and is useful for increasing the bottom frictional resistance force. Maximum friction force is about 400kgf shown in figure 3(d) at 600Gal or figure 4. As static friction load measured before shaking is about 100kgf, total friction force (static plus incremental dynamic force) is about 500kgf (400 plus 100). This large bottom friction force cannot be explained by present design method as following; Vertical load of caisson is 366kgf because mass of the caisson is 582kgf, buoyancy acts on the caisson is 216kgf. The frictional resistance force is calculated as 293kgf even if static friction coefficient were 0.8. However, considering the incremental dynamic vertical reaction ,which is about 300kgf, shown in figure 3(d) at 600 Gal or figure 4, frictional resistance force is calculated with 499.5kgf in condition that vertical load is 666kgf (366 plus 300) and a friction coefficient is 0.75.

Table 1: Horizontal Load Balance

Load Item	At 100 Gal		At 600 Gal	
	to the sea	to the land	to the sea	to the land
Inertia force	-74.7	71.4	-263.2	231.8
Earth pressure	16.2	-18.1	-206.5	-64.1
Friction force	55.9	-55.9	375.3	-151.8
Dynamic water pressure	-6.6	7	-30.4	24.2
Error	-9.2	4.4	-124.8	40.1

unit : kgf

Table 2: Relation of *FP/FI* and *FF/FI*

Gal	FP/FI	Phase of FP/FI	FF/FI	Phase of FF/FI
100	0.206	167.2	0.664	173.7
200	0.199	-176.1	0.657	172.5
400	0.157	-33.8	0.897	172.4
600	0.261	18.4	0.961	-177.7
800	0.243	14.9	0.922	-179.5

unit :degree(phase)

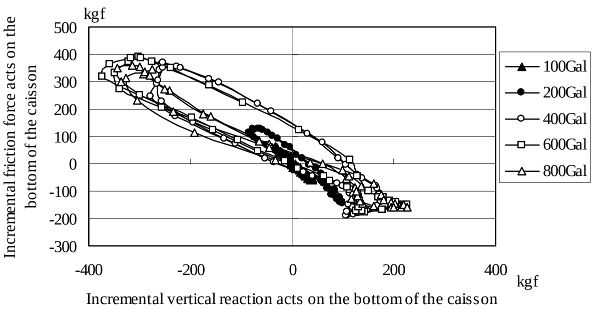


Figure 4: Relation of vertical reaction and friction force

SHEAR STIFFNESS OF THE GROUND:

Shear stiffness of the ground is examined by Fourier analysis for the acceleration data in backfill soil. The ground is modeled with mass, spring and damping shown in figure 5. Vibration equation of the ground is shown as equation 1, where k is shear stiffness, c is damping ratio, m is mass of the ground, a is input acceleration amplitude, b is response acceleration amplitude of the ground, ω is input circular frequency, i is imaginary number. Complex shear stiffness coefficients ($|k-i\omega c|$) calculated from equation 1 are shown in figure 6. It can be seen that the shear stiffness decreases as input acceleration increases. In particular, it decreases drastically in the acceleration range of 400 Gal to 800 Gal.

$$\begin{pmatrix} a-b_1 & b_2-b_1 & 0 & 0 & 0 \\ 0 & b_1-b_2 & b_3-b_2 & 0 & 0 \\ 0 & 0 & b_2-b_3 & b_4-b_3 & 0 \\ 0 & 0 & 0 & b_3-b_4 & b_5-b_4 \\ 0 & 0 & 0 & 0 & b_4-b_5 \end{pmatrix} \begin{pmatrix} k_1-i\omega c_1 \\ k_2-i\omega c_2 \\ k_3-i\omega c_3 \\ k_4-i\omega c_4 \\ k_5-i\omega c_5 \end{pmatrix} = -\omega^2 \begin{pmatrix} m_1 b_1 \\ m_2 b_2 \\ m_3 b_3 \\ m_4 b_4 \\ m_5 b_5 \end{pmatrix} \quad (1)$$

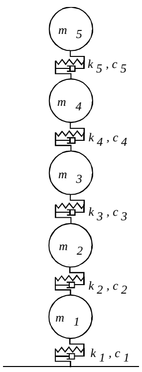


Figure 5: Mass spring model of ground

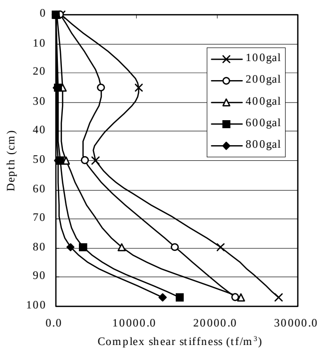


Figure 6: Complex Shear stiffness of the ground

EARTH PRESSURE AND FRICTION FORCE:

Earth pressure and bottom friction force on the caisson are also examined by Fourier analysis. As input acceleration increases, these stiffness decrease as shown in table 3, where k is real part of F/x, c is imaginary part of $F/\omega x$, F is input frequency component of incremental dynamic earth pressure or incremental friction force and x is also input frequency component of relative displacement between caisson and ground. Negative stiffness is seen in earth pressure acts on the side back of the caisson because of displacement phase and force phase difference. And also negative large viscous damping ratio is seen in case of 400 Gal input so far as calculation because it is when these phases are just reversing.

Table 3: Earth pressure stiffness and bottom friction force stifness

Gal	Earth pressure		Bottom friction	
	spring (k)	damping (c)	spring (k)	damping (c)
100	1.5E+06	8.9E+03	3.1E+06	3.1E+04
200	6.1E+05	4.1E+03	8.7E+05	1.0E+04
400	-1.1E+05	-4.1E+05	3.6E+05	4.5E+03
600	-2.9E+05	3.1E+03	3.0E+05	3.1E+03
800	-1.7E+05	1.1E+03	2.2E+05	2.3E+03

unit : k (kgf/m^3), c (kgf/m^3/s)

ANALYSIS

Two Mass Spring Model:

Simple two mass spring model shown in figure 7 is created to clear a factor determining the caisson dynamic characteristics. Its model is consist of mass of the caisson, mass of the backfill soil and three-interaction spring and damping, so the inertia force of the caisson, side earth pressure and bottom friction can be expressed. Actually, though the caisson has rocking motion, it is investigated what kind of force the caisson balances horizontally by.

Dynamic load balance can be given in equations 2 and 3. Where m_c is mass of the caisson, m_s is mass of the backfill soil, k_i is the equivalent soil spring constant between the caisson and backfill soil, k_c is the equivalent friction spring constant between the caisson and the rubble mound, k_s is the equivalent shear spring constant substituted for shear force of the backfill soil, c_i, c_c, c_s are viscous damping coefficient, x is input ground displacement and X_c, X_s are displacement of the caisson and the backfill soil respectively.

$$m_c\ddot{X}_c = k_c(x - X_c) + k_i(X_s - X_c) + c_c(\dot{x} - \dot{X}_c) + c_i(\dot{X}_s - \dot{X}_c) \quad (2)$$

$$m_s\ddot{X}_s = k_s(x - X_s) + k_i(X_s - X_{cc}) + c_s(\dot{x} - \dot{X}_s) + c_i(\dot{X}_s - \dot{X}_c) \quad (3)$$

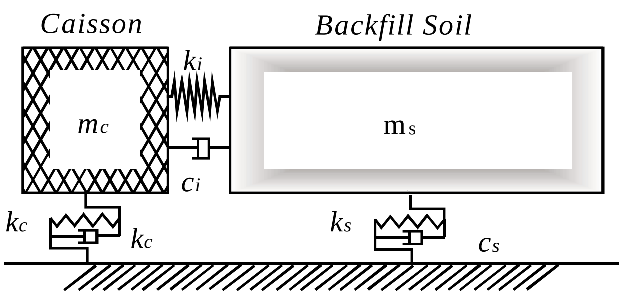


Figure 7: Two mass spring model

Characteristics of the earth pressure, the bottom friction force and the inertia force of the caisson:

Inertia force, friction force and earth pressure force are respectively given by equations 4, 5 and 6 where, $F_I=-(F_F+F_P)$, input acceleration is $ae^{-i\omega t}$, response of the caisson and backfill soil are $b_c e^{-i\omega t}$ and $b_s e^{-i\omega t}$, respectively. Equations 7 and 8 are non-dimensional force compared with inertia force.

$$F_I = \omega^2 b_c e^{-i\omega t} m_c \tag{4}$$

$$F_F = -(b_c - a)(k_c - i\omega c_c)e^{-i\omega t} \tag{5}$$

$$F_P = -(b_c - b_s)(k_i - i\omega c_i)e^{-i\omega t} \tag{6}$$

$$F_F / F_I = \frac{-1}{m_c\omega^2}(1 - \frac{a}{b_c})(k_c - i\omega c_c) \tag{7}$$

$$F_P / F_I = \frac{-1}{m_c\omega^2}(1 - \frac{b_s}{b_c})(k_i - i\omega c_i) \tag{8}$$

Where,

$$(1 - \frac{a}{b_c}) = \frac{\left\{\begin{array}{l}(m_s k_i + m_c k_s + m_c k_i)\omega^2 \\ - i(m_s c_i + m_c c_s + m_c c_i)\omega^3 \\ - m_c m_s \omega^4\end{array}\right\}}{\left\{A - m_s k_c \omega^2 - i(B - m_s c_c \omega^3)\right\}}$$

$$(1 - \frac{b_s}{b_c}) = \frac{\left\{\begin{array}{l}(m_c k_s - m_s k_c)\omega^2 \\ + i(m_s c_c - m_c c_s)\omega^3\end{array}\right\}}{\left\{A - m_s k_c \omega^2 - i(B - m_s c_c \omega^3)\right\}}$$

$$A = (k_c k_s + k_i k_s + k_i k_c) - \omega^2 (c_c c_s + c_i c_s + c_i c_c)$$

$$B = \omega(k_s c_c + k_s c_i + k_c c_s + k_i c_s + k_i c_c + k_c c_i)$$

When a damping can be neglected, F_F/F_I, F_P/F_I are rewritten such as

$$F_F / F_I = -\frac{m_s k_i k_c + m_c k_c (k_s + k_i) - m_c m_s k_c \omega^2}{m_c k_i k_s + m_c k_c (k_s + k_i) - m_c m_s k_c \omega^2} \tag{9}$$

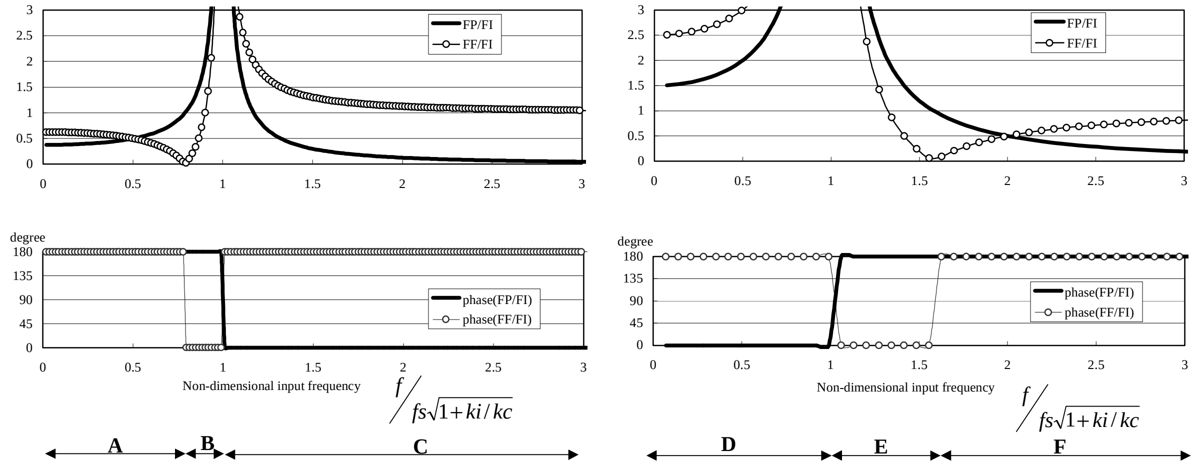
$$F_P / F_I = -\frac{m_c k_i k_s - m_s k_i k_c}{m_c k_i k_s + m_c k_c (k_s + k_i) - m_c m_s k_c \omega^2} \approx \frac{k_i / k_c (f_s^2 - f_c^2)}{(f_s \sqrt{1 + k_i / k_c})^2 - f^2} \tag{10}$$

These equations indicate that a dynamic characteristic of the caisson is determined by the comparison of natural frequency of the backfill soil (f_s) and of the caisson (f_c). When backfill soil is hard ($f_s > f_c$) and input frequency is smaller than $\sqrt{1 + k_i / k_c}$ times as natural frequency of the backfill soil, dynamic earth pressure acts to opposite direction for inertia force of the caisson. In case of soft backfill soil ($f_s < f_c$), this intensity is the reverse as shown in figure 8. Incremental dynamic earth pressure and incremental bottom friction force act in the opposite direction for inertia force of the caisson in region A and F, and the former acts in the same direction in region C and D. In region B and E, so tight region, bottom friction force acts in the opposite direction for inertia force.

In this study, phases of inertia force and dynamic earth pressure are reversed in case of more than 400 Gal input motion examined previously. It seems that ground softness is caused by increasing input level. Also, excess pore pressure ration drastically increased from 200 Gal input to 400 Gal input.

SIMULATION OF THE EXPERIMENT:

In this section, simple two mass-spring model is applied to simulate the experimental results and the possibility is examined. Material quorums are shown in table 4, where m_c is mass of the caisson including added mass caused by dynamic water pressure. In this case, added mass coefficient is 0.143 calculating by potential theory. m_s, k_s, c_s are equivalent in case of one mass-spring for multi mass-spring model shown in section 3.2. Ground mass is employed as large mass so that ground motion is independence of caisson's motion. In addition, k_i, c_i, k_c, c_c are calculated from earth pressure and bottom friction force shown in table 3.



In case of $fc < fs$ In case of $fc > fs$

Figure 8: Characteristics of backfill earth force and friction force act on caisson

Comparisons between experimental responses and these simple simulations are shown in figure 9. Inertia force (F_I) at experiment also includes added mass force. This experimental data copy with table 2. Experimental data absolutely correspond to calculated data with all cases, though the caisson has rocking motion.

Ground natural frequency (fs), caisson natural frequency (fc) and characteristic value ($fs\sqrt{1+ki/kc}$) which is the parameter changing from same phase to opposite phase in case of irrespective of damping are shown in table 5. This important characteristic value ($fs\sqrt{1+ki/kc}$) is smaller than input natural frequency ($f=10Hz$) in case of more than 400 Gal input, so that the phase is reversed. This behavior can be illustrated the state changed not from A stage to D stage but from A to C in figure 8.

Table 4: Material quorums using at simulation

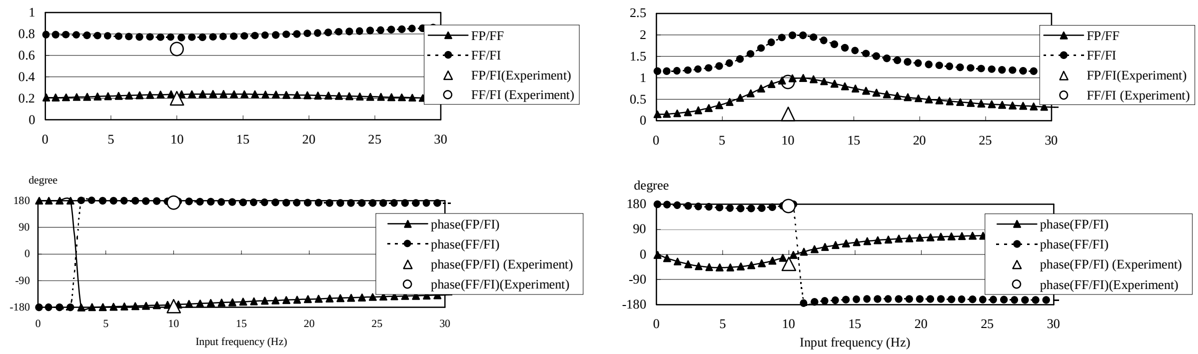
Gal	m_c	m_s	k_i	c_i	k_c	c_c	k_s	c_s
100	6.7E+01	2.3E+04	5.5E+05	3.2E+03	1.4E+06	1.4E+04	4.5E+08	6.4E+06
200			2.2E+05	1.5E+03	3.9E+05	4.6E+03	3.1E+08	5.2E+06
400			-4.1E+04	-1.3E+03	1.6E+05	2.0E+03	9.7E+07	2.4E+06
600			-1.0E+05	1.1E+03	1.3E+05	1.4E+03	6.8E+07	1.9E+06
800			-6.2E+04	4.1E+02	1.0E+05	1.1E+03	4.1E+07	1.4E+06

unit : m (kgf), k (kgf/m), c (kgf/m /s)

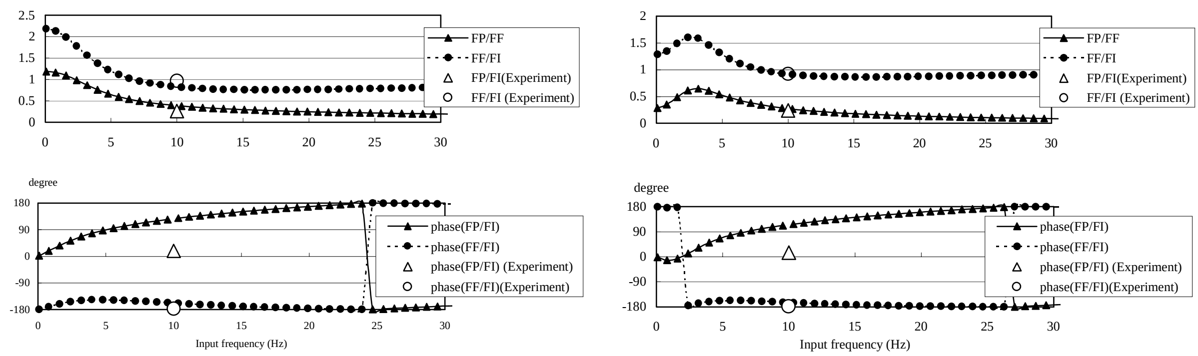
Table 5: Natural frequency of the ground and the caisson

Gal	f_c	f_s	$fs\sqrt{1+ki/kc}$
100	22.9	22.3	26.3
200	12.1	18.5	23.1
400	7.7	10.3	7.6
600	7.0	8.7	4.2
800	6.1	6.7	4.1

unit : f (Hz)



a) At 200Gal b) At 400 Gal



c) At 600Gal　　　　d) At 800 Gal

Figure 9: Comparison of the theory and the experiment about backfill earth pressure and bottom friction force

CONCLUSIONS

1. The simulation correspond to the experimental results, demonstrate that bottom friction of caisson is highly dependent upon the phase between inertia force of the caisson and dynamic earth pressure.
2. When backfill soil is hard (*fs>fc*) and input frequency is smaller than $\sqrt{1+k_i/k_c}$ times as natural frequency of the backfill soil, dynamic earth pressure acts to opposite direction for inertia force of the caisson, so the bottom friction is small. In case of soft backfill soil (*fs<fc*), this intensity is the reverse.
3. Important characteristic value ($fs\sqrt{1+ki/kc}$) , which is the parameter changing the incremental dynamic earth pressure phase in case of irrespective of damping, is smaller than input natural frequency (*f=10Hz*) in case of more than 400 Gal input, so the phase is reversed.
4. The experimental data demonstrate that the bottom frictional resistance force is highly dependent upon the rocking motion of the caisson.

ACKNOWLEGEMENT

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REFERENCES

1. Iai, S. (1988), “Similitude for Shaking Table Tests on Soil-Structure-Fluid Model in 1 G Gravitational Field”, *Report of the Port and Harbour Research Institute, Vol.27, No.3,* pp.3-24.
2. Kazama, M.(1993),”Seismic Stability of Gravity-type Harbour Structures Subjected to Earth Pressure”, *Technical Note of the Port and Harbour Research Institute, Vol.752.*(in Japanese)
3. Ichihara, M. and Mastuzawa, H. (1973), “Earth Pressure during Earthquake”, *Soils and Foundations, Vol.13, No.4, J.S.S.M.F.E.,* pp.75-86.
4. Matsuzawa, H., I. Ishibashi, and M. Kawamura (1985), “Dynamic Soil and Water Pressures of Submerged Soils”, *ASCE Journal of Geotechnical Engineering, Vol.111, No.10,* pp.1161.
5. Miura, K., Kohama, E., Kurita, S., Ohstuka, N. and Yosida, N. (1997), “Behavior of Gravity Type Quay Wall during Earthquake Observed in Model Shaking Table”, *International Offshore and Polar Engineering Conference, Hawaii* (1997)
6. Mononobe, N. and H. Matsuo (1929), ”On the Determination of Earth Pressures During Earthquakes”, *Proceedings of World Engineering Conference, Vol.9,* pp.176.
7. Noda, S. , T. Uwabe, and T. Chiba (1975), “Relation Between Seismic Coefficient and Ground Acceleration for Gravity Quaywall”, *Report of the Port and Harbour Research Institute, Vol.14, No.4,* pp.67-111 (in Japanese).
8. Ohara, S. (1970), “Experimental Studies of Seismic Active and Seismic Passive Earth Pressure”, *Proceedings of the 3 Japan Earthquake Engineering Symposium, Vol.3,* pp.137-144.
9. Okabe, S. (1926), ”General Theory of Earth Pressure”, *Journal, Japanese Society of Civil Engineers, Vol.12, No.1.*
10. Seed, H. B. and R. V.Whitman(1970), “Design of Earth Structures for Dynamic Loads”, *Lateral Stresses in the Ground and Design of Earth-Retaining Structures, ASCE Specialty Conference, Cornell Univ., Ithaca, N. York.*