SIMPLIFIED METHOD TO EVALUATE CAISSON TYPE QUAY WALL MOVEMENT

Masayuki SATO[1], Hiroyuki WATANABE[2], Tomoyoshi TAKEDA[3] And Masayoshi SHIMADA[4]

SUMMARY

The mechanism of movement of caisson type quay wall with reclaimed ground was investigated from the results of centrifuge model vibration tests, then a simplified method to evaluate the amount of caisson's movement was proposed. From the results of the analysis on dynamic earth pressure observed in experiments, it was found that when input acceleration is small, the dynamic earth pressure acts so as to restrain the movement of caisson and the excess pore water pressure hardly occurs. On the other hand, when the input acceleration is large enough to occur liquefaction, dynamic earth pressure acts rather so as to promote the movement of caisson. Based on these results, a simplified analytical model for evaluating the amount of caisson's sliding when the backfill was liquefied was conceived. By using the model, simulations of experimental results were performed in order to investigate the sensitivities of each parameters and the validity of the model to the actual structures.

INTRODUCTION

linear FEM [Ozutsumi et al., 1998] or effective-stress FEM [Wang et al., 1998, Sawada et al., 1998] have been made. However, each method has some points of issue. For example, though the empirical procedure is very simple, it cannot take account of input motion level and liquefaction potential of the ground. The gravity analysis method seemed to be proper for post liquefaction behavior, but it cannot take account of influences of inertia force of caissons and dynamic earth pressure due to liquefied back-fill. Though the dynamic FEM is a sophisticated method, it is very complicated to assess the constitution low of soils and their properties.

In this study, a simplified model for evaluating the amount of caisson's sliding is conceived. In spite of its simplicity, the proposed model is able to take account of influences of input-motion and liquefied backfill.

CENTRIFUGE TEST

Centrifuge Test Configuration

Centrifuge model vibration tests on caisson type quay wall movements were performed by the authors [Ozeki et al., 1997]. From the results of these tests, relationships between behaviors of a caisson model and earth pressures recorded by the pressure meters attached behind the caisson model were analyzed in order to construct a simplified model for calculating the sliding of the caisson.

In the centrifuge tests [Ozeki et al., 1997], a rigid vessel made of aluminum plates having its inner dimension, 110 cm long, 40 cm wide, and 30 cm high, was fixed on the shaking table which was connected to a steel basket supported by a hinge at the end of rotating arm of about 6.5m in length. Inside the vessel, the model consisting of front water, caisson model, water saturated rubble mound, rubble back-filling and back-fill soil was installed as

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[1] *Tokyo Electric Power Services Co., Ltd., ,Tokyo, 110-0015 Japan. E-mail; sato@tepsco.co.jp*
[2] *Dept of Civil and Envl Eng, Faculty of Eng, Saitama University, Japan. E-mail; hiroyuki@sacs.sv.saitama-u.ac.jp*
[3] *Tokyo Electric Power Company, Yokohama, 230-8510 Japan. E-mail; takeda-t@rd.tepco.co.jp*
[4] *Tokyo Electric Power Company, Yokohama, 230-8510 Japan. E-mail; t0594366@pmail.tepco.co.jp*

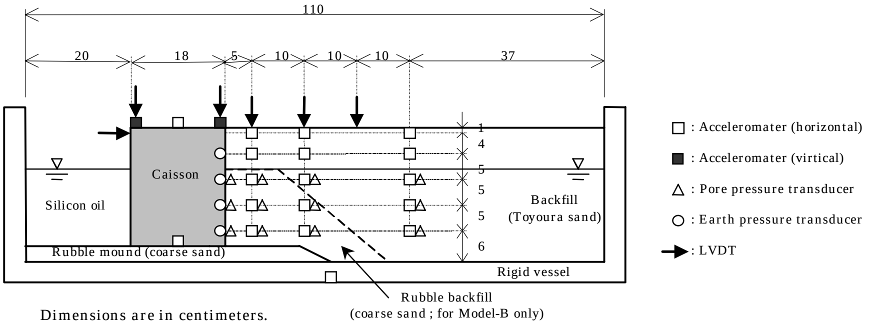


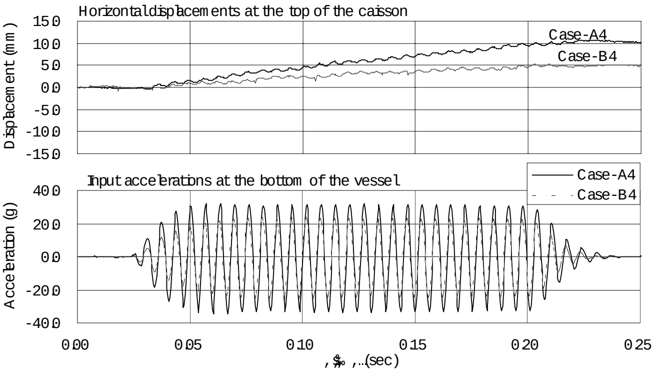
Figure-1: Centrifuge model configuration

TABLE-1: EXPERIMENTAL CASES OF CENTRIFUGE TESTS

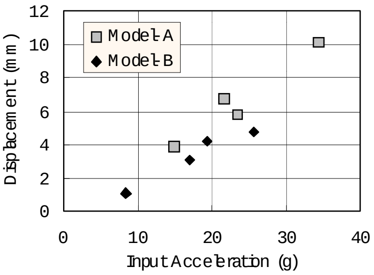
	Model-A (without rubble backfill)				Model-B (with rubble backfill)			
Case	A1	A2	A3	A4	B1	B2	B3	B4
Maximum value of input motion (g)	14.8	21.6	23.5	34.4	8.5	17.1	19.4	25.7

shown in Figure-1. The rubble mound and the rubble back-filling were made of well-compacted coarse sand (1.3mm of mean grain size). Toyoura sand (0.15mm of mean grain size) was used for the back-fill. Two models were prepared for experiments, one without the rubble back-filling (Model-A) and another with the rubble backfill (Model-B). After the model was constituted in dry condition, in which the relative density of the sand was 65%, then silicon-oil was introduced to the soil through the inlet tube at the base of the rXigid vessel which was put in the evacuated container. In the tests, from the law of similarity, silicon-oil at 50 cSt dynamic coefficient of viscosity was used as pore fluid and front water. Sensors and measurement positions of the model are also shown in Figure-1.

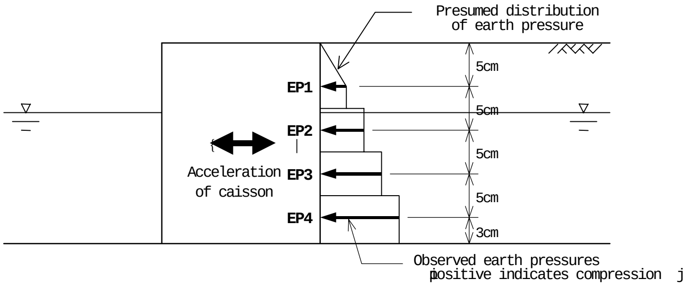
Four cases of experiments were performed for each model as shown in Table-1. The models were subjected to maximum about from 10g to 30g (g= 980cm/sec^2) sinusoidal input acceleration of 150Hz for 0.2 seconds under the initial confining pressure of 50g given by the centrifuge test facility.



Figute-2: Time histories of horizontal displacement at the top of caisson and input acceleration



Figute-3: Acceleration level of input motion versus residual displacement of caisson



Figute-4: Presumed distribution of the earth pressure for estimating time histories of the dynamic earth thrust on the caisson

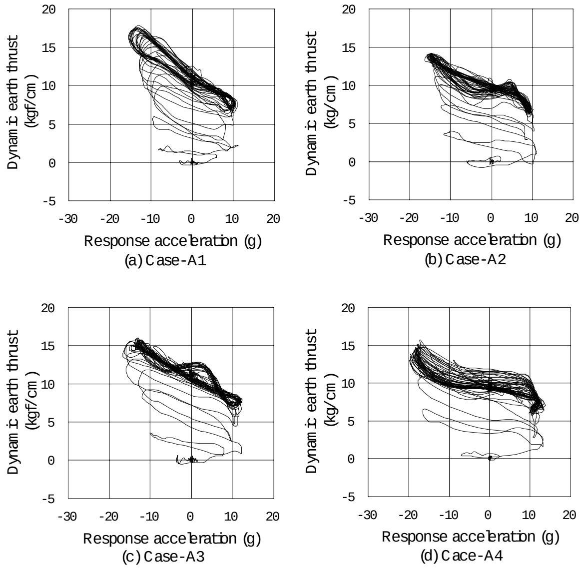
1.1 Experimental Results

Figure-2 shows horizontal displacement measured at the top of the caisson model and horizontal input acceleration recorded at the base in Case-A4 and Case-B4. Horizontal displacement of the caisson occurred only during excitation in both cases. Figure-3 shows a relationship between maximum acceleration of the input motion and maximum displacement of the caisson for all experimental cases. It is noted that the caisson's horizontal displacements of Model-A without rubble backfill are apparently larger than that of Model-B with rubble back-fill. In order to investigate such differences in horizontal displacements between Model-A and Model-B, measured dynamic earth pressures acting on the caisson at the location of EP1•EP4 in Figure-1 were analyzed as below.

Figure-4 shows a presumed distribution of earth pressures for estimating time histories of the dynamic earth thrusts on the caisson. The arrow and the signs of plus and minus in Figure-4 indicate the direction for the accelerations and earth pressures. Relationships between above mentioned time histories of dynamic earth thrusts and mean response acceleration of the caisson are shown in Figure-5 and Figure-6. Figure-7 shows a relationship between inertia forces of the caisson ($F = -m\alpha$: m ; mass of the caisson, α ; response acceleration of the caisson) and dynamic earth thrusts in Case-A1.

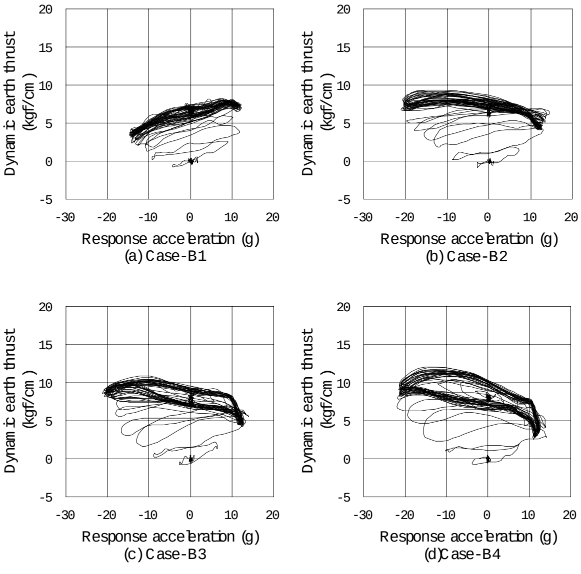
It is noted from Figure-2 and 7 that sliding of the caisson occurs only during excitation, and inertia force of the caisson is almost the same level as the dynamic earth thrust. In the case where the soft ground just below the caisson is very thick, or in the case when a higher level of excitation is applied, the possibility of post-excitation displacements of the caisson might not be denied, however, it must be impossible to predict the displacements of caisson and the deformation of back-fill ground unless both inertia force of caisson and dynamic earth pressure are taken account.

As indicated in Figure-5 and 6, mean values and fluctuations of the dynamic earth thrusts in Model-A in which liquefaction occurred in back-fill are larger than Model-B in which liquefaction didn't occur in the vicinity of the caisson. Inclinations of the loops in Model-A are all negative, which means the earth pressure was in harmony with the inertia force of the caisson, in other words, the earth pressure was acting to promote the caisson's movement. Besides, in Model-A, it is recognized that the inclinations of the loop degrease as the input acceleration levels increase. On the other hands, in Model-B, inclinations of the loops are smaller than Model-A, and they increase as the input acceleration levels increase. Particularly in Case-B1, the inclination is contrary (negative) to the other cases, which means the dynamic earth pressure acted so as to restrain the movement of the caisson.



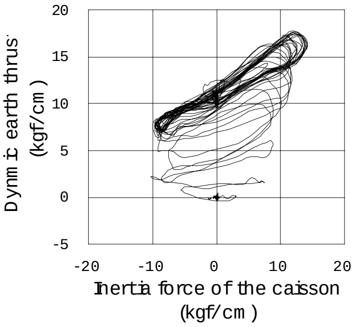
(a) Case-A1
(b) Case-A2
(c) Case-A3
(d) Cace-A4

Figute-5: Relationship between dynamic earth thrust and response acceleration of the caisson (Model-A)

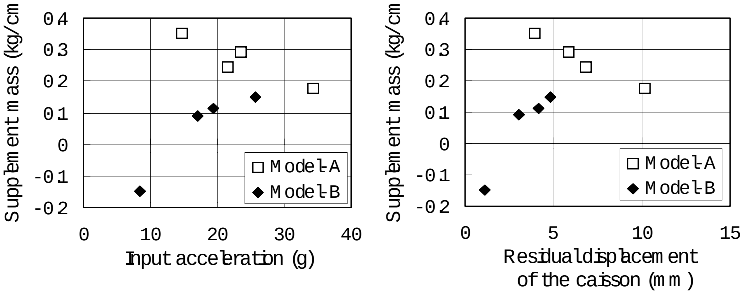


(a) Case-B1
(b) Case-B2
(c) Case-B3
(d)Case-B4

Figute-6: Relationship between dynamic earth thrust and response acceleration of the caisson (Model-B)



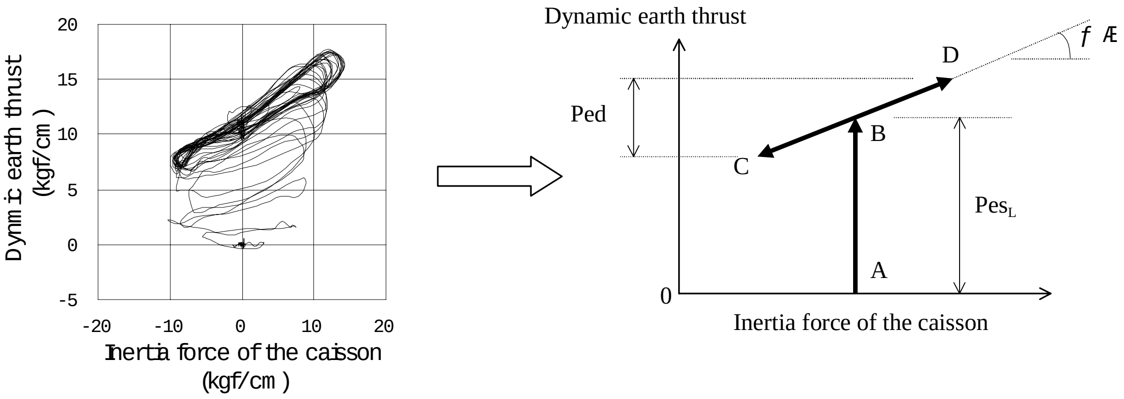
Figute-7: Relationship between earth thrust and inertia force of the caisson (Case-A1)



(a) (b)

Figute-8: Supplement mass for dynamic earth thrust versus acceleration level of input motion and residual displacement of caisson

Using the data obtained after the time when the loops became steady state, average inclination of the each loop was calculated, which is considered to denote supplement mass corresponding to the dynamic earth thrust. Relationships between obtained supplement masses and the maximum levels of the input motions during excitation are shown in Figure-8(a). Similarly, relationships between supplement masses and residual displacements of the caisson after excitation are shown in Figur-8(b). Liquefaction occurred in every case of Model-A, and the supplement mass degreases as the input motion level increases. It is considered that effective stress of the liquefied backfill could recover due to the volumetric expansion caused by the moving of the caisson toward sea side. On the contrary, in Model-B, the supplement mass increases according to an increase of input motion level. It is considered that because the backfill just behind the caisson could not liquefy no matter how the input motion level was large, shear modulus of the backfill degreased with an increase of the pore water pressure.



(a) Actual behavior (b) Simplification

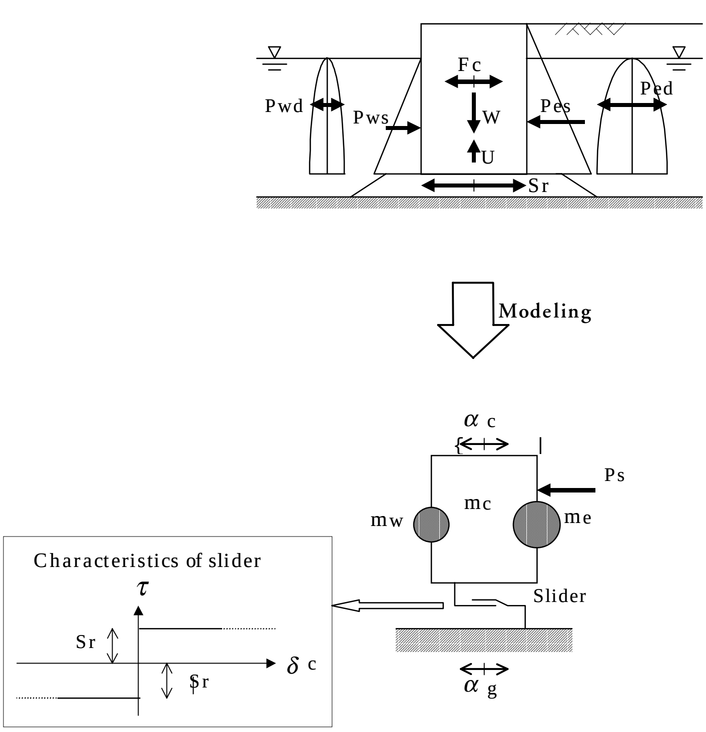
Figute-9: Simplification on the behavior of the dynamic earth thrust

SIMPLIFIED METHOD

Analytical Model

Based on the experimental results, simplification on the behavior of the dynamic earth thrust (combined lateral earth pressures) on the caisson was made as illustrated in Figure-9. Because of the increase of excess pore water pressure due to the liquefaction, dynamic earth pressure rises up from point A to point B, so that, Pes_L corresponds to an increment of the lateral earth pressure from the static state to the over burden pressure. After the initial liquefaction, dynamic earth thrust (Ped) changes linearly with inertia force of the caisson along the line through point C and point D. Because of this assumption, influence of the dynamic earth thrust can be explain by using supplement mass which controls the gradient of the pass (θ).

Proposed model and simplified method by using the model are shown in Figure-10 and 11 respectively. Caisson is represented as a concentrated mass (m_c) which has one-dimensional (horizontal) degree of freedom. Two supplement masses are attached to the caisson, one is representing dynamic earth thrust due to liquefied backfill (m_e), and another is representing dynamic water pressure due to front water (m_w). Horizontal load (Ps), which is a combined force of hydraulic pressures of seawater (Pws) and static load from liquefied backfill (Pes), is applied on the caisson. At the boundary between bottom of the caisson and ground surface, a slider element is attached. Shear strength (Sr) of the slider element can be decided from friction angle between caisson and ground and vertical forces of caisson's weight and buoyancy force.



Fc FInertia force of the caisson
Pes FStatic load from liquefied backfill (Pes$_L$ plus initial lateral stresses)
Ped FDynamic earth thrust
Pws FStatic lord by hydraulic pressure
Pwd FDynamic water pressure
Wc FWeight of the caisson
U FBuoyancy force of the caisson
Sr FShear strength between the bottom of the caisson and rubble mound
@ @ @Sr (Wc ΨU)¥tan ϕ_c
ϕ_c FFriction angle between bottom of the caisson and rubble mound

α g FInput motion
α c FResponse acceleration of the caisson
mc FMass of the caisson
@ @ @ @c ϸmc¥ α c
me FSupplement mass representing dynamic earth thrust
@ @ @ @ed ϸme¥ α c
mw FSupplement mass representing dynamic water pressure
@ @ @ @wd ϸmw¥ α c
Ps FTotal load of Pes and Pws
@ @ @ @s Pes ϷPws
Sr FShear strength of the slider
δ c FRelative displacement between the caisson and the ground

Figute-10: Simplified model to evaluate caisson's sliding

Input motions are input from the ground to the caisson through the slider element. Inertia force of the caisson and supplement masses are generated due to excitation. Sliding occurs at the time when the total force exceeds shear strength of the slider element. Since the time history of total force acting on the caisson shifts toward positive direction (sea side) due to the static load (Ps), displacement of the caisson accumulates toward sea as shown in Figure-11.

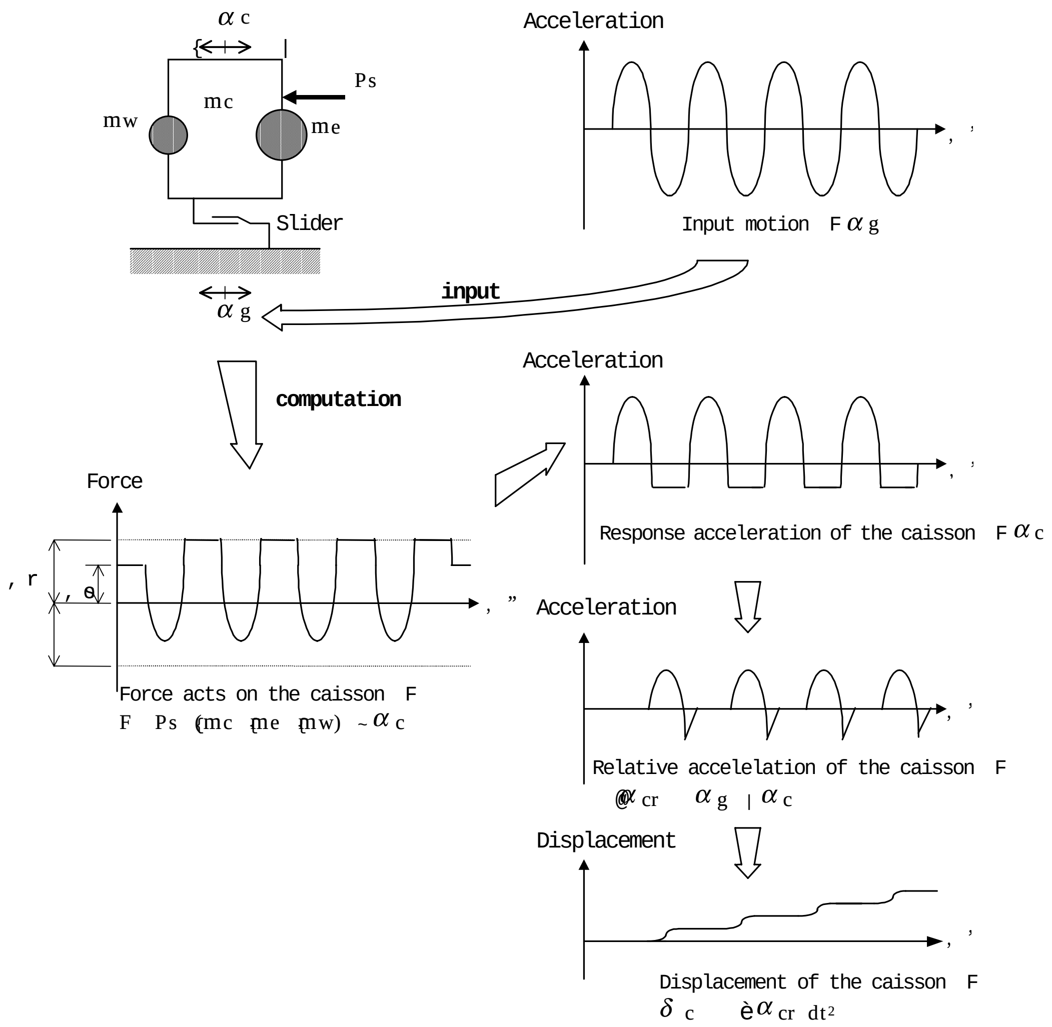
Simulation on Centrifuge Test

Simulations on the centrifuge tests were performed by using the proposed method. Supplement masses, m_e and m_w, were calculated by Equation (1) which was transformed from Equation (2) [Westergaard, 1933].

$$m = P \cdot \frac{g}{\alpha} = \frac{7}{12} \cdot \gamma \cdot H^2 \tag{1}$$

$$P = \frac{7}{12} \cdot \frac{g}{\alpha} \cdot \gamma \cdot H^2 \tag{2}$$

supplement masses are attached to the caisson, one is representing dynamic earth thrust due to liquefied backfill (m_e), and another is representing dynamic water pressure due to front water (m_w). Horizontal load (Ps), which is a combined force of hydraulic pressures of seawater (Pws) and static load from liquefied backfill (Pes), is applied on the caisson. At the boundary between bottom of the caisson and ground surface, a slider element is



Figute-11: Proposed method to evaluate caisson's sliding

attached. Shear strength (Sr) of the slider element can be decided from friction angle between caisson and ground and vertical forces of caisson's weight and buoyancy force.

Input motions are input from the ground to the caisson through the slider element. Inertia force of the caisson and supplement masses are generated due to excitation. Sliding occurs at the time when the total force exceeds shear strength of the slider element. Since the time history of total force acting on the caisson shifts toward positive direction (sea side) due to the static load (Ps), displacement of the caisson accumulates toward sea as shown in Figure-11.

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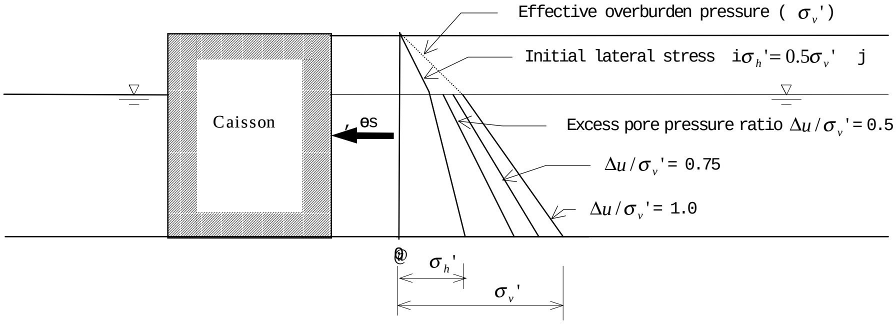
$$P = \frac{7}{12} \cdot \frac{g}{\alpha} \cdot \gamma \cdot H^2 \qquad (2)$$

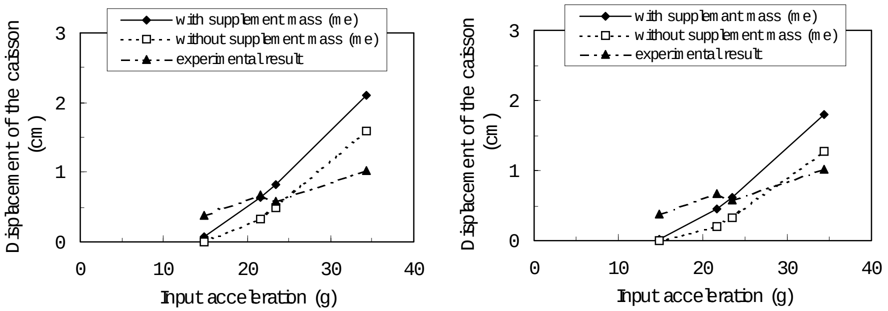
where m is supplement mass (m_w or m_e), P is total force of dynamic water pressure (for m_e; dynamic earth thrust), g is gravity in centrifuge test (50 times of 980cm/sec^2), α is response acceleration of the caisson, γ is unit weight of the water (for dynamic lateral thrust; unit weight of the saturated soil), and H is depth from the water surface. In the simulations, two types of models were prepared, one with supplement mass m_e and another without m$_e$. The friction angle of the slider was assumed $\phi = 42°$, which is the internal friction angle of well-compacted coarse sand for the rubble mound. Total stress of the static lateral stress and the excess pore water pressure in backfill (Pes) were supposed as in Figure-15, then four values of Pes, corresponding to excess pore pressure ratios of 0%, 50%, 75% and 100% respectively, were assumed.

Computed residual displacements of the caisson are compared with the experimental results in Figure-13. Effects of the supplement mass (m$_e$) is fairly large in the computation. Computed displacements increase according to the input motion level, though, increasing late of the numerical results is larger than that of the experimental results. Regarding such a difference, it is supposed that the actual friction angle between caisson and ground might be smaller than the assumed value. It could be a reason why the computed displacements at

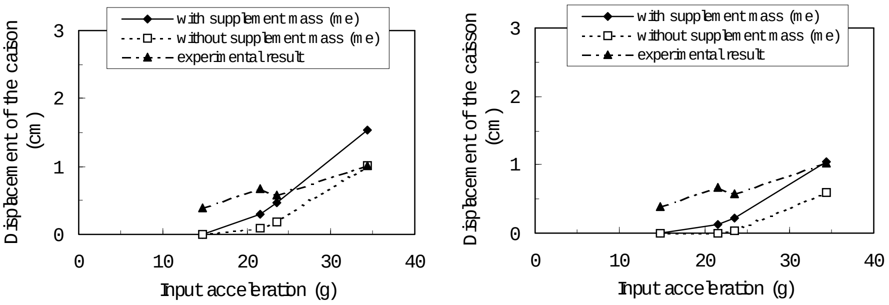
ow input motion level were smaller than the test results, in spite of the proposed method seems to have a tendency to give conservative results because of its assumptions, for example, liquefaction is assumed to have generated from the beginning of the excitation, and another, dynamic thrust due to backfill is assumed to be completely proportional to inertia force, although actual relationships between these two forces display flattened loops as shown in Figure-7. In the case of large input motions, it is considered that the influences of caisson's rocking, which could restrain the sliding of the caisson due to deformation or partial failures of the mound, became larger in experiments. Furthermore, volumetric expansion of the backfill could restrain caisson's sliding also. It might be a reason why computed displacements using internal friction angle of rubble mound ($42°$) for slider's friction angle are rather similar to the experimental results in the cases of high input motion levels.



Figute-12: Total load of lateral stress from backfill



(a) Exess pore pressure ratio :100%　(b) Exess pore pressure ratio :75%



(c) Exess pore pressure ratio : 50%　(d) Exess pore presure ratio :0%

Figute-13: Comparison of the calculated residual displacements of the caisson with experimental results

CONCLUDING REMARKS

The mechanism of the movement of caisson type quay wall with reclaimed ground was investigated from the results of centrifuge model vibration tests, then a simplified method to evaluate the amount of caisson's movement was proposed.

According to the results of the experiments, sliding of caissons occurred only during excitation. In the case where the ground just below the caisson is very thick, or in the case when the extremely large level of excitation is applied, the possibility of post-excitation displacements of caissons might not be denied, however, it seemed to be impossible to predict the displacement of caisson and the deformation of back-fill ground but for taking account of both inertia force of caisson and dynamic earth pressure from backfill, which changes depending upon characteristics of the input motions and liquefaction potentials .

A simplified analytical model for evaluating the amount of caisson's sliding when the backfill was liquefied was conceived. In the model, a lumped mass explaining caisson and supplemental masses explaining dynamic earth and water pressures were attached on the slider element which could express the sliding between the caisson and base ground. In the calculation of sliding, concentrated forces which explain static earth pressure and risen up excess pore water pressure were applied to the lumped mass, then dynamic wave was input through the slider element. Simulations of experimental results were performed in order to investigate the sensitivities of each parameters and the validity of the model to the actual structures. Through the simulations, quantitative evaluations on the sliding of caissons seemed to be possible by using the proposed model considering the characteristics of input motions and the liquefaction potentials of backfill.

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