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Dynamic behavior of semigravity type offshore structure

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ABSTRACT:Investigations were conducted on the response characteristics of new semi-gravity type offshore structures during large earthquakes. These are rational and economic structures designed under a new concept allowing the structures to slide within a range that would not jeopardize their functions during large earthquakes. A number of underwater sliding tests were conducted and further investigations were made through analyses. It was confirmed through these tests and analyses that the response acceleration, hydrodynamics pressure and sliding displacement of the structures could be predicted if the sliding resistance of the ground could be evaluated accurately. In the test calculations the sliding displacement remained within several tens of centimeters even under large earthquakes, a result that takes the semi-gravity type offshore structures a step further towards reality.

1. INTRODUCTION

While there are all kinds of offshore structures, it is possible to classify them largely into floating and non-floating types. The floating type structures are relatively free of the effects of earthquakes, but their use is restricted by problems over their stability as they are subject to movements due to waves and winds, as well as movements with the tides. The non-floating type structures, on the other hand, though they are subject to the effects of earthquakes, are stable as they are in contact with the seabed and are comfortable to live and work on and easy to operate when used, for example, as offshore hotels, industrial plants and leisure facilities.

Of the non-floating type offshore structures, gravity type structures are used for a large number of purposes (e.g. as oil rigs) because of the possibility of making effective use of the space inside them. Normal gravity type structures, however, will slide much more easily than structures on land when subjected to seismic forces, since they are subject to hydrodynamics pressure in addition to the inertia force acting on them, while the contact pressure is reduced by buoyancy. Measures are taken to counter these problems, for example, by increasing the weight of the structures by increasing the number of ballasts, but this leads to further problems, such as increased costs and, in the case of structures on soft seabed, the need for measures against settlement.

In view of these circumstances, the authors have developed the concept of "semi-gravity type offshore structures," which allows the structures to slide within the range that would not jeopardize their functions.(1) These semi-gravity type structures will not slide under external forces due to waves and winds during typhoons and under seismic forces up to around 100 gals, but a certain amount of sliding is allowed under large seismic forces exceeding 100 gals. This provides a kind of isolation system, as the structure is out of contact with the seabed while it is in sliding motion and the seismic forces are not transmitted to the structure. Rational and economic design is made possible by the decrease in the seismic forces acting on the structures and decrease in the contact pressure, which removes the need for large-scale ground improvement even on soft seabeds.

The seismic response behavior of the sliding semi-gravity type offshore structures is expected to be complex because of the combination of such factors as the hydrodynamic pressure and the interaction of the structure with the seabed, as well as the inertia force acting on the structure. Past studies on the mechanism of sliding include that on rigid body sliding on dams by Newmark et al.(2) and that on the vibration characteristics using rigid body models by Fujino et al.(3) Yamamoto et al.(1) and Fujii(4) have conducted seismic response analyses involving sliding on offshore structures. A large number of studies have also been conducted on strict solutions based on the potential theory and approximate solutions concerning hydrodynamic pressure at times of earthquakes with regard to wall-shaped structures,(5) columnar structures,(6) cylindrical structures,(7), plane symmetrical structures(8) and submerged cylinders,(9) but there are only a few studies concerned with the hydrodynamic pressure on sliding underwater structures including those by Uwabe(10) and Kanaya.(11)

In the study reported below, underwater sliding tests were carried out to examine the sliding behavior of semi-gravity type offshore structures during earthquakes and comprehensive investigations were made on the same behavior through analysis, to confirm the feasibility of the semi-gravity offshore structures as a new concept.

2. EXPERIMENTAL STUDIES

2.1 SUMMARY OF EXPERIMENTS

The underwater vibration experiments conducted are listed in Table 1. The structure used was a rigid cylinder and the experiments were carried out on rigid and elastic ground. The purpose of the experiments on elastic ground was to examine the vibration characteristics when the structure was subject to a rocking motion due to the flexure of the ground. The purposes of the experiments were as follows.

Experiment A: assessment of the hydrodynamic pressure distribution when there is no sliding
Experiment B: assessment of the hydrodynamic pressure distribution when rocking motion prevails
Experiment C: assessment of the hydrodynamic pressure, response acceleration and sliding displacement under translational sliding
Experiment D: assessment of hydrodynamic pressure, response acceleration and sliding displacement under a combination of sliding and rocking

For the representation of the ground and the fluid system, as the motion of fluids predominated, such factors as the dimensions of the model, excitation conditions and the elasticity coefficient of the ground were determined using Froude's laws of similitude for the 1/100 model.

2.2 METHODS AND CONDITIONS

(1) Apparatus and Measurement Items

The small vibration device used in the underwater vibration tests is shown in Figure 1. The water tank was 2 m by 2 m by 0.7 m, with glass on all sides. The removable vibration ground on which the test piece was installed could be fixed with bolts. A rigid, model seabed conforming to the surface of the ground was installed in the tank during the underwater vibration tests. The model seabed was given a structure that would transmit the compression waves generated by the vibration of the vibration table and the ground model through the bottom of the tank to the edges of the tank where they would not affect the test results. Wave absorbers were installed around the tank to prevent the reflection of scattering waves on the water surface.

Minute acceleration and pressure gauges were used for the measurement of the acceleration on the ground surface and the model and the hydrodynamic pressure acting on the surface of the cylindrical model. The measurement positions are shown in Figure 2. The sliding displacement of the model was calculated by numerical integration of the acceleration wave forms, while the cumulative sliding displacement was measured using no-contact type displacement gauges and high-speed video cameras.

(2) Test Conditions

Horizontal sinusoidal waves were used as the input acceleration waves into the vibration table. Taking into account the predominant frequencies in actual earthquakes, the excitation frequency was made to vary within the 4 to 20 Hz range in accordance with Froude's law. The excitation acceleration was made to vary between 100 and 700 gals in correspondence with the resistance ratio of sliding at the bottom of the model and in the ground.

Waterproof sandpaper was attached to the contact faces of the model and the ground to ensure the resistance ratio of sliding (friction coefficient) would be constant during the experiments. The static and dynamic sliding ratios of sliding of the sandpaper had been measured in advance.

2.3 RESULTS

(1) Experiment A

In this experiment, the model was fixed to the rigid ground and investigation was made on how the distribution of the hydrodynamic pressure acting on the cylindrical model would correspond with the equations proposed in the past. Although the wave forms are not shown, the inertia force acting on the model can be regarded as being in phase with the hydrodynamic pressure and it was observed that the hydrodynamic pressure distribution shown in Figure_ 3 agreed closely with the equation proposed by Goto and Toki.(8)

(2) Experiment B

In this experiment, the model was fixed to the elastic ground and investigation was made on the hydrodynamic pressure distribution when the model was in rocking motion. The response acceleration of the model and hydrodynamic pressure distribution are shown in Figure 4. While the response acceleration is large at the top of the model in correspondence with the rocking mode, when the response acceleration at each point is taken as the reference value and applied to the equation proposed by Goto and Toki, it can be seen that there is a close agreement with the equation in this experiment also. Only, it is to be noted that the values observed are smaller than the theoretical values at 4 Hz. This is thought to be due to the effects of the scattering waves.

(3) Experiments C and D

Observation was made on the response characteristics when sliding occurred on rigid and elastic ground. The measurement results for the response acceleration wave forms and dynamic pressure wave forms are shown in Figure 5. The dynamic pressure wave forms correspond well with the response acceleration of the model, and it was observed that there was a tendency for the wave forms to approach a rectangular shape, the tops of the waves being flattened out when sliding occurred.

Under water, contact pressure is reduced by the buoyancy acting on the model, while hydrodynamic pressure is also in action. The acceleration at which sliding commences and the acceleration during sliding can therefore be represented by the following equation.

The response acceleration of the model is shown against the ground acceleration in Figure 6. The results of vibration tests conducted in air are shown together in the figure. The acceleration at which sliding begins under water has been reduced from around 500 gal to 200 gal, giving a clear indication of an isolation effect. Although, before sliding began, the acceleration increased as one moved up the model because of the effect of rocking on elastic ground, once sliding began, the rocking component decreased, reducing the difference in acceleration between the top and bottom of the model.

3. ANALYTICAL STUDIES

3.1 METHODS

When designing offshore structures that are allowed to slide, there is a need to predict the amount of sliding under the seismic waves expected at the proposed construction site and to check that the amount of sliding is kept within the permissible range. Dynamic non-linear analysis is required in analyzing sliding. The following two analyses were conducted.

a. Rigid body sliding analysis: The structure and the ground are assumed to be rigid bodies. Only Coulomb friction force acts on the contact face and the interaction with the ground is not taken into account.
b. Non-linear FEM analysis: The structure and the ground are represented by FEM models. The contact face is represented by a non-linear connection element and the interaction with the ground is taken into account.

Comparative analysis was first carried out for comparison between these two analysis methods to examine the dynamic interaction between the ground and the structure. A detailed account of the results are given below. It should be noted at this point that at least for the amount of sliding similar results were obtained under the conditions used on this occasion. An attempt was then made at simulation of the results of the sliding tests discussed above by a relatively simple rigid body sliding analysis.

3.2 COMPARISON OF TWO METHODS

The rigid body sliding model and non-linear FEM model are shown in Figures 7 and 8, respectively. The non-linear spring characteristics at the contact face are shown in Figure_ 9. The spring along the direction of the sliding is set so that sliding motion begins when the static friction force is exceeded and dynamic friction force comes into effect while the structure is in motion. For the input seismic motion, El Centro waves were used and the horizontal and vertical acceleration at the surface of the seabed was set at 200 and 100 gals, respectively. In the case of the rigid body sliding model, these waves were inputted unaltered. In the case of the non-linear FEM model, the input waves were obtained by deconvolution in a free field and inputted at the bottom of the model.

The analysis results are shown in Figure_ 10. While there are differences in the response characteristics of the structures because of the effects of the interaction between the ground and the structure and the effects of the vertical seismic motion, the effects as observed in the cumulative displacement are not so large, indicating that the rigid body model would be adequate at least for evaluation of the sliding displacement.

3.3 SIMULATION ANALYSIS

A simulation of the sliding experiment was carried out to verify the validity of the analysis method. The experiment simulated was the sliding experiment on rigid ground, and the analysis method used was the rigid body sliding analysis. The measurement wave forms on rigid ground were used for the input waves into the analysis model.

An example of the analysis results is compared with the test results in Figure 11. The points at which sliding begins were more or less the same and similar results were obtained for the cumulative displacement. As regards the acceleration wave forms of the structure, the thin, hair-shaped waves observed at the transition from static to dynamic friction when sliding begins have disappeared and the waves become completely rectangular. The experiment values also approach rectangular shapes, but the rectangles are irregular as the friction conditions are not completely in accordance with theory. It can be seen from the above results that the experiments can be simulated with rigid body sliding models when the friction conditions at the contact face are known.

4. CONCLUSION

Investigations were conducted on the response characteristics of new semi-gravity type offshore structures during large earthquakes. These are rational and economic structures designed under a new concept allowing the structures to slide within a range that would not jeopardize their functions during large earthquakes. A number of underwater sliding tests were conducted and further investigations were made through analyses. It was confirmed through these tests and analyses that the response acceleration, hydrodynamic pressure and sliding displacement of the structures could be predicted if the sliding resistance of the ground could be evaluated accurately. In the test calculations the sliding displacement remained within several tens of centimeters even under large earthquakes, a result that takes the semi-gravity type offshore structures a step further towards reality.

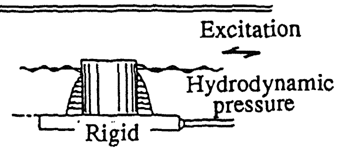
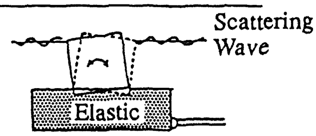
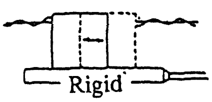
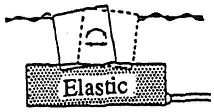
There is need now to conduct further investigations on various mechanisms of sliding resistance on the seabed and on the applicability of the concept to the deep underwater.

References

1)Yamamoto,H., Kimura,T., Hirashima,S., and Ohta,T., :New aseismic design method of offshore gravity structure in highly seismic regions, 5th International Offshore Mechanics and Arctic Engineering Symposium, 1986, pp693-700.
2)Newmark,N.M. : Effects of Earthquakes on Dams and Embankments, Geotechnique, Vol.15, No.2, Jan.1965.
3)Fujino,Y., Sasaki,Y., Hakuno,M. : Sliding Characteristics of Structure during Earthquakes, Trans. of Eathquake Inst. of Tokyo Uni., Vol.53, 1978, pp461-480.
4)Fujii,S., : Sliding Behavior of Offshore Plant

Structure during Eathquakes, ; Doctor thesis of Tokyo Uni., April, 1988.
5)Westergaad,H.M. ; Water pressures on dams during earthquake, Proc. of ASCE, No.1835, 1931, pp418-472.
6)Sakurai,A., : Vibration Behaviors of Colum Structure in water, Civil Engineering, Vol.16, No.6, 1961, pp11-17.
7)Goto,H.,Toki,K., : Fundamental studies on vibration characteristics and aseismic design of submerged bridge piers, Trans. of JSCE,No.100,1963,pp1-8.
8)Kiyokawa,T.,Kobayashi,H., ; Hydrodynamic pressures and added mass of plane symmetrical structures, Proc. of JSCE, No.321, 1982, pp79-90.
9)Kiyokawa,T., Tanaka,M., Kobayashi,H., : Hydrodynamic pressures and added mass of submerged structures, Proc. of Coastal Engineering, JSCE(29th), 1982, pp457-461.
10)Uwabe,T.,Higaki,N., : An experimaental study on sliding block in water during earthquake, Report of the Port and Harbour Research Inst. Vol. 23, No.3, 1984, pp154-186.
11)Kanatani,M.,Nishi,K.,;Shaking table tests on sliding of structure in the water during earthquake, Proc.ofJapan national Conf.on Soil Mechanics and Foundation Engineering,1988,pp983-984.

Table.1 Underwater shaking table test

Experiments	Schematic diagram
Experiment A: No-sliding, Swaying Mode	
Experiment B: No-sliding, Rocking Mode	
Experiment C: Sliding, Swaying Mode	
Experiment D: Sliding, Swaying+Rocking	

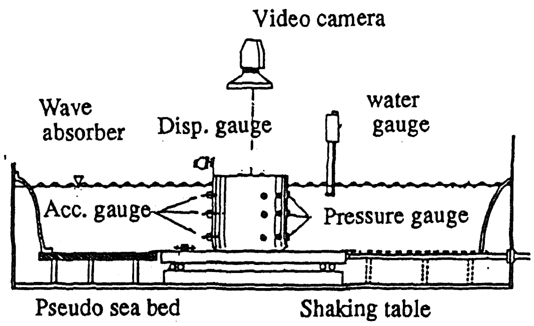


Fig. 1. Underwater Shaking table test devices

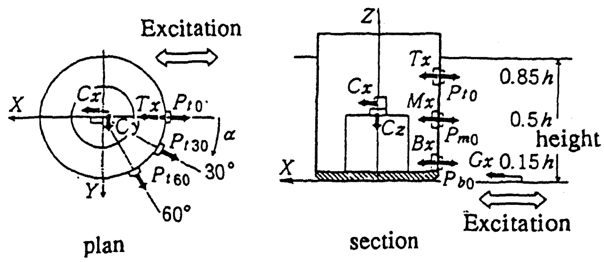


Fig.2. Measuring points of model

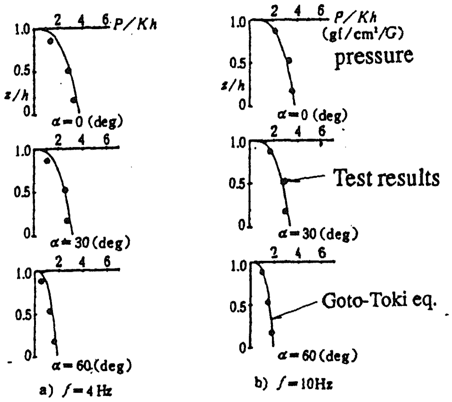


Fig.3. Distributions of Hydrodynamic Pressures around Cylinder Model

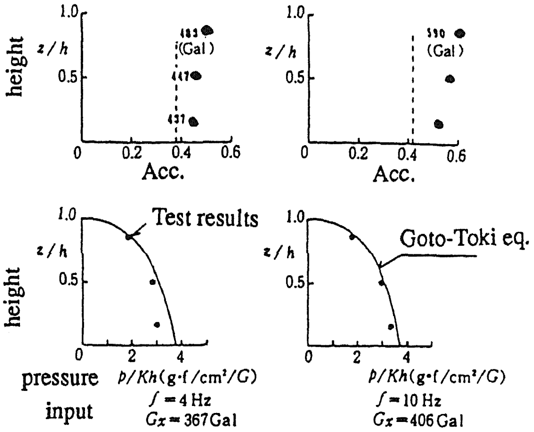


Fig.4. Distributions of Acc. and Hydrodynamic pressures around Model

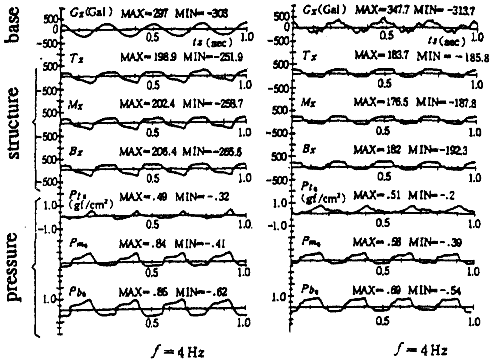


Fig.5. Response Acc. and Hydrodynamic pressures wave forms

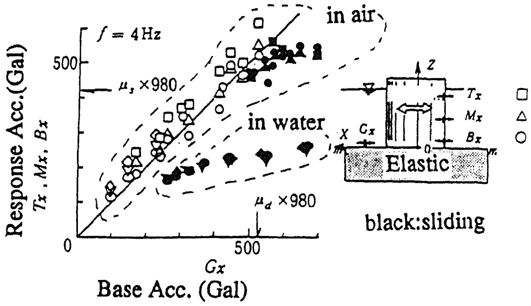


Fig.6. Comparison of Acc. in water and in air

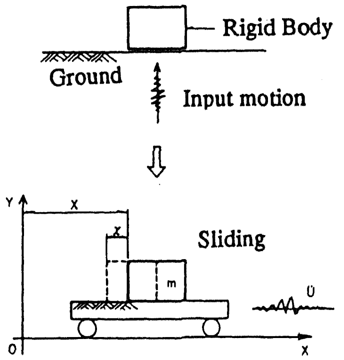


Fig.7. Modeling of Rigid body Sliding Analysis

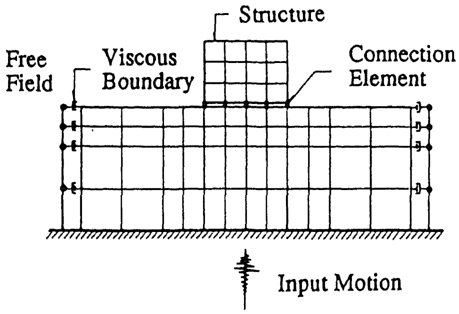


Fig.8. Modeling of Nonlinear Dynamic FEM analysis

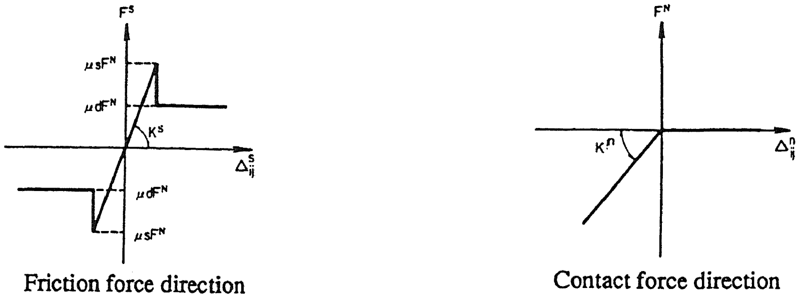


Fig.9. Nonlinear Spring Constants

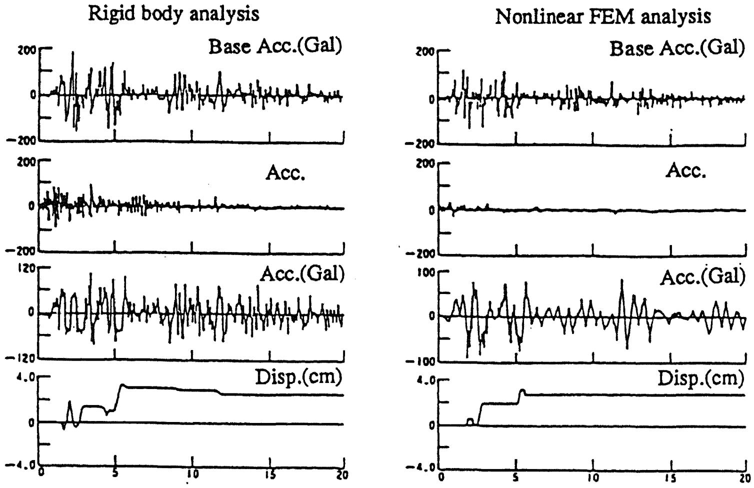


Fig.10. Comparison of Response Wave forms in Rigid body analysis and nonlinear FEM analysis

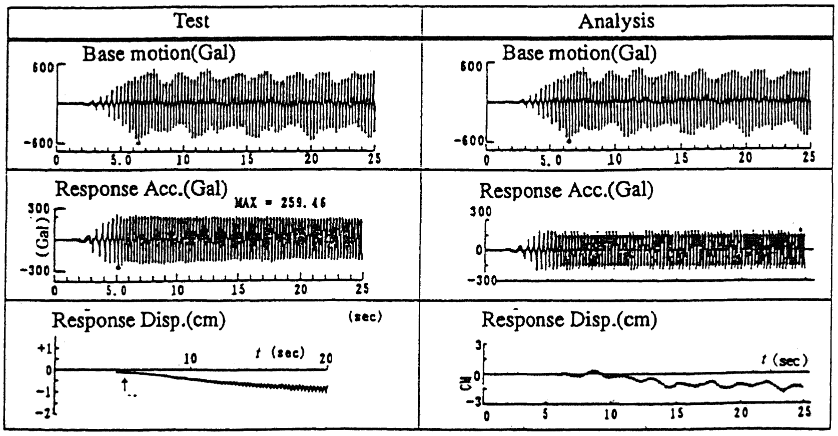


Fig.11. Comparison of Response Wave forms in test and analysis