International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

2001 - Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

Mar 26th - Mar 31st

Analytical Evaluation for Seismic Behavior of Shore Structures on Liquefied Area During Earthquakes

Kenji Hayashi
Chuo Fukken Consultants Co., Ltd., Japan

Tomonari Imono
Chuo Fukken Consultants Co., Ltd., Japan

Tamotsu Matsui
Osaka University, Japan

Kazuhiro Oda
Osaka University, Japan

Hitoshi Miyamoto
Osaka University, Japan

Recommended Citation

Hayashi, Kenji; Imono, Tomonari; Matsui, Tamotsu; Oda, Kazuhiro; and Miyamoto, Hitoshi, "Analytical Evaluation for Seismic Behavior of Shore Structures on Liquefied Area During Earthquakes" (2001). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 10.
http://scholarsmine.mst.edu/icrageesd/04icrageesd/session07/10

ANALYTICAL EVALUATION FOR BEHAVIOR OF SHORE STRUCTURES ON LIQUEFIED AREA DURING EARTHQUAKES

Kenji Hayashi, Tomonari Imono
Chuo Fukken Consultants Co. Ltd.
Osaka, Japan

Tamotsu Matsui, Kazuhiro Oda and Hitoshi Miyamoto
Osaka University
Osaka, Japan

ABSTRACT

In this paper, focusing on the caisson type quay wall, which is a typical gravity type of shore structures, the seismic behavior of the structures was discussed when the liquefaction occurs, by applying the dynamic response analysis and a simplified prediction method which was proposed by the authors. Firstly, a simplified and reasonable method for predicting the seismic behavior of shore structures during earthquakes was proposed. In the proposed analytical method, the structure is replaced by a simplified model, and the ground contacting the structure by subgrade springs. There are two types of subgrade springs employed as elasto-plastic spring and liquefied spring. Secondly, the seismic behavior of shore structures in liquefied areas was evaluated through case study by dynamic response analysis. As the result, it was elucidated that the residual horizontal displacement of structures depends on the maximum horizontal acceleration acting at the center of structures, and the duration of earthquake motion is closely related to the residual horizontal displacement. It is also confirmed that the residual horizontal displacement of irregular seismic wave is 1/3 to 2/3 times smaller than that of regular seismic wave. After then, in order to confirm the applicability of the proposed simplified prediction method, a case study was performed to compare the result of the simplified analysis with that of the dynamic response analysis. As the result, the relationships between the horizontal acceleration at ground surface and the residual horizontal displacement by both analyses without liquefaction showed a similar trend, while those with liquefaction showed different trends, which was due to the difference of evaluating the semi-liquefaction. It was confirmed that the proposed simplified prediction method was applicable to predicting the actual seismic behavior of shore structures with good accuracy by adequately adjusting the reduction ratio of liquefied spring in the semi-liquefaction condition.

INTRODUCTION

The 1995 Hyogoken-Nambu Earthquake had caused severe damages to many structures in ports and harbors. Especially, the damage of gravity type structures such as caisson type quay wall in the shore structures was very heavy. The causes of the damage were due to the occurrence of liquefaction and the earthquake motion over the design seismic coefficient. In this paper, focusing on the caisson type quay wall, which is a typical gravity type of shore structures, the seismic behavior of the structures is discussed when the liquefaction occurs, by applying the dynamic response analysis and a simplified prediction method which is proposed by the authors, followed by confirming the applicability of the latter.

SEISMIC BEHAVIOR OF SHORE STRUCTURES DURING EARTHQUAKE

Fig. 1 schematically shows such behavior as earthquake motion, excess pore water pressure of ground and displacement of shore structures, which consists of three phases: phase 1 (before earthquake), phase 2 (during the time subjected to inertial force by earthquake motion) and phase 3 (during liquefaction). It is sure that the liquefaction after the completion of earthquake motion makes the deformation of structures increase. Therefore, such three factors as inertial force, earth pressure and liquefaction are picked up as the causes of damage to the shore structures during earthquake. It should be noted that these factors do not always occur at the same time. Each factor is explained below.

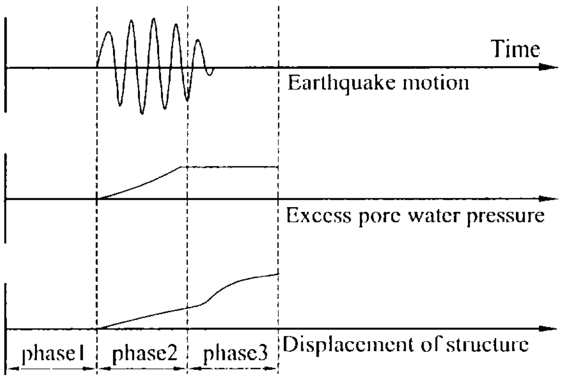


Fig. 1. Behavior of shore structures during earthquake

Inertial Force

Whenever any earthquake produces a certain acceleration, the inertial force acts on a structure both in vertical and horizontal directions. Assuming that the vertical motion of earthquake has rather small influence on the structures, the inertial force by horizontal motion has generally been adopted for the aseismic design of structures. The larger the dead weight of a structure is, the larger the inertial force acting thereon becomes. The inertial force is therefore thought to be a factor that greatly contributes to the seismic damage of the gravity type shore structures.

Earth Pressure

The lateral earth pressure acting on the structures is usually the earth pressure at rest under the static condition. During earthquakes, however, it becomes a seismic earth pressure which is larger than the earth pressure at rest. When the liquefaction occurs, it will become still larger, because the ground is changed to liquefied condition. Since, in particular, the gravity type quay wall must stand against the earth pressure, the earth pressure may become a significant factor of seismic damage to these structures.

Liquefaction

The liquefaction phenomenon is closely related to the seismic damage to shore structures. Most of the seismic deformation of shore structures is attributed to the liquefaction, either directly or indirectly. The occurrence of liquefaction generates excess pore water pressure in the ground, which will cause the shear strength reduction of the foundation ground, followed by occurring such damage as rising of structures by buoyancy, settlement of structures or lateral flow of ground. Because the liquefaction occurs with a time lag after the completion of earthquake motion, it should also be considered as a factor that keeps giving the deformation or damage to structures for a longer time. It cannot be ignored even in the case of semi-liquefaction where excess pore water pressure ratio is less than the unity.

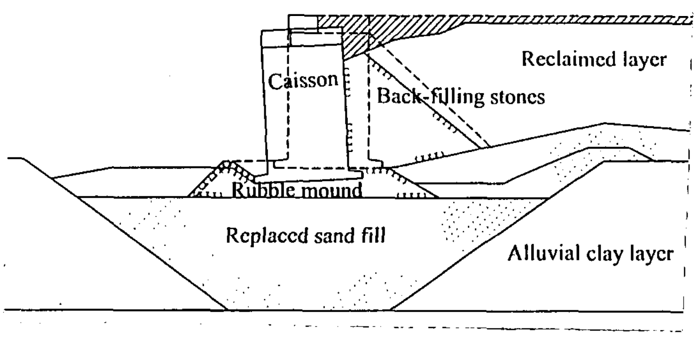


Fig. 2. Typical damage pattern of caisson type quay wall

Fig. 2 shows a typical damage pattern of the caisson type quay wall in the 1995 Hyogoken-Nambu Earthquake. The greater residual horizontal displacement was observed on caisson type quay walls located at the normal to the direction where the horizontal motion of earthquake was predominant. This fact suggests that the main cause of the horizontal displacement is the excessive inertial force and the seismic earth pressure during earthquake, together with the rise of excess pore water pressure due to liquefaction of replaced sand fills and reclaimed back fills. Since it might be possible that the replaced sand fills just beneath the caisson did not liquefy completely, it is necessary to discuss in detail damages to shore structures due to semi-liquefaction.

As mentioned above, the following causes of damage are summarized for gravity type structures such as caisson type quay walls.

(1) Inertial force resulting from horizontal earthquake motion
(2) Seismic earth pressure during earthquake
(3) Liquefied earth pressure of reclaimed back fill
(4) Shear strength reduction of replaced sand fill due to semi-liquefaction

PROPOSITION OF SIMPLIFIED PREDICTION METHOD

In dynamic response analyses, it is possible to appropriately express the seismic behavior of structure during earthquakes. However, it is complicated and cannot be used frequently in the conventional aseismic design. Therefore, a simplified and reasonable method for predicting the seismic behavior of shore structures during earthquakes is required.

In the available aseismic design method against Level 1 (small scale) seismic waves, shore structures has been examined by the allowable stress based on the conventional seismic coefficient method. However, in case where the structures are subjected to Level 2 (large scale) seismic waves like in the 1995 Hyogoken-Nambu Earthquake, it is unreasonable for the shore structures to require the same earthquake-proof ability as in the structures against Level 1 seismic waves. And also, it is indispensable to make aseismic evaluation by an index corresponding to importance of structures. Therefore, a simplified prediction method is proposed herein, which should be practical and respond to the Level 2 seismic waves.

In the proposed simplified prediction method, the structure is replaced by a simplified model, and the ground contacting the structure by subgrade springs. The simplified analysis consists

Table 1. Analytical conditions in simplified analysis

Phase	External force	Subgrade spring
1	Dead weight Earth pressure at rest	Elasto-plastic spring
2	Inertial force Dead weight Seismic earth pressure	Elasto-plastic spring
3	Dead weight Liquefied earth pressure	Liquefied spring

of three phases: phase 1 (before earthquake), phase 2 (during the time subjected to inertial force by earthquake motion) and phase 3 (during liquefaction). The deformation of structure in each phase is analyzed under the conditions of appropriate loads and subgrade springs of ground, followed by calculating the final residual deformation by summing up the deformation in three phases. Table 1 and Fig. 3 show the analytical conditions and schematic analytical models in the three phases.

As shown in Table 1, as for the external force, dead weight and earth pressure at rest are considered in phase 1, inertial force, dead weight and seismic earth pressure during earthquake in phase 2, and dead weight and liquefied earth pressure (when back fill is liquefied) in phase 3. The inertial force herein is calculated from the horizontal seismic coefficient obtained based on the maximum acceleration of horizontal earthquake motion. It is assumed that the liquefied earth pressure by the back fill acts only after the main earthquake motion. This means that the liquefied earth pressure and inertial force do not act at the same phase.

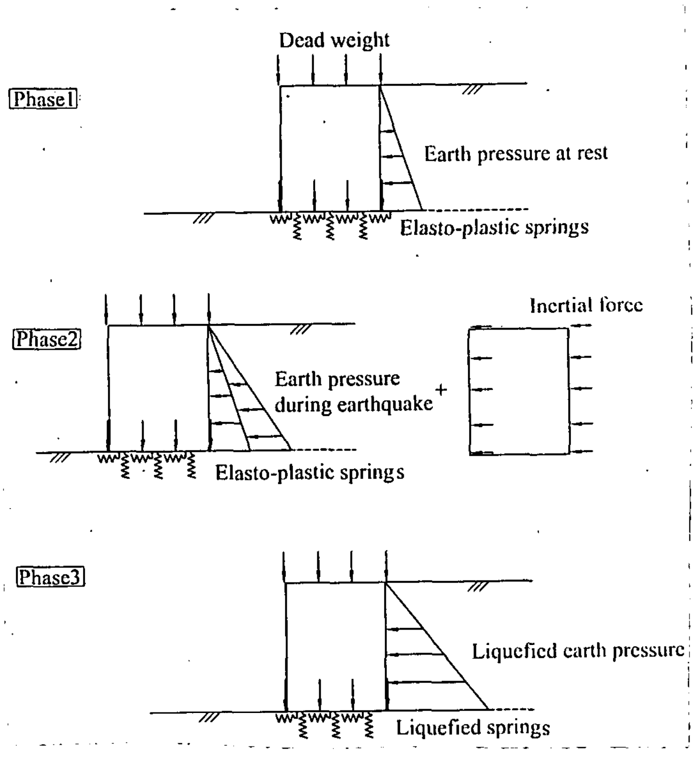
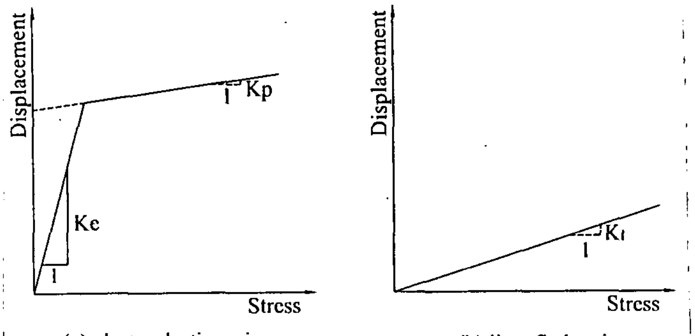


Fig. 3. Schematic analytical models in simplified analysis



(a) elasto-plastic spring (b) liquefied spring

Fig. 4. Stress-displacement relationships of subgrade springs

There are two types of subgrade springs employed as elasto-plastic spring and liquefied spring. Fig. 4 illustrates the stress-displacement relationships of the subgrade springs. The bilinear type subgrade spring for elasto-plastic condition is used in the non-liquefied grounds (phases 1 and 2), while the liquefied subgrade spring is used in phase 3. The reduced rigidity of ground due to liquefaction is changed by reducing spring constant, which is assumed to be equivalent in the vertical and horizontal directions.

The constants of subgrade springs are represented as follows:

Spring constant for plastic condition $K_p = \alpha_p \cdot K_e$ (1)

Spring constant of liquefied ground $K_l = \alpha_l \cdot K_e$ (2)

in which K_e : Constant of subgrade spring for elastic condition
α_p: Reduction ratio of yielded spring
α_l: Reduction ratio of liquefied spring

APPLICABILITY OF SIMPLIFIED PREDICTION METHOD

In this chapter, firstly, the seismic behavior of shore structures in liquefied areas is evaluated through case study by dynamic response analysis. Secondly, in order to confirm the applicability of the proposed simplified prediction method, a case study is performed to compare the results of the simplified analysis and the dynamic response analysis. It has previously been elucidated that the seismic behavior of shore structures during earthquake can be expressed with high accuracy by dynamic response analysis (Hayashi et al.[1998]).

Table 2. Analytical parameter for dynamic response analysis

	Unit weight γ (kN/m^3)	Poisson's Ratio ν	Initial shear modulus G0 (kN/m^2)	Damping constant h_{max}
Caisson	20	0.33	–	–
Reclaimed layer	20	0.33	69,000	0.24
Replaced sand fill	19	0.33	95,000	0.24
Alluvial clay layer	16	0.33	37,000	0.24
Diluvial sand layer	20	0.33	129,000	0.24
Diluvial clay layer	20	0.33	95,000	0.24

Dynamic Response Analysis

The dynamic response analysis is carried out by FLIP, which is a prediction program of liquefaction damage (Iai et al. [1992]). The objective structure for evaluating the seismic behavior is a caisson type quay wall that showed a large residual deformation in the 1995 Hyogoken-Nambu Earthquake. Fig. 5 and Table 2 illustrate the analytical model and the parameters used, respectively. The regular and irregular seismic waves with the frequency of 1Hz are used as input earthquake motion, which continues for about fifteen seconds. As for the irregular seismic wave, the seismic wave observed at a location of Port Island in the1995 Hyogoken-Nambu Earthquake is applied modifying the maximum acceleration.

Fig. 6 shows the relationships between the horizontal acceleration at the base layer and the residual horizontal displacement of structures for both regular and irregular seismic waves. As shown in Fig. 6, the residual horizontal displacement increases as increasing the input earthquake motion for both seismic waves. However, the residual horizontal displacement of irregular seismic wave is 1/3 to 2/3 times smaller than that of regular seismic wave.

Fig. 7 shows the relationships between the horizontal acceleration at the base layer and the residual settlement of structures for both regular and irregular seismic waves. As shown in Fig. 7, the residual settlement increases as increasing the input earthquake motion for both seismic waves. The residual settlement of irregular seismic wave is 1/3 to 1/2 times smaller than that of regular seismic wave.

Fig. 8 shows the relationships between the maximum horizontal acceleration acting at the center of structure and the residual horizontal displacement for both regular and irregular seismic waves. As seen in Fig. 8, the residual horizontal displacement increases as increasing the maximum horizontal acceleration for both seismic waves, showing an almost linear unique relationship for each seismic wave. Therefore, the residual horizontal displacement of structures depends on the maximum horizontal acceleration acting at the center of structures.

Fig. 9 shows the variation of horizontal and vertical displacements of structure with the elapsed time, in case where a regular seismic wave having the maximum horizontal acceleration of 200gal is input at the base layer. As shown in Fig. 9, the horizontal displacement of structure increases greatly during earthquake, while the settlement of structure increases at the beginning of earthquake motion till the elapsed time of about 10 seconds, then becomes constant during earthquake. It is clear that the duration of earthquake motion is closely related to the residual horizontal displacement.

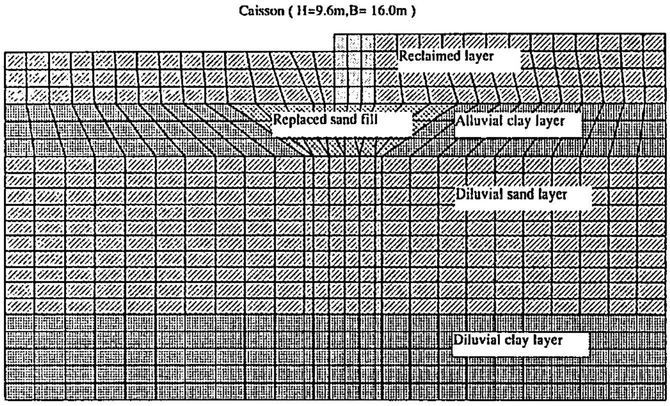


Fig. 5. Analytical model for dynamic response analysis

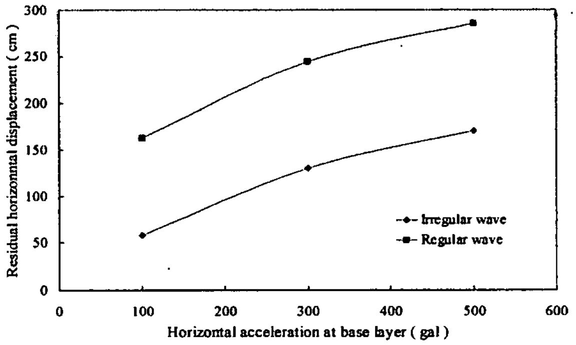


Fig. 6. Relationships between horizontal acceleration at base layer and residual horizontal displacement of structures

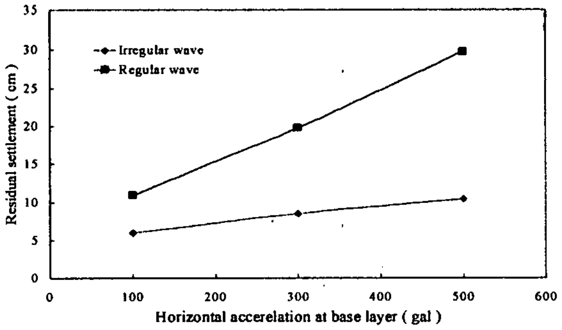


Fig. 7. Relationships between horizontal acceleration at base layer and residual settlement of structures

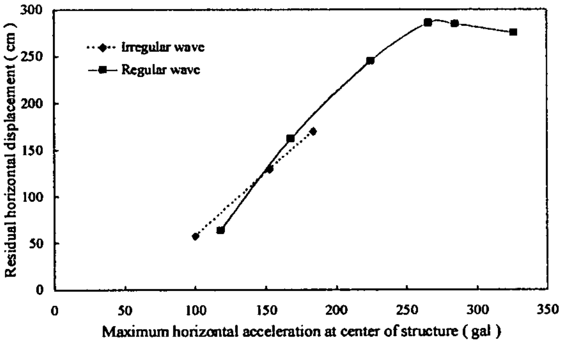


Fig.8.Relationships between maximum horizontal acceleration of structures and residual horizontal displacement

Comparison of Analytical Results between Simplified and Dynamic Response Analyses

In order to confirm the applicability of the proposed simplified prediction method, a case study is performed to compare the analytical results of the simplified analysis and the dynamic response analysis. The caisson type quay wall as shown in Fig. 5, which was used in the dynamic response analysis previously mentioned, is selected as the analytical model. Table 3 gives the analytical parameters for the simplified analysis, in which the subgrade spring constants are calculated as coefficient of subgrade reaction. The reduced spring constants both for the elasto-plastic and liquefied springs are decided based on the results of the inverse analysis of damaged case histories (Matsui et al. [1998]).

Fig. 10 shows the relationships between the horizontal acceleration at ground surface and the residual horizontal displacement both in the simplified analysis and the dynamic response analysis. The residual horizontal displacements in both analyses are illustrated for two cases, that is, the one accompanies semi- to complete liquefaction, and the other non-liquefaction. In the results of the simplified analysis, the residual horizontal displacement increases as increasing the earthquake motion at ground surface, regardless of the liquefaction occurrence. This trend is similar to the result of the dynamic response analysis.

As shown in Fig. 10, the residual horizontal displacements by both analyses without liquefaction show a similar trend, while those with liquefaction show different trends. The difference is due to the difference of evaluating the semi-liquefaction between the simplified analysis and the dynamic response analysis in the case of smaller horizontal acceleration (the range is from about 100gal to 270gal in this case). That is, the results of dynamic response analysis express the actual seismic behavior of structures with good accuracy including the semi-liquefaction condition, which is the intermediate condition between non-liquefaction and complete liquefaction. Therefore, in order to match the result of the simplified analysis with that of the dynamic response analysis, the simplified analysis must be modified considering the influence of semi-liquefaction. This modification can be easily carried out, adequately adjusting the reduction ratio of liquefied spring corresponding to the process of liquefaction.

Fig. 11 shows the relationship between the horizontal acceleration at ground surface and the logarithmic reduction ratio of liquefied spring α_l adjusted for this case study. As shown in Fig. 11, the reduction ratio of liquefied spring α_l is changed from 1.0 to 0.025 in between non-liquefaction and complete liquefaction conditions.

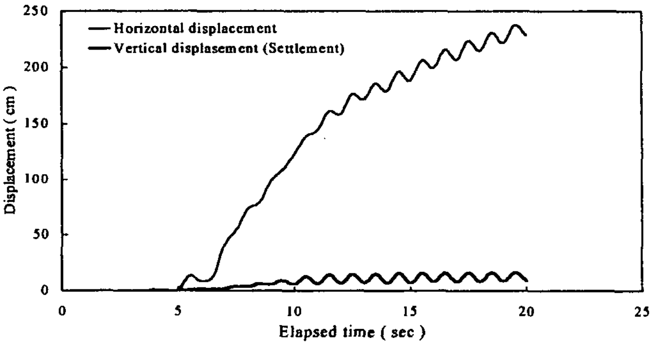


Fig. 9. Variation of horizontal and vertical displacement of structures with elapsed time

Table 3. Analytical parameter for simplified analysis

Constant of subgrade spring for elastic condition K_p (vertical)	8,958 kN/m^3
Constant of subgrade spring for elastic condition K_p (horizontal)	10,070 kN/m^3
Yield value of subgrade spring (vertical)	753 kN/m^2
Yield value of subgrade spring (horizontal)	70.3 kN/m^2
Reduction ratio of yielded spring α_p	0.0030
Reduction ratio of liquefied spring α_l	0.0250

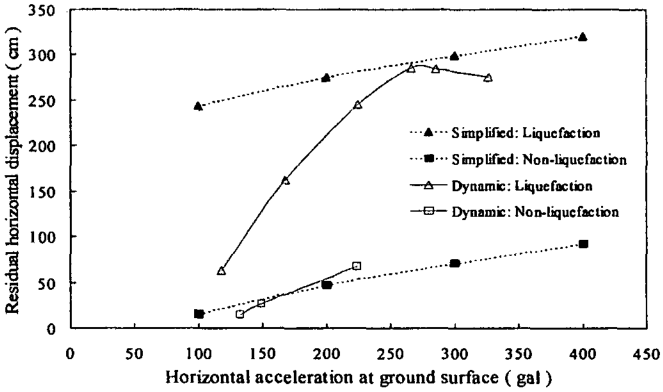


Fig. 10. Relationships between horizontal acceleration at ground surface and residual horizontal displacement

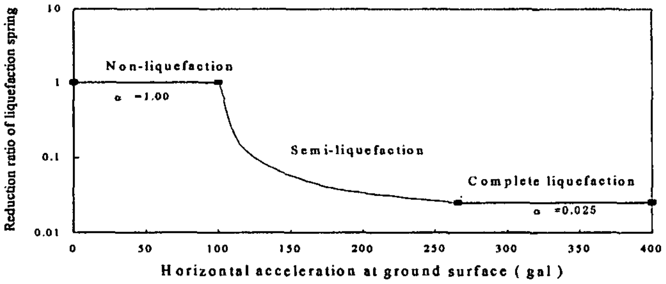


Fig.11.Relationships between horizontal acceleration at ground surface and logarithmic reduction ratio of liquefied spring

Since the simplified analysis includes the same static model as the seismic intensity method, the external force resulting from the earthquake motion is a static inertial force obtained by the horizontal seismic coefficient multiplied by the dead weight. Therefore, generally speaking, it is not easy to simulate dynamic response behavior of structures by using the static inertial force. However, the proposed simplified prediction method can be applicable to reasonably evaluate seismic behavior of shore structures on liquefied areas.

CONCLUSIONS

In this paper, focusing on the caisson quay wall, which is a gravity type of shore structures, the seismic behavior of shore structures was discussed when the liquefaction occurs, by applying the dynamic response analysis and a simplified prediction method which was proposed by the authors. Main conclusions are summarized as follows:

(1) A simplified and reasonable method for predicting the seismic behavior of shore structures during earthquakes was proposed, in which the structure is replaced by a simplified model, and the ground contacting the structure by subgrade springs.

(2) The seismic behavior of shore structures in liquefied areas was evaluated by dynamic response analysis. That is, the residual horizontal displacement of structures depends on the maximum horizontal acceleration acting at the center of structures, the duration of earthquake motion is closely related to the residual horizontal displacement, and the residual horizontal displacement of irregular seismic wave is 1/3 to 2/3 times smaller than that of regular seismic wave.

(3) As for the relationships between the horizontal acceleration at ground surface and the residual horizontal displacement both in the simplified analysis and the dynamic response analysis, the residual horizontal displacements by both analyses without liquefaction show a similar trend, while those with liquefaction show different trends. The difference is due to the difference of evaluating the semi-liquefaction between the simplified analysis and the dynamic response analysis in the case of smaller horizontal acceleration.

(4) It was confirmed that the proposed simplified prediction method was applicable to predicting the actual seismic behavior of shore structures with good accuracy by adequately adjusting the reduction ratio of liquefied spring in the semi-liquefaction condition.

REFERENCES

Hayashi, K., Matsui, T., Oda, K. and Matsumura K. [1998] Method for evaluating aseismic stability of gravity type structures, Proc. 10th Earthquake Engineering Symposium, JGS, Vol. III, pp. 3009-3014. (in Japanese)

Iai, S., Matsunaga, Y. and Kameoka, T. [1992] Strain space plasticity for cyclic mobility, Soils and Foundations, Vol.32, No.2, pp. 1-15

Matsui, T., Akakuma, M., Hayashi, K., Ishikawa, T., Nakano, T. and Imono, T. [1998] Aseismic evaluation against rare big earthquake for shore structures, Proc. 8th International Offshore and Polar Engineering Conference, Montreal, Vol. 1, pp. 610-614.