EVALUATION OF THE SEISMIC PERFORMANCE OF GRAVITY TYPE QUAY WALL USING EFFECTIVE STRESS ANALYSES

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SUMMARY

Seismic performance evaluation for the quay wall designed with a high seismic coefficient in Japanese ports are commonly conducted in these days, since the applicability of the effective stress analysis method has been verified using case histories of damage to port structures in Kobe Port during the 1995 Kobe earthquake. However, it is difficult to conduct effective stress analyses for all varieties of quay walls which may be considered during the design procedure due to the limitation of costs and time. Therefore, it is desirable to establish a simple estimation technique for deformation of quay walls.

To establish a simple estimation technique for deformation of gravity type quay walls, more than two hundreds cases of effective stress analyses with variations of seismic coefficient and liquefaction resistance are conducted. The computed deformations are verified with measured deformations of quay walls during several earthquakes in Japan and a simplified procedure is proposed to evaluate the order-of-magnitude displacement of a gravity quaywall.

INTRODUCTION

To establish a simple estimation technique for deformation of gravity type quay walls, a comprehensive parameter study is performed through the effective stress analyses, varying geotechnical and structural parameters for a gravity quaywall under various levels of seismic excitation. More than two hundreds cases of effective stress analyses with variations of seismic coefficient and liquefaction resistance are conducted in this study. This parameter study aims to achieve two objectives. One is to identify major parameters governing the seismic performance of a gravity quaywall. The other is to develop a simplified procedure for evaluating order-of-magnitude displacement of a gravity quaywall. The computer code FLIP (Iai et al, 1992) is used, which is the same computer code as used in the previous studies.

PARAMETERS CHARACTERIZING GRAVITY QUAYWALL

The factors governing seismic performance of a gravity quaywall include wall dimensions, thickness of soil deposit below the wall, liquefaction resistance of subsoil below and behind the wall, as well as levels of seismic shaking at the base layer. In this study, the soil deposit below the wall was represented by a sand backfill used for replacing the original soft clay deposit in order to attain the required bearing capacity. The effects of this soil deposit on the deformation of a gravity quaywall may be approximately the same as those of a natural sand deposit below the wall and, thus, the results of the parameter study may be applicable not only for a quaywall with sand replacement studied here but also for a quaywall constructed on a natural sand deposit.

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The standard cross section used for the parameter study is shown in Fig. 1. Major cross sectional dimensions were specified by a width (W) and height (H) of a gravity wall, and a thickness of subsoil (D1). For simplicity, the thickness of backfill (D2) was assumed the same as the wall height (H). A width to height ratio of a gravity wall (W/H) is one of the most important parameters in the conventional seismic design and correlated with the seismic coefficient used in the pseudo-static method as shown in Fig. 2. The width to height ratio (W/H) was thus considered a major parameter in this study. The parameters used in this study were W/H=0.65, 0.90, 1.05, which correspond to the seismic coefficients of K_h=0.1, 0.2, 0.25, respectively.

The peak accelerations of the input seismic excitation assigned at the base layer as incident wave (as of 2E) ranged from 0.1 to 0.6 g. The time history of the earthquake excitation was that of the incident wave (2E) at the Port Island (Kobe) vertical seismic array site at a depth of –79m. This time history, shown in Fig. 3, is often used in Japan for evaluating seismic performance of high earthquake resistant quaywalls under Level 2 earthquake motions (Ministry of Transport, 1997).

Thickness of the soil deposit below the wall (D1) was specified by a ratio with respect to the wall height (H), ranging from D1/H=0.0 (i.e. a rigid base layer located immediately below the wall) to D1/H=1.0 (i.e. thick soil deposit below the wall). For simplicity, the geotechnical conditions of the soil deposits below and behind the wall were assumed to be the same with each other, represented by equivalent SPT N-value (SPT N-value corrected for the effective vertical stress of 65 kPa). The equivalent SPT N-value has been widely used for assessment of liquefaction potential in Japanese port areas (Iai et al, 1989). Model parameters for the effective stress analysis were determined from the equivalent SPT N-values based on a simplified procedure (Morita et al., 1997). Other conditions assumed for the effective stress analysis include: wall height H=13m, water level=2m lower than the top of the wall, thickness of the rubble mound=4m, and unit weight of caisson=2.3tf/m^3.

All the analyses were performed for the plane strain condition based on finite element method. Before the earthquake response analysis, a static analysis was performed with gravity under drained conditions to simulate the stress conditions before the earthquake. The results of the static analyses were used for the initial conditions in the earthquake response analyses. The seismic analyses were performed under undrained conditions (Zienkiewicz and Bettess, 1982) to approximate the behavior of saturated soils under transient and cyclic loads during earthquakes. The input earthquake motion mentioned earlier was specified at the bottom boundary through equivalent viscous dampers to simulate a incident transmitting wave (i.e. 2E). In order to simulate the incoming and outgoing waves through the side boundaries of the analysis domain, equivalent viscous dampers were also used at the boundaries. The effect of the free field motions was also taken into account by performing one dimensional response analysis at the outside fields and assigning the free field motion through the viscous dampers.

The structures made of concrete caissons were modeled using linear elastic solid elements. The soil-structure interfaces were modeled by the joint elements. The sea water was modeled as incompressible fluid and was formulated as an added mass matrix based on the equilibrium and continuity of the fluid at the solid-fluid interface (Zienkiewicz, 1977). For more details, refer to Iai et al. (1998).

PARAMETER SENSITIVITY ON QUAYWALL DISPLACEMENT

Results of the parameter study were summarized in terms of residual horizontal displacement (d) at the top of the wall. The residual horizontal displacement was normalized with respect to the wall height (H). Effects of the major parameters on the normalized residual horizontal displacement (d/H) will be discussed below.

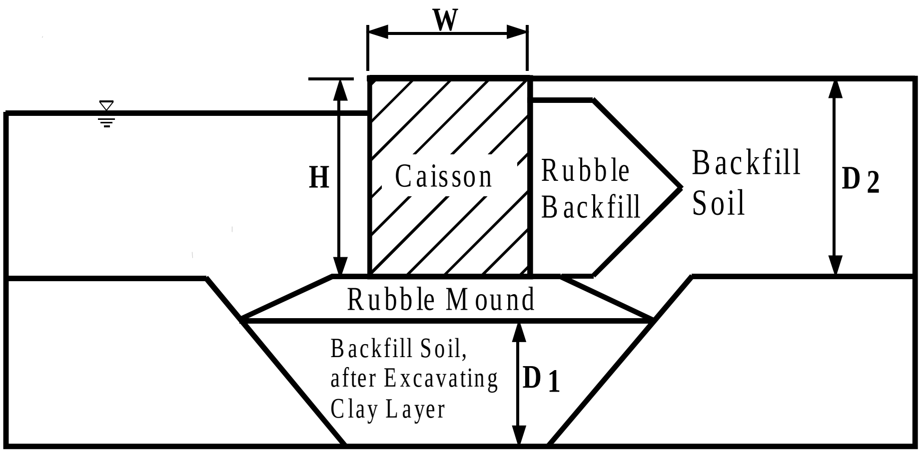


Fig.1 Typical cross section of a gravity quaywall for parameter study

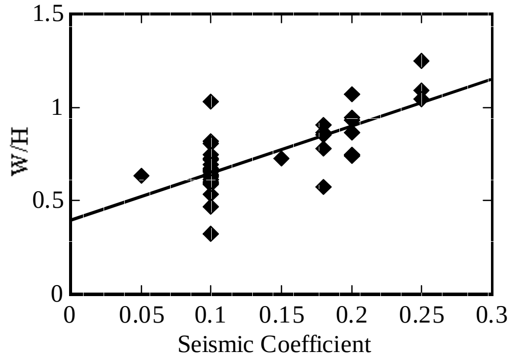


Fig.2 Correlation between the width to height ratio (W/H) and seismic coefficient of a gravity quaywall

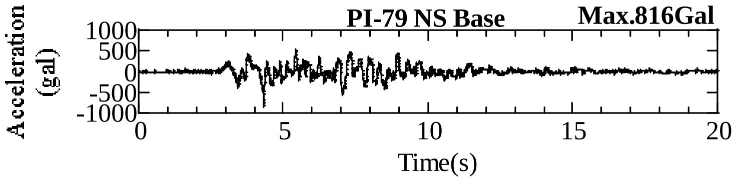


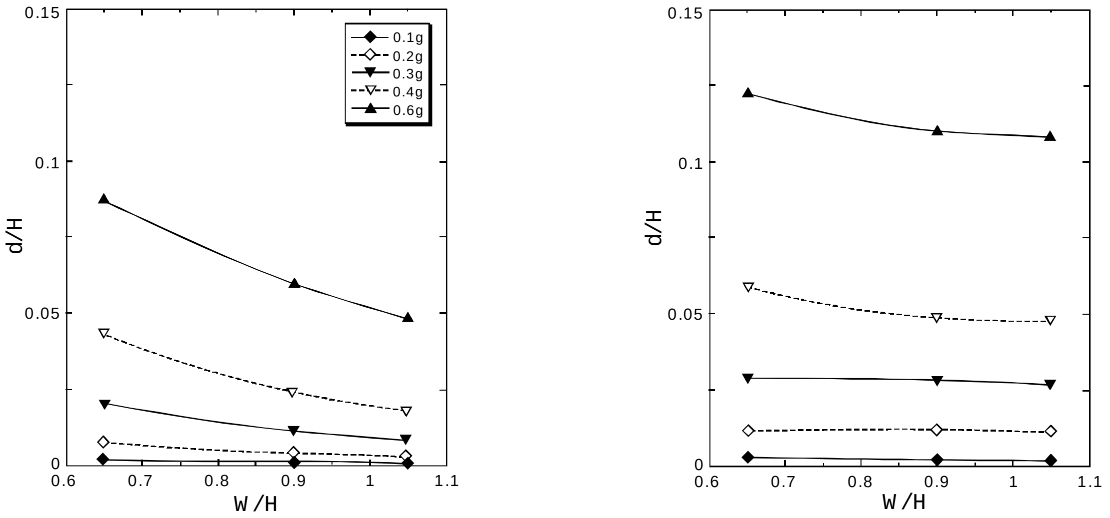
Fig.3 Time history used as input excitation (2E)

Width to Height Ratio (W/H)

Effects of width to height ratio (W/H) on the displacement are shown in Fig. 4 for equivalent SPT N-value of 15. When the foundation below the wall is rigid (i.e. D1/H=0), increasing W/H reduces the wall displacement. When the foundation soil is medium to dense (i.e. with equivalent SPT N-values of 15) and thick (i.e. D1/H=1.0), however, the effects of W/H become less obvious.

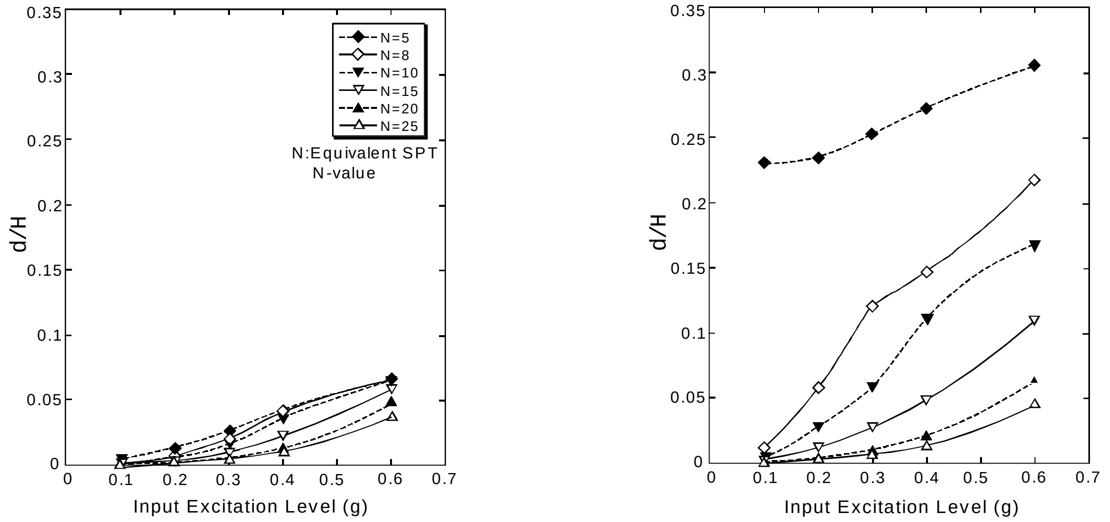
Input Excitation Level

Effects of input excitation level are shown in Fig. 5 for W/H=0.9, which corresponds to the seismic coefficient of k_h=0.2 (see Fig. 2). Except for the equivalent SPT N-values of 5 and 8, at which extensive liquefaction significantly increases the displacement, the normalized displacement for the excitation of 0.2 g at the base layer are within d/H<0.03. The horizontal displacement of a wall for d/H=0.03 is, for example, 0.3 m for a gravity quaywall with H=10 m, suggesting that the quaywall designed with the seismic coefficient of 0.2 based on the conventional pseudo-static method withstands the excitation of 0.2 g at the base layer if a margin of displacement in the order of 0.3 m is allowed.



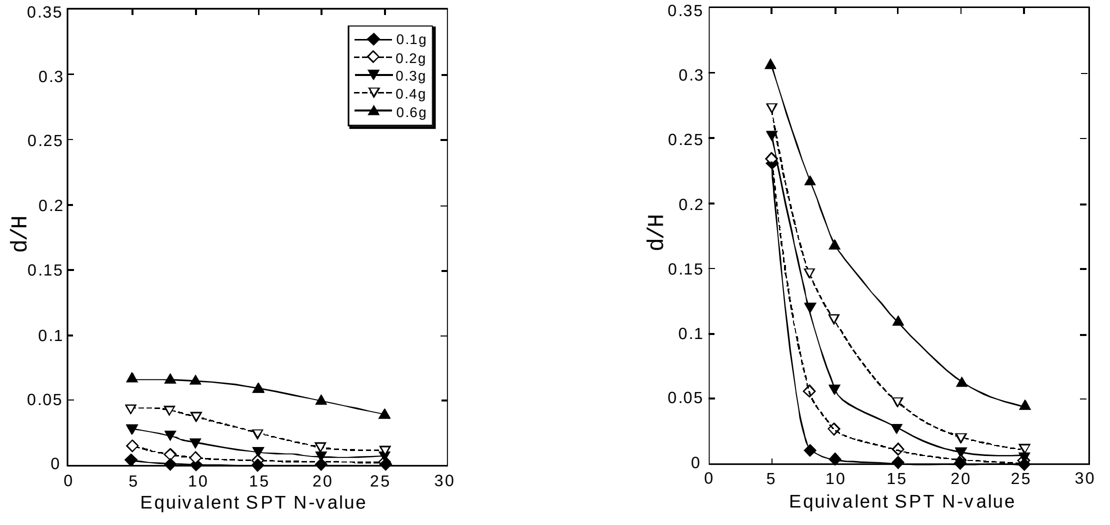
(a) D1/H=0.0 (b) D1/H=1.0

Fig.4 Effects of width to height ratio W/H (for equivalent SPT N-value of 15)



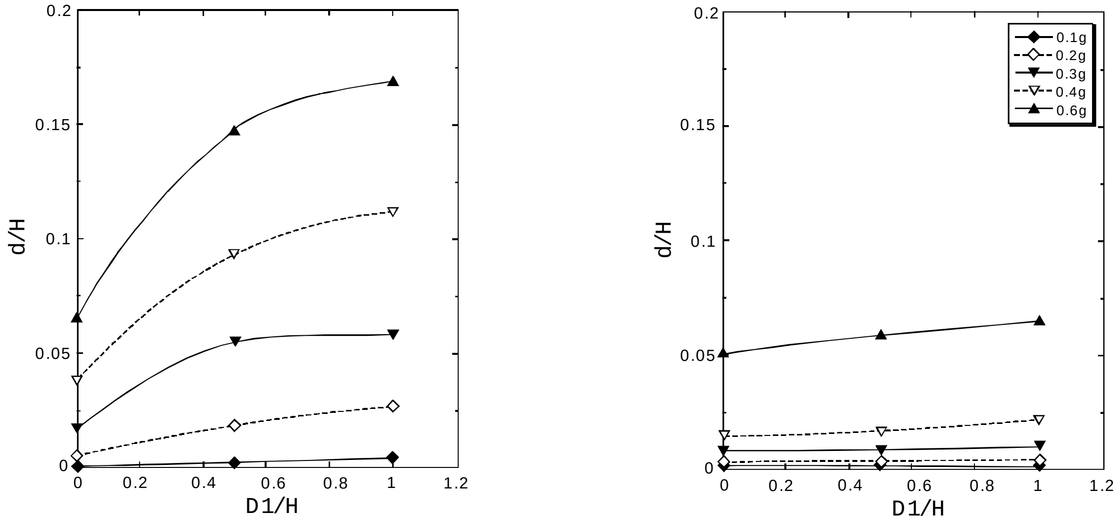
(a) D1/H=0.0 (b) D1/H=1.0

Fig.5 Effects of input excitation level (for W/H=0.9)



(a) D1/H=0.0 (b) D1/H=1.0

Fig.6 Effects of equivalent SPT N-value (for W/H=0.9)



(a) Equivalent SPT N-value (10)   (b) Equivalent SPT N-value (20)

Fig.7 Effects of thickness of soil deposit below the wall (for W/H=0.9)

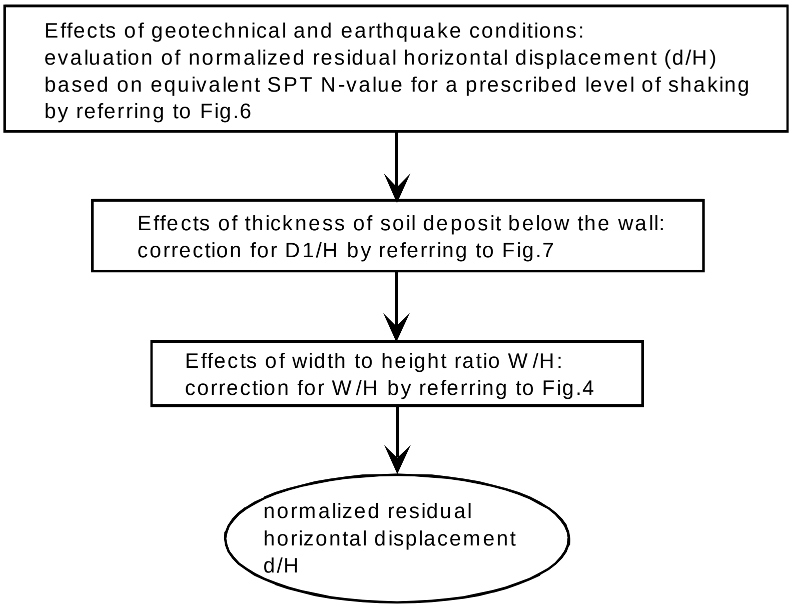


Fig.8 Flow chart for simplified evaluation of residual displacement of a gravity quaywall

Equivalent SPT N-value

Effects of equivalent SPT N-value are shown in Fig. 6 for W/H=0.9. Obviously the thickness of soil deposit below the wall significantly affects the displacement. For a wall put on a rigid foundation (D1/H=0), effects of the equivalent SPT N-value of soil behind the wall are relatively small. For a wall put on a thick soil deposit (D1/H=1.0), effects of the equivalent SPT N-values of soil below and behind the wall are significant.

Thickness of Soil Deposit below Wall

Effects of thickness of soil deposit below the wall are shown in Fig. 7 for W/H=0.9. When the level of excitation is high, significant increase in the displacement is recognized for D1/H<0.5 and for smaller SPT N-values, suggesting that the existence of soil deposit below the wall and its SPT N-values are two important factors to affect the displacement.

Overall Parameter Sensitivity

Among the parameters considered in this study, the most sensitive parameter affecting the quaywall displacement under a prescribed level of shaking is the SPT N-values of subsoil below and behind the wall. The second is the thickness of the soil deposit below the wall. Although the width to height ratio of a gravity wall is a sensitive parameter for a quaywall with firm foundation, the effects of this parameter become less obvious when the soil deposit below the wall is thick.

SIMPLIFIED PROCEDURE FOR EVALUATING WALL DISPLACEMENT

As mentioned earlier, the effective stress analysis is particularly useful for identifying deformation/failure modes and evaluating limit-state performance of quaywalls and bulkheads. The effective stress analysis, however, requires high level of engineering and reasonable amount of resources and, hence, it is not always easy to apply for routine design practice. A simplified procedure is needed for evaluating order-of-magnitude displacement in routine design practice.

Although Newmark type analysis is often adopted as a simplified procedure to evaluate earthquake induced displacement, the Newmark type analysis often underestimates displacement of those retaining structures with submerged backfill (Iai, 1998). A new procedure is needed to include the cyclic behavior of saturated soil below and behind the wall in evaluating the quaywall displacement. The results of the parameter study obtained in the previous chapter offer a basis to meet this need.

Based on the results of the parameter study shown in the previous chapter, a simplified procedure is easily developed for evaluating gravity quaywall displacement. The flow chart for the simplified procedure is shown in Fig. 8. In this procedure, the displacement is evaluated with respect to the parameters in the order of its sensitivity to the displacement.

Overall applicability of the proposed procedure was evaluated based on the case history data. Two case histories were used. One was the quaywall performance at Kushiro Port during the 1993 Kushiro-oki earthquake. A typical cross section of gravity quaywalls at Kushiro Port is shown in Fig. 9. As shown in this figure, a caisson wall was put on a firm foundation with SPT N-values ranging from 30 to 50, with a loose backfill having equivalent SPT N-values of about 5 to 10. Shaken with a peak bedrock acceleration of 0.28g, residual displacement of the caisson walls in the Kushiro port ranged from d/H=0.0 to 0.06, on the average d/H=0.02 (Iai and Mizuno, 1994).

The other was the quaywall performance at Kobe Port during the 1995 Hyogoken-Nambu earthquake. A typical cross section of gravity quaywalls at Kobe Port was shown in Fig. 10. As shown in this figure, a caisson wall was put on a loosely deposited decomposed granite. The equivalent SPT N-values for subsoil below and behind the wall were 10 on the average. Shaken with a peak acceleration of 0.55g at a depth of GL-32m, as recorded at the Port Island vertical seismic array site, residual displacement of the caisson walls having sand deposit D1/H=1.0 (for D1 ranging from 15 to 20m) ranged from d/H=0.10 to 0.30, on the average d/H=0.20 (Inagaki et al, 1996).

The order-of-magnitude displacements of a gravity quaywall were evaluated based on the major parameters relevant to these two case histories. The results are shown in Table 1. They are basically consistent with those measured, suggesting reasonable applicability of the simplified procedure. In particular, the simplified procedure demonstrated the capability to evaluate wide range of displacements, ranging from the displacement in the order of one-tenths of meters to those with one order higher.

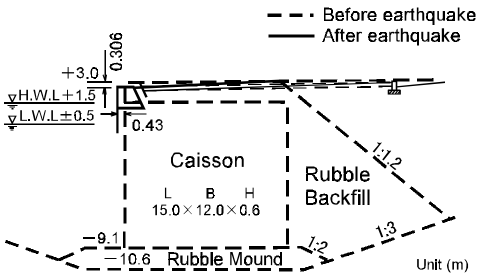


Fig.9 Cross section and deformation of a quaywall at Kushiro Port (West Port District No.2 West quaywall –9m)

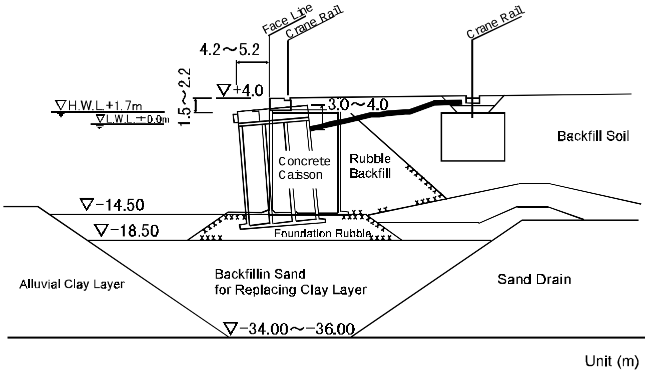


Fig.10 Cross section and deformation of a quaywall at Kobe Port (RC-5, Rokko Island)

Table 1 Simplified evaluation of residual horizontal displacements

Case Histories		
Case History	Kushiro Port, West Port District 1993 Kushiro-oki earthquake	Kobe Port, Rokko Island 1995 Hyogoken-Nambu earthquake
measured horizontal displacement at the earthquake (d/H)	d/H=0 to 0.06 on the average d/H=0.02	d/H=0.1 to 0.3 on the average d/H=0.2
Simplified Evaluation		
input excitation level	0.28 g recorded at -79m at the vertical seismic array site To be rounded to 0.3 g for simplified evaluation	0.55 g at –32m at the vertical seismic array site To be rounded to 0.6 g in simplified evaluation
equivalent SPT N-value	equivalent SPT N-values about 5 to 10 d/H=0.018 to 0.028 based on Fig. 6(a)	equivalent SPT N-value about 10 d/H=0.17 based on Fig. 6(b)
D1/H	D1/H=0 no correction needed for D1/H based on Fig. 7	D1/H=1.0 no correction needed for D1/H based on Fig. 7
W/H	W/H=1.04 to 1.09 correction factor of 0.7 to 0.8 is needed for W/H=0.9 based Fig. 4(a)	W/H=0.64 to 0.74 correction factor of 1.1 is needed for W/H=0.9 based on Fig. 4(b)
normalized horizontal displacement based on simplified procedure (d/H)	d/H=0.013 to 0.022 To be rounded to d/H=0.02	d/H=0.19 To be rounded to d/H=0.2

CONCLUSIONS

Seismic performance of a gravity quaywall was studied through effective stress analysis by varying structural and geotechnical parameters under various level of shaking. Major conclusions obtained from this parameter study are as follows.

(1) Among the parameters considered in this study, the most sensitive parameter affecting the quaywall displacement under a prescribed level of shaking is the SPT N-values of subsoil below and behind the wall. The second is the thickness of the soil deposit below the wall. Although the width to height ratio of a gravity wall is a sensitive parameter for a quaywall with firm foundation, the effect of this parameter becomes less obvious when the soil deposit below the wall is thick.

(2) A simplified procedure is proposed to evaluate the order-of-magnitude displacement of a gravity quaywall. In this procedure, residual horizontal wall displacement under a prescribed level of shaking is evaluated based on the three parameters mentioned above.

(3) Applicability of the proposed simplified procedure was confirmed by case history data. The procedure demonstrated the capability to evaluate a wide range of displacements, ranging from the displacement in the order of one-tenths of meters to those with one order higher.

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