*Earth Reinforcement, Ochiai, Yasufuku & Omine (eds) © 1996 Balkema, Rotterdam. ISBN 90 5410 833 9*

# Damage performance of steel-reinforced earth structures in the 1995 Hyogoken-Nambu Earthquake

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ABSTRACT: Reinforced earth structures has been used at many sites for stabilizing slopes and embankments even during earthquake. However, there are little experience for reinforced earth structures to suffer earthquake. Around the area where the 1995 Hyogoken-Nambu Earthquake hit, more than 40 reinforced earth structures including root piles and teree armée are available. In this paper, the authors try to estimate performance of reinforced earth structures during earthquake through damage investigation. Also, they try to assess quake-resistance of reinforced earth structure, comparing damage of reinforced and unreinforced slopes. As a conclusion, it is shown that no severely damaged reinforced earth structures are available located even at around severe intensity area, and that reinforcement increases resistance and toughness of slope stability against earthquake.

## 1 INTRODUCTION

After the 1995 Hyogoken-Nambu earthquake, damage investigation of reinforced earth structures with steel reinforcements was carried out in the southern part of Hyogo Prefecture, Japan. The reinforced earth structures investigated are "terre armée" which is reinforced earth for retaining walls with steel strips layered in banking material and reinforced natural ground structures with root piles. The investigated area is located within a circle with a radius of 70km at the epicenter, where 76 reinforced earth structures exist. The damage investigation concerns on the 47 reinforced earth structures among these, including 37 reinforced earth walls and 10 reinforced natural ground structures, which are located within area having maximum acceleration of more than 100 gal. In this paper, the damage performance of reinforced earth structures is first described, together with a comparison of the damage performance of unreinforced and reinforced natural ground structures. Also, seismic integrity of reinforced earth structures is discussed.

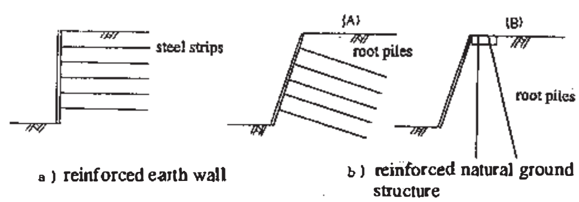


Figure 1 Reinforced earth structures investigated

Table 1 Characteristics of steel reinforcements

| | Reinforcement | Material characteristics・Dimension |
|---|---|---|
| Reinforced earth wall | Highly adherent strip | Galvanized steel (SS400) with norm JIS G 3101<br>Zinc coat : HDZ35 with norm JIS H8641<br>(no coat; temporally use)<br>Section : 60mm x 5mm, rib : 3mm |
| | Smooth strip | Galvanized steel (SPGS) with norm JIS G 3302<br>Zinc coat : Z27 with norm JIS H8641<br>(no coat; temporally use)<br>Section : 100mm x 3.2mm |
| Reinforced natural ground structure | Mortar | ø 100mm ~ 135mm, f'ck=240kgf/cm² |
| | Steel bar | Deformed reinforcing bar : SD295A with norm JIS D25~D32 |

## 2 OUTLINE OF INVESTIGATION

The reinforced earth structures investigated are shown in Figure 1, which consist of reinforced earth walls and reinforced natural ground structures with root piles. Both reinforced earth structures are unified with the ground through friction between reinforcement and soil. Table 1 shows the descriptions of characteristics of steel reinforcements.

The investigation items are damage condition of wall surface, surrounding areas and the boundary, which are visually investigated, and their damage is ranked. Figure 2 shows the investigated locations with damage degree of reinforced earth structures on contour map of maximum horizontal acceleration of the earthquake. According to the investigation, no complete collapse or destruction in either reinforced earth walls or reinforced natural ground stuctures with root piles. However, some examples of minor damage and deformation were observed, which might characterize the general performance of reinforced earth structures during earthquake.

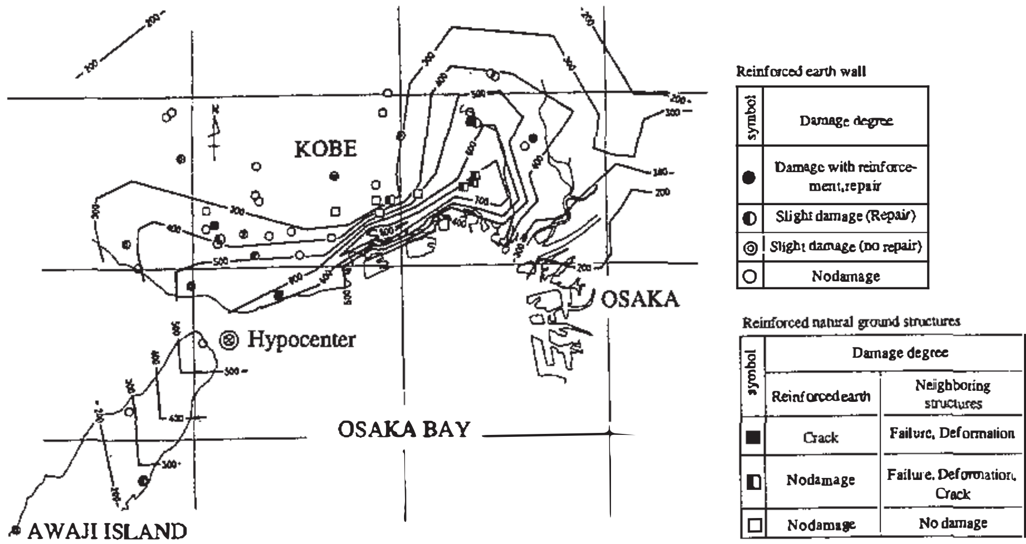


Figure 2 Investigated locations with damage degree of reinforced earth structures on a map displaying contour lines of maximum horizontal acceleration

## 3 DAMAGE PERFORMANCE OF STEEL-REINFORCED EARTH STRUCTURES

Figure 3 shows the relationship between wall height of reinforced earth structures and estimated maximum horizontal acceleration at each investigated site, together with their damage degree. The height of reinforced earth structures ranges from 1.5m to 16.0m, and the average is around 6m. The damage degree tends to be moderately higher, as increasing the maximum horizontal acceleration. However, in the region of similar maximum acceleration, higher structures do not necessarily suffer more extensive damage. Structures required some repair (five cases marked by ●, ◐, and ■) are located within area of maximum horizontal acceleration of greater than 300 gal and their wall heights are lower than 8m. In other words, there is no trend that the damage of structures becomes more severe, as increasing wall height and maximum acceleration. It is difficult to generalize the seismic performance of reinforced earth structures, because the ground motion at each site is not available and the topography and geological and geotechnical properties differ at each site. Therefore, seismic performance of reinforced earth structures are estimated based on their damage condition of wall surface and surrounding ground. The reinforced earth structures investigated have shotcrete wall, thin RC plate or a combination of concrete panels, which makes comparatively flexible wall structures. No overall cracks were found in these concrete wall surfaces after the earthquake, suggesting that the reinforcements absorbed a significant earth pressure acting on walls during earthquake with no meaningful damage, such as failure and overturning of walls. However, the wall surfaces deform following deformation of whole reinforced earth and, in consequence, this could result in damage to joints between wall elements and between adjacent structures.

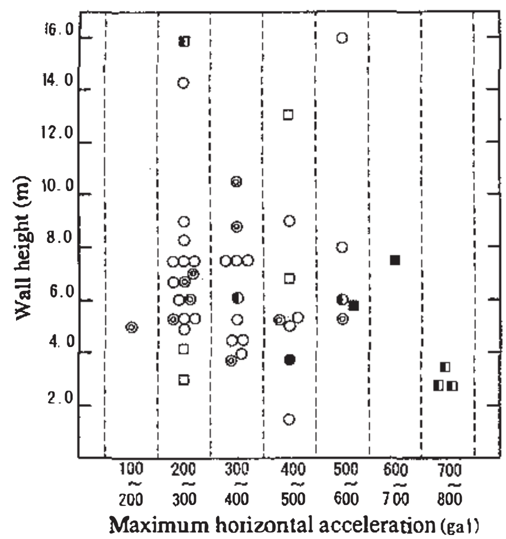


Figure 3 Relationship between wall height and estimated maximum horizontal acceleration as related to damage degree (same symbols as used in Figure 2)

### *3.1 Results of damage investigation of reinforced earth walls*

The types of damage resulting from the earthquake can be classified into such five categories as (1) cracks at corners of wall element concrete and separation of concrete fragments; (2) settlements of ground surface at the top of wall and filled ground surface in front of wall; (3) cracks in the cap concrete; (4) forward inclination and bulging of wall; and (5) detachment of angle type joint elements covering joints of wall elements and opening of joints between adjacent structures. As for the causes for the damage to reinforced earth walls can be classified into the following three groups, based on their estimated performance.

(1) Damage due to movement of wall elements

Between the upper and lower concrete wall elements, plates of cork or hard rubber are used as horizontal joint bond, while between the right and left elements, a gap of approximately 15mm exists. Therefore, each wall elements can move flexibly, following seismic performance of backfills. A few types of damage as (1) (see Photo 1) and (4) above-mentioned might be caused as a result of wave-form deformation of the entire wall during earthquake. Especially, damage to corners of wall elements might be caused as a result of direct contact of keyed joints around wall elements, owing to the relatively large displacement between adjacent wall elements as compared to movement of an entire wall. In all reinforced earth walls investigated which suffer damage only at the corners of wall elements, no large cracks were observed, followed by judging them as slight damage that do not need any repair.

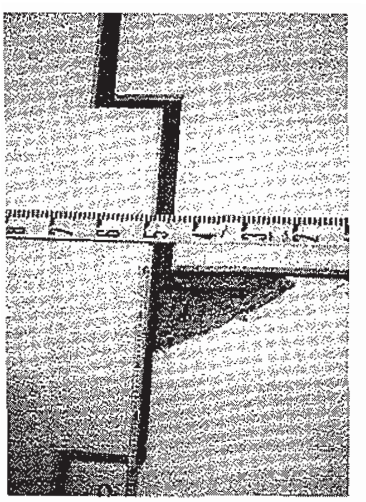

Photo I Example of separation of a concrete fragment at a corner of wall element

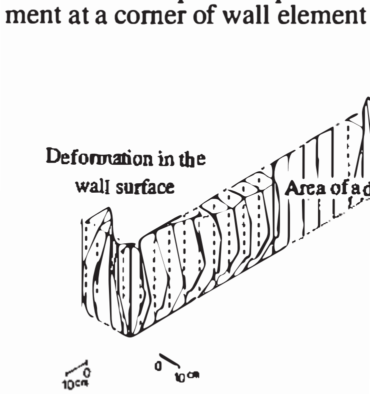


Figure 4 Example of deformation of wall surface in reinforced earth wall

Figure 4 shows an example of three-dimensional deformation in the wall surface of a reinforced earth wall of 3.75m high significantly damaged. The displacement is represented choosing the bottom of wall as the reference point, because of no record before earthquake. The wall surface inclines forward as a whole, but the top of wall tends to incline toward backfill. Although the long-term stability of the wall should be discussed based on a long-term observation of wall deformation and an investigation for confirming sufficient friction acting on reinforcements, the measured deformation which corresponds to about 3% of wall height at most might not be caused a significant problem. This is because 3% of wall height is a reference for vertical accuracy of wall in execution management when construction. In this case history, however there was some observed damage to the structure, including cracks and separation of concrete fragments at the corners of wall elements, or settlement of ground surface at the top of wall. Therefore, this reinforced earth wall was ranked as needed reinforcement or repair.

(2) Damage due to seismic behavior difference between adjacent structures

In reinforced earth structures located at near abutments or concrete retaining walls, steel angles are fixed with anchor bolts to adjacent abutment or retaining wall to restrict forward inclination of wall during compaction work of backfills. The concrete separation surrounding the anchor bolts was observed in two reinforced earth walls (Photo 2), in which settlement of ground surface at the top of wall was observed, but no deformation of reinforced earth wall, and no cracks of wall elements. These structures were judged to be in need of repair in order to prevent the steel angles detaching from their anchors in future, although the reinforced earth walls and the adjacent structures were sound.

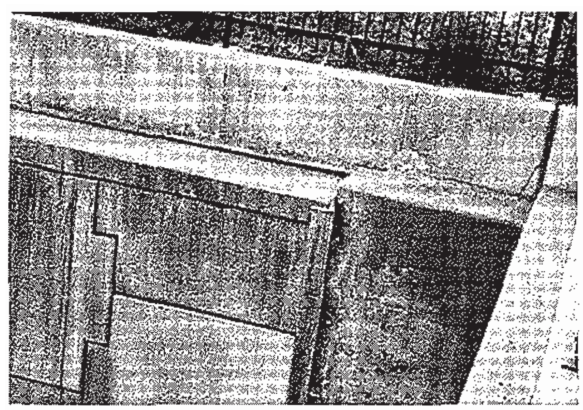

Photo 2 Damage example of joints of reinforced earth structure

(3) Damage due to movement of ground surface

In some reinforced earth walls investigated relative settlement of 1~2cm of the ground surface was observed at the top or in front of walls as well as cracking on pavement surface (Photo 3). In the reinforced earth wall, sandy material are used as backfills to ensure adequate drainage of rain water. Therefore, this type of damage was little significant among investigated structures, followed by judging as no need to repair.

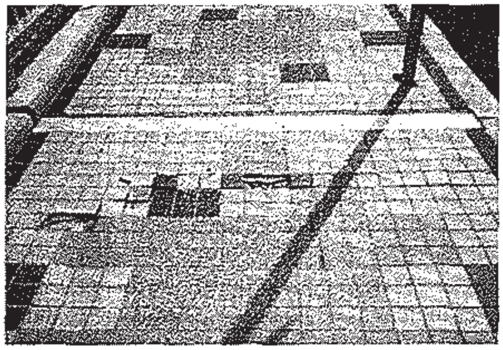

Photo 3 Example of relative settlement of ground surface at the top of wall

*3.2 Results of damage investigation of reinforced natural ground structures*

As shown in Figure 2, all sites where neighboring structures around reinforced natural ground structures were damaged were located within area of maximum horizontal acceleration greater than 300 gal. Four sites among them are greater than 700 gal. The reinforced natural ground structures investigated, however, has slightly damaged. In two case histories, only slight damage of cracks was observed in the reinforced natural ground structures of Type B (see Figure 1), which were located on inclined ground experienced by maximum horizontal acceleration as high as 500 gal (see Figure 2). In these two sites, unreinforced natural ground structures, which were significantly damaged, are available adjacent to reinforced natural ground structures. This will make the comparison of damage between unreinforced and reinforced natural ground structures. These examples are described in detail below.

(1) Case history 1
As shown in Figure 5, two types of facing were used in the construction of the reinforced natural ground structures (6m to 7m in height). One consists of a retaining wall of piled stones and the other a shotcrete wall. Adjacent to the shotcrete wall, an unreinforced retaining wall (3m or less in height) was constructed by piled stones.
Cracks were observed in the ground surface at the top of shotcrete wall and hair cracks were also detected on the face of the shotcrete wall. An opening of 5cm was observed at the facing boundary of reinforced earth structures (Photo 4). The adjacent unreinforced retaining wall was destroyed after falling forward, in spite of lower wall height. Houses located in front of reinforced structures suffered some significant damage.
Significant damage was observed in the facing of shotcrete, which has less rigidity than in piled stone retaining walls. Comparing the performance of the unreinforced and reinforced structures above-mentioned, it can be confirmed that the advantage of seismic integrity of reinforced earth structures.

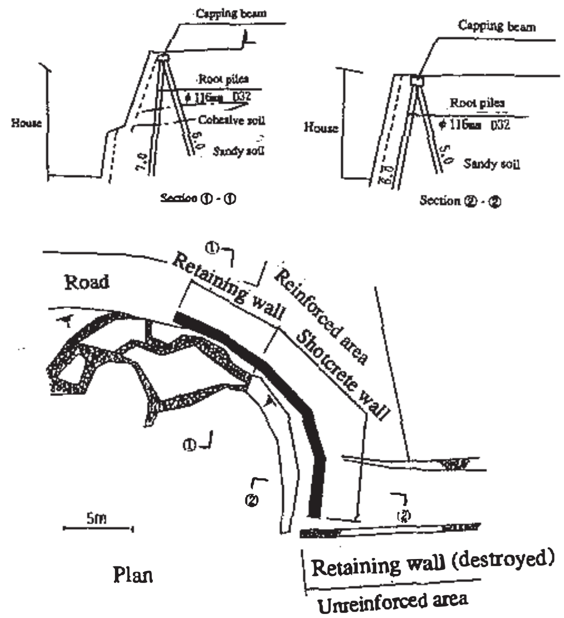


Figure 5 Location of Case history 1

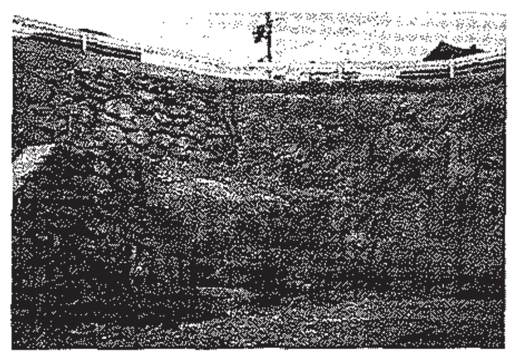

Photo 4 Damage example at facing boundary of reinforced earth structure

(2) Case history 2
As shown in Figure 6, an investigation of the post-earthquake condition of the site involved two locations, namely the reinforced retaining wall (H=7.5m) of Type B in Fig. 1 and an unreinforced retaining wall which is located orthogonal to the reinforced wall.

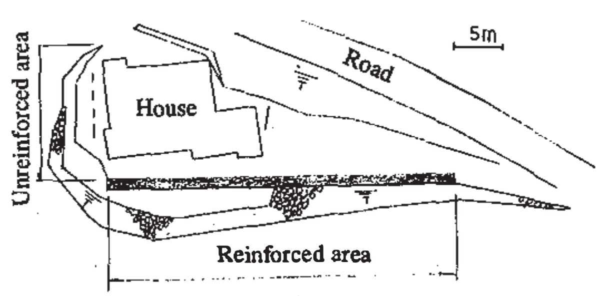


Figure 6 Location of Case history 2

The unreinforced retaining wall deformed forward with an opening of 20cm at most between wall top and backfills, together with cracks on ground surface along the wall. The ground caved-in parallel to cracks by 7cm difference in areas of 20m off the top of retaining wall. This suggests that the natural ground might slightly slide in the unreinforced area.
In the reinforced area, several cracks on ground surface were detected and the ground mass deformed forward in the front of the reinforced retaining wall, although no cracks or deformations were found at the backfills. In this site, the direction of ground motion is approximately orthogonal to the reinforced retaining structure, suggesting that more severe seismic force acted on the reinforced retaining wall. Consequently, it is suggested that the reinforced earth structure has a strong seismic resistance.

## 4 SEISMIC PERFORMANCE OF STEEL-REINFORCED EARTH STRUCTURES

All reinforced earth structures investigated were checked their aseismicity by the seismic coefficient method. Structures judged to need repair (marked with ●, ◐, and ■ in Figs. 2 and 3) had not been designed to withstand the real seismic motion in the earthquake, even though they did not reach whole failure. Also, the shape of reinforcements was determined through the specification at normal or detail of structure. Therefore, the seismic integrity of the structures judged to need repair is examined below, using the seismic coefficient method.

### *4.1 Method for examining performance during earthquake*

Four cases of reinforced earth structures were selected for examination herein; that is, Case histories 3 and 4 as shown in Figures 7 and 8 respectively and Sections ① and ② in the reinforced natural ground structure in Case history 1 as shown in Figure 5. The seismic integrity of reinforced earth walls and reinforced natural ground structures was evaluated using Equations (1) and (2), and Equations (3) and (4) respectively, using horizontal seismic coefficient $k_h$.

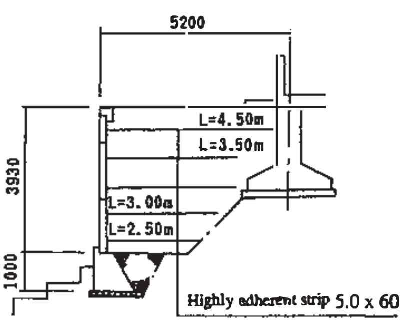


Figure 7 Cross section of Case history 3

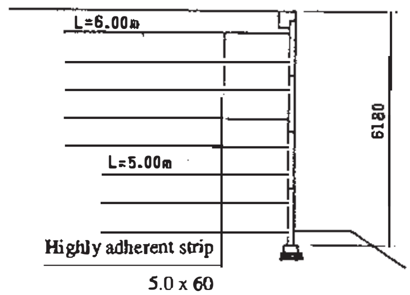


Figure 8 Cross section of Case history 4

1) Reinforced earth wall

$$P_1' = \Sigma\{P_{1i} + 1/2(1 + z/H_a)1.4\, k_h P_{1n}\} \quad (1)$$
$$P_{1i} = (K_i \sigma_{vi} + \Delta\sigma_{Hi})\Delta H \quad (2)$$

where

- $P_1'$ : Earth pressure acting on the reinforcement during earthquake (kN/m)
- $P_{1i}$ : Normal earth pressure acting on the i th reinforcement (kN/m)
- $H_a$ : Assumed wall height (m)
- $z$ : Depth from the top of assumed wall height to the position of the i th reinforcement (m)
- $k_h$ : Horizontal earthquake intensity seismic coefficient for design
- $P_{1n}$ : Normal earth pressure acting on the lowest position of reinforcement (kN/m)
- $K_i$ : Earth pressure coefficient at the i th position of reinforcement
- $\sigma_{vi}$ : Vertical normal stress of ground at the i th position of reinforcement (kN/m$^2$)
- $\Delta\sigma_{Hi}$: Inherent horizontal normal stress of ground caused by the horizontal force at the i th position of reinforcement (kN/m$^2$)
- $\Delta H$ : Vertical interval of reinforcements (m)

2) Reinforced natural ground structure

$$F_s' = \frac{\Sigma(W_i \cos\theta_i - k_h W_i \sin\theta_i)\tan\varnothing + c\, l_i}{\Sigma(W_i \sin\theta_i + k_h W_i \cos\theta_i)} \quad (3)$$

$$P_2' = (F_{sp}' - F_s')\,\Sigma(W_i \sin\theta_i + k_h W_i \cos\theta_i) \quad (4)$$

where

- $P_2'$ : Sliding force acting on reinforcement (reinforced earth) during earthquake (kN/m)
- $F_{sp}'$ : Design safety factor of reinforced natural ground structure during earthquake
- $F_s'$ : Minimum safety factor of unreinforced natural ground during earthquake
- $c$ : Cohision of soil (kN/m$^2$)
- $\varnothing$ : Internal friction angle of soil (°)
- $\gamma_t$ : Unit weight of soil (kN/m$^3$)
- $l$ : Bottom length of a slice (m)
- $W$ : Total weight of soil above sliding plane (kN/m)

θ : Angle between sliding plane and horizontal plane (°)

For both reinforced earth wall and reinforced natural ground structure, the failure mode is assumed by the pull-out or rupture of reinforcement. The tensile force of reinforcement is calculated as the smaller value of the two resisting forces based on both failure modes.

### 4.2 *Evaluation of seismic integrity*

In all reinforced earth structures, the safety factor due to failure mode of pull-out was smaller than that of rupture, and the tensile force of reinforcement was calculated by the pull-out resistance of reinforcement. Figures 9 and 10 show the relation between the horizontal seismic coefficient $k_h$ for design and the safety factor Fg to minimum pull-out resistance of reinforcement for reinforced earth wall and reinforced natural ground structure respectively. It is seen in these figures that the safety factor Fg decreases as increasing horizontal seismic coefficient, and becomes less than 1.0 for the range of $k_h \simeq 0.3$ (0.24 to 0.35). A comparison between Case histories 3 and 4 of the reinforced earth wall and between Section ① and ② of Case history 1 of reinforced natural ground structure revealed that a lower safety factor was obtained in more severely damaged structure in both types of structures. Considering the seismic performance of these reinforced earth structures, the horizontal seismic coefficient of about 0.3 in the seismic coefficient method corresponds to the estimated maximum horizontal acceleration of about 500 to 600 gal.

## 5 CONCLUSIONS

In this paper, the damage performance of steel-reinforced earth structures in the 1995 Hyogoken-Nambu Earthquake was investigated, together with discussing their seismic integrity.

(1) The steel-reinforced earth structures such as reinforced retaining wall and reinforced natural ground structure did not suffer any catastrophic damage, fulfilling their structural functions, despite their subjection of a strong seismic motion by maximum scale inland type earthquake as the 1995 Hyogoken-Nambu Earthquake. Consequently, it is concluded that the steel-reinforced earth structures have excellent seismic integrity with sufficient ductility.

(2) Based on their investigated damage performance such as cracks on wall surfaces and residual deformation, it is suggested that reinforced earth structures are flexible ones deforming in response to the seismic motion.

(3) The reinforced earth structures investigated had been designed by the seismic coefficient method. It is identified that the horizontal seismic coefficient of about 0.3 corresponds to the estimated maximum horizontal acceleration of about 500 to 600 gal for the investigated structures. It is necessary to carry out further research works to properly evaluate their seismic integrity for establishing an aseismic design method of reinforced earth structures, based on investigated damage performance.

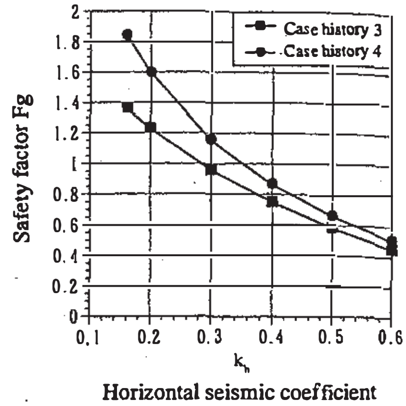


Figure 9 Relationship between safety factor and horizontal seismic coefficient in the reinforced earth structures

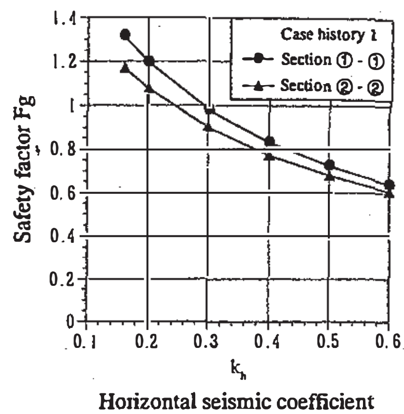


Figure 10 Relationship between safety factor and horizontal seismic coefficient in the reinforced natural ground structure

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