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Earthquake resistance of geogrid-reinforced soil walls based on a study conducted following the southern Hyogo earthquake

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ABSTRACT: The earthquake at the southern Hyogo early on the morning of January 17, 1995, with its epicenter on the northern tip of Awaji Island, cause tremendous damage to the southern district of Hyogo prefecture. Earth– retaining walls, including gravity and semi– gravity types, were no exception. The Earthquake is reported to have severely damaged such earth structures in this region. We investigated ten Geogrid– reinforced soil walls that existed prior to the earthquake, near the hypocenter where a seismic intensity of 6 to 7 was recorded. We found that although the earthquake caused some settlement and cracks in the foundation, the walls themselves were almost free of deformations. In this study, we will report the findings of our on– site investigation of the Geogrid– reinforced soil walls and will verify the earthquake resistance of each ten structures on the basis of some established aseismic design procedures.

1 INTRODUCTION

At 5:46 a.m. on January 17, 1995, the Southern Hyogo earthquake struck the southern areas of Hyogo Prefectures. The epicenter of the local earthquake was at the northern tip of Awaji Island. The hypocenter was approximately 20km deep. The earthquake registered 7.2 in magnitude, and brought tremendous damage to various urban functions in the area, as well as civil engineering structures.

A large number of Geogrid–reinforced soil walls had been constructed in the cities in Hyogo Prefecture, including Takarazuka, Kobe and Nishinomiya, as well as in the northern area of Awaji Island. In these areas, earthquake activity with a seismic intensity of 7 was observed. After the earthquake, we promptly carried out research on condition in the Geogrid–reinforced soil walls, as well as peripheral damage around these structures. As a result of our research, no failure or large deformation that would cause damage to the integrity of the Geogrid–reinforced soil walls was observed.

As design methods for the Geogrid–reinforced soil walls, the Geogrid Research Board (GBR) and the Public Works Research Institute (PWRI) published design and construction manuals in Japan. In the process of production of these manuals, both the GRB and PWRI carefully discussed the resistance of earthquake for Geogrid–reinforced soil walls. Basically, their design methods are in line with conventional seismic design methods for retaining walls.

Based on the research results, we conducted analysis on ten selected Geogrid–reinforced soil walls by using the two design methods with the seismic coefficient, and verified earthquake resistance of the Geogrid–reinforced soil walls.

2 RESEARCH

2.1 *Existing Geogrid–reinforced soil walls*

Table 1 shows a number of existing structures constructed using the Geogrid reinforcement in the southern areas of Hyogo Prefecture, where an earthquake with a seismic intensity of 5 or greater was observed. Most of the structures were reinforced soil walls, and were concentrated in the areas hit by an earthquake with a seismic intensity of 6 to 7, where peripheral damage was particularly severe.

As for other reinforced soil structures by Geogrid (reinforced slopes, foundation, etc.), no deformation that would cause problems with their integrity was observed. The reason for this is that those reinforced structures were constructed on strong ground enough to resist influence by an earthquake.

Table 1. Existing Geogrid–reinforced soil structures in south Hyogo Prefecture

	In areas with intensity of 5	6 to 7	Total
Soil walls	8	16 (64)	24 (57)
Slopes	4	4 (16)	8 (19)
Foundations	2	2 (8)	4 (10)
Others	3	3 (12)	6 (14)
Total	17	25 (100%)	42 (100%)

*Cities with seismic intensity of 7 : Kobe,Nishinomiya, Ashiya, Takarazuka, and Tsune– gun(northern Awaji Island)

2.2 *Location of the structures*

From among the existing structures mentioned in section 2.1, we selected ten Geogrid–reinforced soil walls in the areas where a seismic intensity of 6 to 7 was observed. Detailed verification of earthquake resistance was conducted. The location of these ten structures are shown in Fig. 1. The numbers in Fig. 1 correspond to those in Table 2 in section 2.3.

Also include in Fig. 1 are tbe areas hit by an earthquake with a seismic intensity of 7 and the maximum ground acceleration values published by the Committee of Earthquake Observation and Research in Kansai. According to a research report by the Ministry of Construction, maximum ground acceleration exceeding 800 gals was even observed in some places.

Comparison of the location of Geogrid–reinforced soil walls with distribution of maximum ground acceleration values shows that these places experienced tremendous seismic load, with ground acceleration between 300 and 700 gals. This ground acceleration can be

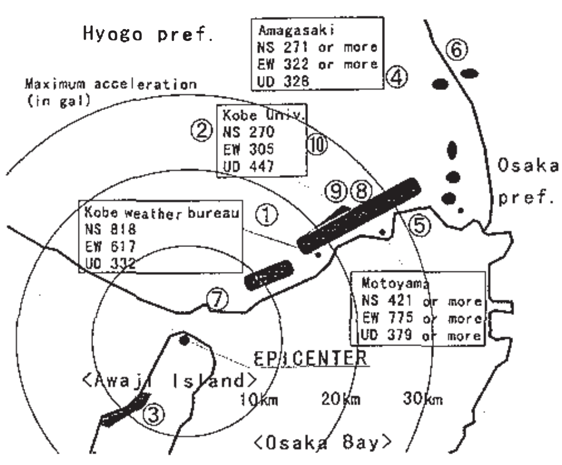


Fig. 1. Location of the Geogrid–reinforced soil walls

converted into a horizontal seismic coefficient of between approximately 0.3 and 0.7, providing that tbe shaking direction by the earthquake is not taken into consideration.

In addition to the disastrous power of the earthquake, retaining walls in general are not designed to withstand such a disastrous earthquake as when there is a maximum ground acceleration between 300 and 700 gals. Thus, it is understandable that such structures were extensively damaged.

2.3 *Structure of the Geogrid–reinforced soil walls*

Table 2 outlines the structure of the Geogrid–reinforced soil walls checked in our detailed research. The numbers in the table correspond to those in Fig. 1 in section 2.2.

The present research could not completely confirm the concept used in designing these structures. However, we were able to confirm the main materials used in the structures and their allocation.

For facing materials, either steel frame, sandbags, or concrete blocks were used. Physical properties of Geogrid used as reinforcing material are shown in Table 3.

The angle of internal friction of filling material shown in Table 2 is determined at the judgement of designers during construction. Thus, the angle of internal friction was not always obtained through highly precise soils tests.

The wall inclination of the structures was within the range of 1:0.5 from vertical, and the height was 8m or lower except No.6. Generally, earth–retaining walls lower than 8m are not required seismic design. Therefore, it seems that not all of these structures were examined for eartbquake resistance during the design stage.

The results of the present research show that even though the Southern Hyogo eartbquake hit the area with such tremendous seismic load, the Geogrid–reinforced soil walls maintained adequate stability, and no wall developed a problem that would hamper serviceability.

Table 3. Physical properties of Geogrid

Raw material	Designed strength (kN/m)	Product's strength (kN/m)
SR35	18	30
SR55 HDPE	30	50
SR80	42	70

Product's strength is obtained by the tensile tests at the low tensile speed.

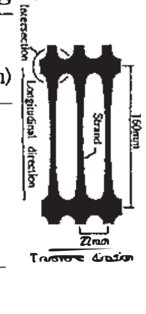


Table 2. Structure of Geogrid–reinforced soil walls and observation them after earthquake

No.	Completion of Construction	Facing	Geogrid	Reinforcement length (m)	Height of Wall (m)	Inclination	Internal friction angle (degree)	observation
1	Jun.1990	Steel frame	SR55	4.8	6.5	1:0.1	30	No damage
2	Feb.1991	Concrete block	SR55	3.0	4.0	1:0.3	30	No damage
3	Aug.1991	Sandbag	SR55	5.5	6.2	1:0.5	30	No damage
4	Feb.1992	Sandbag	SR55	5.0	6.6	1:0.3	30	No damage
5	Mar.1993	Concrete block	SR55	4.5	5.25	1:0.5	30	Small gaps between concrete blocks and a few centimeters settlement occurred
6	Dec.1993	Sandbag	SR80	7.5	11.0	1:0.3	30	No damage
7	Jul.1994	Steel frame	SR55	2.0	5.0	1:0.5	35	No damage
8	Aug.1994	Sandbag	SR35	4.0	5.5	1:0.2	30	A crack ran parallel to wall face on the crest because of unstable foundation
9	Sep.1994	Sandbag	SR35	3.5	5.0	1:0.0	30	No damage
10	Dec.1994	Sandbag	SR80	5.5	5.0	1:0.3	30	No damage

3 COMPARATIVE ANALYSIS WITH EXISTING DESIGN METHODS

3.1 *Outline of design methods proposed in Japan*

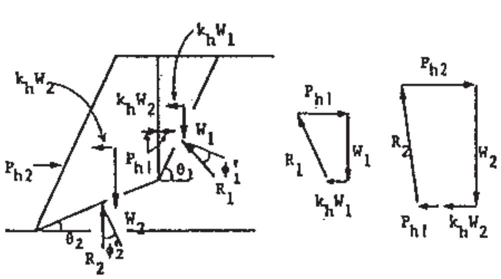
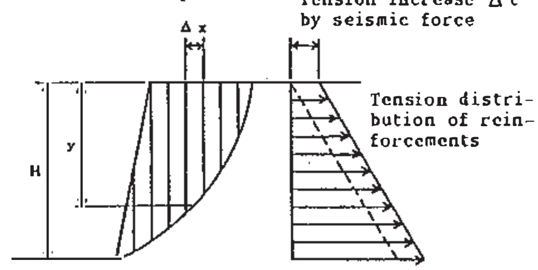
Table 4 outlines the design methods for Geogrid–reinforced soil walls proposed by the GRB and PWRI. The main differences in design concept between the two design methods are the shape of the sliding surface and determining method for earth pressure to withstand seismic load. Meantime, both design methods are based on similar ideas in terms of external stability by regarding the zone reinforced by Geogrid as pseudo retaining wall.

For aseismic design, both design methods use the seismic coefficient in calculation of the earth pressure that acts on the wall face when determining the position of Geogrid to be installed, as well as in calculation of the earth pressure applied to the rear surface of reinforced zone (pseudo retaining wall) when examining external stability.

3.2 *Analysis of the structures*

We verified stability of the Geogrid–reinforced soil walls by using the horizontal seismic coefficient from 0.1 to 0.5 in increment of 0.1. Although this analysis was made on all of the ten Geogrid–reinforced soil walls, we show here results for two structures that seemed to be stricken by very large seismic load, and whose surrounding areas suffered severe damage. The analysis is based on an assumption that the bearing capacity of the foundation is adequate, with the interaction coefficient between soil and Geogrid defined as 1.0.

Table 4. Design method for Geogrid–reinforced soil walls

	GRB	PWRI
Failure mode	Two–part wedge sliding 	Circular slip 
Design procedure	1.Calculate the length of reinforcement by external stability (sliding forward <La>, overturning <Lb> of reinforced zone 2.Determine K for internal stability based on above failure mode 3.Calculate Lc by pull–out failure 4.Determine Lreq = max.(La, Lb, Lc) 5.Determine vertical spacings of reinforcement using coeff. K	1.Determine k based on above failure mode 2.Determine vertical spacings of reinforcement 3.Determine the length of reinforcement based on overall circular slip surface 4.Study of external stability of reinforced zone (as pseudo retaining wall)

1) Geogrid–reinforced soil wall of No.5

This structure was constructed as part of developing land (see Fig. 2). As the structure was constructed on reclaimed land facing the sea, the seismic intensity could be 7 , with ground acceleration of approximately 700 gals. Damage to surrounding structures was tremendous. The ground in front of the Geogrid–reinforced soil wall had a crack approximately 30cm wide, which met the wall at a right angle.

In spite of such considerable seismic load, the Geogrid–reinforced soil wall exhibited only minor damage, such as slight gap between concrete blocks used as facing material. No deformation was observed that would damage serviceability. Adequate stability was confirmed.

Fig. 3 show the results of analysis of this structure using the design methods proposed by the GRB and PWRI. Obviously, earthquake resistance was not taken into consideration in the design stage. The safety factor by circular slip was below 1.0, which value was 0.910 at a horizontal seismic coefficient of merely 0.1. At a horizontal seismic coefficient of 0.2, as well, the safety factor by circular slip was 0.768. The stability analyzed by two–part wedge was also below critical condition.

With both design methods, the strength required for Geogrid exceeds the designed strength at a horizontal seismic coefficient of 0.1 or 0.2. This designed strength was set according to the creep characteristics based on long–term serviceability. Thus, no breaking will occurred during earthquake.

The maximum ground acceleration that acted on the structure is estimated as between 500 and 700 gals. This can be converted into horizontal seismic coefficient of approximately 0.5 to 0.7. From the view of either failure modes, the structure could be destroyed. In addition, the concrete blocks and Geogrids were not connected, thus they did not contribute to stabilization of the reinforced soil wall.

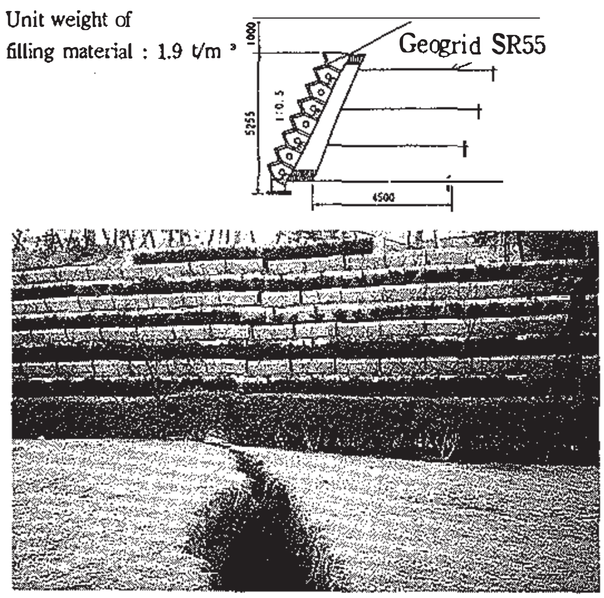


Fig. 2. Structure and appearance of No.5

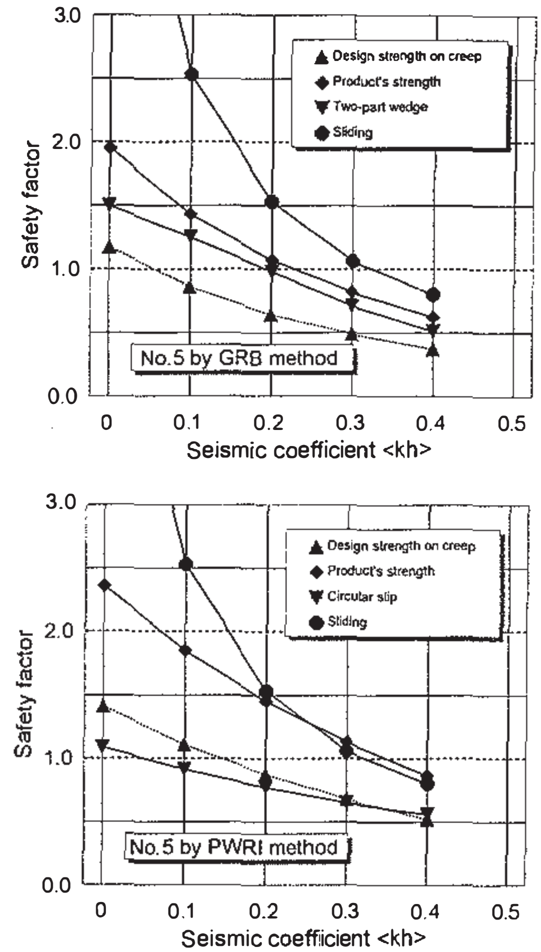


Fig. 3. The results of analysis by GBR & PWRI

2) Geogrid–reinforced soil wall of No.8

This structure, located within a residential area developed on hills in Higashi–Nada–ku, Kobe, suffered the largest damage. The structure was constructed to expand the area of a site for a parking lot (see Fig. 4). Adjacent houses were partially or completely destroyed. Roads were also much damaged, with landslides and falling rock. This Geogrid–reinforced soil wall was located in an area adjacent to the spot hit by a seismic intensity of 7. thus, ground horizontal acceleration is estimated at approximately 400 gals.

A crack parallel to the wall surface ran on the crest, approximately 4 m from the wall face (see

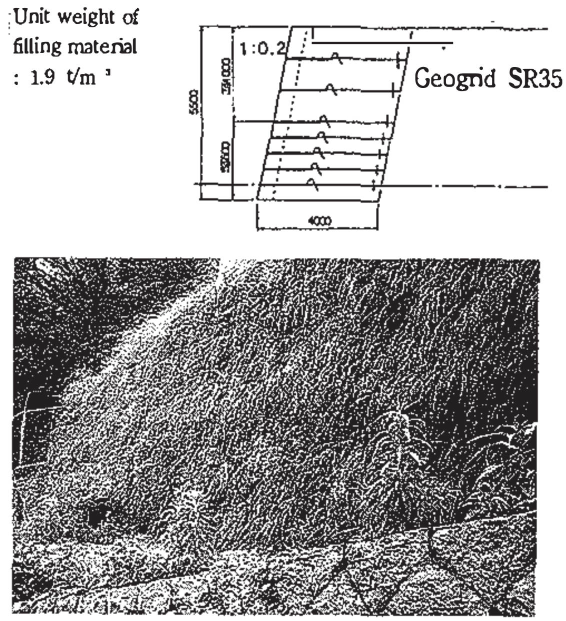


Fig. 4. Structure and appearance of No.8

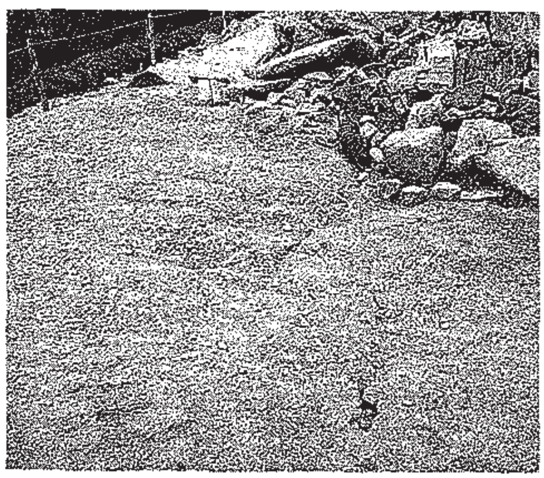


Fig. 5. A crack ran on the crest of No.8

Fig. 5). The wall was slightly deformed forward.

This structure was constructed onto a conventional retaining wall using concrete blocks with a height of 3m. Thus, its bearing capacity is considered insufficient.

The results of analysis shown in Fig. 6 are based on the assumption that the ground bearing capacity is adequately strong. Thus, it dose not explain how the phenomenon in this case occurred during the earthquake. Nevertheless, circular slip or two−part wedge sliding exceed the critical point at a horizontal seismic coefficient of 0.2.

At this stage, the strength required for Geogrids has not reached the designed strength or even the product's strength. Therefore, it shows instability, because the length of the Geogrids in the upper portion of the reinforced zone was insufficient.

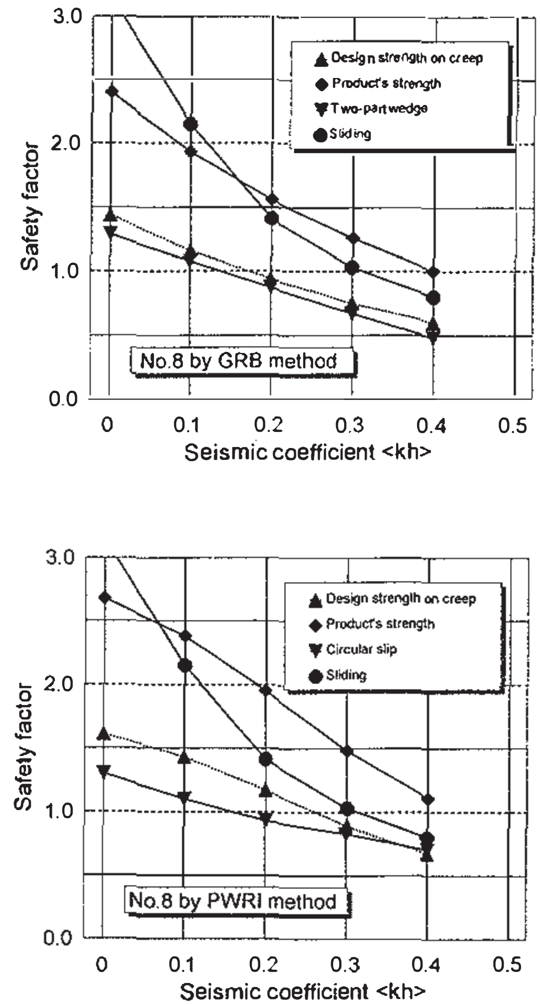


Fig. 6. The results of analysis by GBR & PWRI

3) Results of analysis of the structures

Table 5 outlines the results of analysis of all ten cases. The table lists the horizontal seismic coefficient resulting as failure and each types of failure in respective cases. In almost all cases, stability was critical at a horizontal seismic coefficient of approximately 0.2. Also, two−part wedge sliding or circular slip became critical condition, because the length of the Geogrids was insufficient.

When horizontal seismic coefficient is more than 0.4, breaking of Geogrid and sliding forward of reinforced zone must also be taken into consideration.

Thus, as measures for enhancing earthquake resistance, taking into consideration failure modes, in particular the Geogrids in the upper portion of the reinforced zone must be adequately long.

Table 5. The results of analysis for ten Geogrid–reinforced soil walls

No.	Geogrid breaking by GBR method	Two–part wedge sliding	Reinforced zone sliding forward	Geogrid breaking by PWRI method	Circular slip	Reinforced zone sliding forward
1	>0.5	0.2	0.4	>0.5	0.4	0.4
2	>0.4	0.2	0.4	>0.4	0.1	0.4
3	0.4	0.2	0.3	0.4	0.1	0.3
4	>0.4	0.3	0.4	>0.5	0.3	0.4
5	0.3	0.2	0.4	0.4	0.1	0.4
6	>0.4	0.2	0.4	>0.4	0.2	0.4
7	>0.4	0.1	0.3	>0.4	0.1	0.3
8	0.4	0.2	0.4	>0.4	0.2	0.4
9	>0.4	0.1	0.4	>0.4	0.1	0.4
10	>0.5	0.4	0.4	>0.5	0.4	0.4

4 CONCLUSIONS

We conducted research on Geogrid–reinforced soil walls stricken by the Southern Hyogo earthquake on January 17, 1995. Based on the two design methods proposed by the GRB and PWRI in Japan, the earthquake resistance of these walls was analyzed. We have reached conclusions as follows :

1. Ten Geogrid–reinforced soil walls were constructed in the areas hit by an earthquake with an estimated seismic intensity of 6 or more . All of them had no large deformation or failure, and maintained adequate stability.
2. Based on the two design methods proposed in Japan, analysis using the seismic coefficient was conducted on the ten structures in the areas with an estimated seismic intensity of 6. As a results, stability was critical at a small horizontal seismic coefficient, such as 0.1 to 0.2.
3. As for as verification of the structures upon which research was conducted using the two design methods is concerned, the failure modes of the Geogrid–reinforced soil walls during an earthquake were circular slip or two–part wedge sliding. Taking such failure modes into consideration, stability will be enhanced by adequately increasing the length of the Geogrids in the upper portion of the reinforced zone.
4. Comparison of the present research with the analysis results allows us to judge that the stability of Geogrid–reinforced soil walls was higher than the results of calculation by the two design methods.

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