Investigation of Reinforced Earth Structures Following the 2011 Tohoku Earthquake

Etude des structures en Terre Armée suite au séisme de Tohoku de 2011

Otani Y., Takao K.
Hirose & co., Ltd.

Sakai S., Kimura T.
JFE Shoji Terre One Corporation

Kuwano J.
Saitama University

Freitag N., Sankey J.
Freyssinet/Terre Armée Internationale

ABSTRACT: An investigation of mechanically stabilized earth (MSE) structures constructed with Reinforced Earth (Terre Armee) technology[1] was carried out after the 2011 Tohoku Earthquake in Japan. Reinforced Earth walls examined for the survey were ranked according to associated disaster-caused damages. The results of this research indicated high levels of earthquake resistance in the steel-reinforced structures constructed with this technology method.

RESUME : Une recherche sur les structures de terre stabilisées mécaniquement construits avec la technologie de la Terre Armée a été menée après le séisme de Tohoku de 2011 au Japon. Les murs en terre renforcés analysés pour cette étude ont été classés suivant les dommages associés à cette catastrophe. Les résultats montrent un haut niveau de résistance aux séismes des structures renforcées en acier construites avec cette technologie.

KEYWORDS: Mechanically Stabilized Earth. Reinforced Earth Walls, Investigation, Earthquake.

1 SURVEY OF DAMAGE CAUSED BY THE TOHOKU EARTHQUAKE

1.1 *Damage evaluation method for survey*

The Terre Armee Association in Japan has developed a systematic way of evaluating disaster damage and recommending a restoration plan by which it can determine emergency measures that are commensurate with the extent and degree of damage caused by an earthquake or storm2). This evaluation method is consistent with emergency determination lists prepared for past earthquakes. Based on the results of the survey, structural integrity evaluations and assessments of required emergency measures were carried out according to ranking of the walls into six levels of disaster damage (Table 1)[3].

1.2 *Survey results*

The Tohoku Earthquake that took place on March 11, 2011 was a reverse fault type earthquake with its epicenter in an ocean trench at the boundary of the Pacific Plate and North American Plate. It registered a moment magnitude (Mw) of 9.0 and a seismic intensity of 7.0, the maximum intensity on the JMA scale (MM scale ≒ 5.5・JMA scale + 0.5). The earthquake generated tsunami waves that affected not only Japan, but also other Pacific Rim countries, with the height of tsunami waves travelling upstream and over land reaching as high as 40.1 meters. In addition, the earthquake caused landslides, liquefaction and subsidence. During the one-month period after the earthquake, over 100 aftershocks registering intensity of 4.0 or greater on the Japanese scale occurred. Figure 1 shows the distribution of Reinforced Earth walls that were classified as Damage Rank II or higher. In Figure 2, a pie chart of the Reinforced Earth wall numbers by Damage Rank is provided for 1,419 of the structures. The walls in the figure represent 55% of the 2,540 such walls subjected to upper intensity 5 or higher tremors. It is noted that a total of 4,127 Reinforced Earth walls were located in what was considered the overall disaster stricken area[3]. Of the 1,419 walls surveyed, 1,400 (approximately 98.4%) had non-existent to light damage (Damage Rank I or II). Only 4 walls (0.28%) rated Damage

Table-1 The damage rank judged by conditions

Damage Rank	Description	Operation in emergency conditions
VI	Complete collapse or massive deformation.	Not Applicable and access should be prohibited
V	Largely deformed but functions as a structure for the moment.	Applicable by emergency measures of panel deformation, restrictions or monitoring either independently or in combination.
IV	Partly deformed and unstable but functions as a structure for the time being.	
III	Largely deformed but not influenced by its stability	Applicable by monitoring
II	Partly deformed but stable	
I	No damage	Applicable

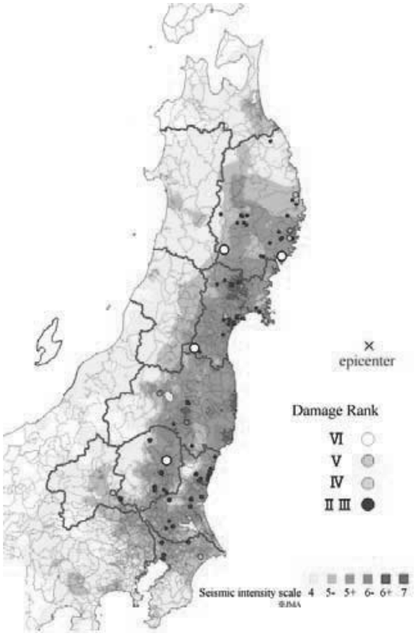

Figure 1. Distribution of walls classified as damage rankII or greater

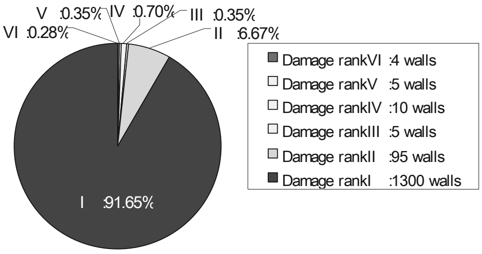

Figure 2. Percentages of each Damage Rank

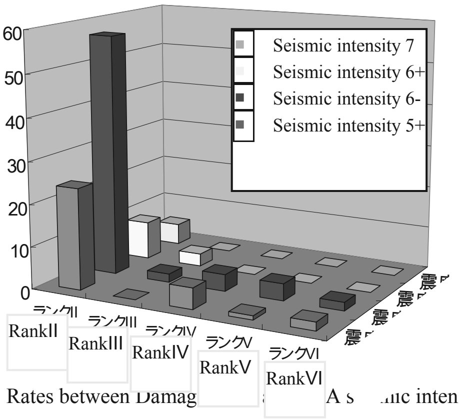

Figure 3. Rates between Damag A s nic intensity

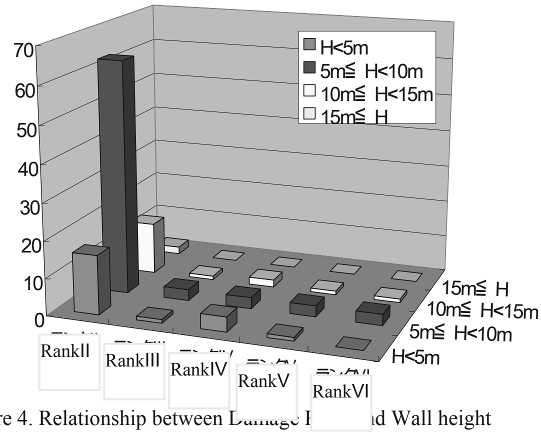

Figure 4. Relationship between D I d Wall height

Rank VI, meaning damage was so severe that they were no longer functional; including one wall in a construction site where measures to counter frost heave were being implemented before putting the wall into service.

As shown in Figures 3 and 4, the Damage Rank VI walls were at sites that were hit by upper intensity 5 to lower intensity 6 tremors, and in terms of their damage occurrence rates by wall height (5 m ≤ H < 10 m, 10 m ≤ H < 15 m). They represent the same 0.4% rate in each seismic intensity and wall height. Therefore, the high degree of damage was not necessarily as a result of the strongest tremors or tallest wall heights.

As for the resulting tsunami waves, which characterize the collateral effects caused by the earthquake, damage from overland flows were observed on walls at 14 sites. For two sites where an exposed sloped earth fill surface was unaccompanied by any protective cover such as concrete, the earth wall was severely damaged when the earth fill was washed away. At other sites, however, walls were classified as Damage Rank I or II, which means light damage.

For the Tohoku Earthquake, there was no instance where compromised stability of a Reinforced Earth wall led to the loss of functional integrity in a supported superstructure such as a road, thus high earthquake resistance performance was confirmed.

Photo 1. Wall in the area of seismic intensity upper 7 (Rank II)

Photo 2. Wall in the area of seismic intensity 7(Rank I)

2 DISASTER CONDITIONS OF DAMAGED STRUCTURES

Disaster conditions are described by their causes for structures in areas subjected to high-intensity seismic tremors and those whose rating was at Damage Rank VI.

2.1 *Minimally damaged structures at a site hit by strong tremors (intensity upper 6 to 7)*

Surveyed walls at sites hit by strong tremors (intensity upper 6 to 7) were all classified as Damage Rank I or II.

2.1.1 <*Case 1.1 wall* $H_{max} = 15.7$ *m , bank* $h = 0.0$ *m, Total length* $L = 46$ *m, Area of wall* $A = 285$ m^2 >

Damage to a pair of wing walls constructed adjacent to an abutment in an area hit by intensity 7 tremors (shown in Photo 1) was evaluated as Damage Rank II, and the only defects that could be observed were displacement in the foundation of a protective fence and broken corners of a single wall panel.

2.1.2 *< Case 1.2 wall H_{max} = 6.0 m, bank h = 0.0 m, L = 20 m, A = 60 m^2>*

All of the 10 walls in the surveyed area that were subjected to high-intensity tremors (upper 6 to 7) resulted in classifications of only Damage Rank I or II. In the wing wall shown in Photo 2 that was constructed adjacent to an abutment in an area hit by intensity 7 tremors, no distress could be observed at all, hence its classification as Damage Rank I.

2.2 *Examples of structures damaged by the earthquake*

2.2.1 *< Case2.1 wall H_{max} = 9.0 m, bank h = 4.0 m, L = 76 m, A = 453 m^2>*

Photo 3. Collapse of embankment and the deformation of wall's surface

Shown in Photo 3 is a wall whose panels displaced, not because of earthquake tremors, but rather from increased earth and water pressures coupled with decreased pullout resistance by steel reinforcing strip members. Damage was brought about by incursion of rain water into the wall due to inadequate drainage and earth turning into mud, because of slaking earth fill, normally unsuitable for the use in reinforced fill structures. Since the wall facing panels displaced, earth fill flowed out of the wall, and the surface pavement of a road over the earth fill subsided approximately 700 mm. The structure was determined to be at Damage Rank VI.

2.2.2 *< Case 2.2 wall H_{max} = 9.0 m, bank h = 5.0 m, L = 200 m, A = 1,500 m^2>*

Along the boundary of a manufacturing site located in an area hit by lower intensity 6 tremors, a wall slipped forward by up to 7.0 m, accompanied by the uplift of the ground in front (by 3.0 m) and the subsidence of the embankment at its back (Photo 4). The structural integrity of the wall itself was confirmed through a strength test on the steel reinforcements and panels, an in-situ pull-out test on the reinforcing strips and laboratory tests on the embankment fill. The presence of very soft foundation ground was confirmed as a result of the in-situ boring and SPT tests carried out after the earthquake (Figure 5); the entirety of the reinforced earth fill seems to have slipped forward due to general movement at depth with soil characteristics lower than assumed during the design stage. This mechanism of general sliding was confirmed by an analysis of safety rating carried out considering soil characteristics assumed to have been present at the time of the earthquake.

2.3 *Example of damage caused by tsunami waves*

2.3.1 *< Case 3.2 wall H_{max} = 6.0 m, bank h = 0.0 m, L = 60 m, A = 332 m^2>*

A levee for land reclamation which was retained with a Reinforced Earth wall was washed away by the tsunami (Photo 5). Scouring of the foundation soil, loss of fill, and road subsidence on top of the structure were observed near the intersection point between the levee and the wall (Photo 6). The height of the tsunami that went upstream exceeded the height of the wall. The Reinforced Earth wall was divided into two walls on each side of the levee, a seaside wall and a land-side wall.

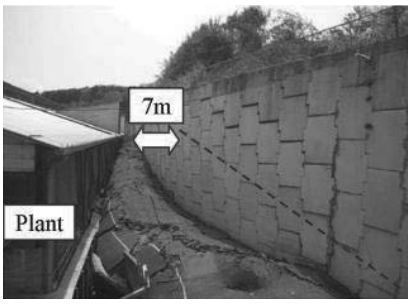

Photo 4 . TA wall damaged by slipping forward

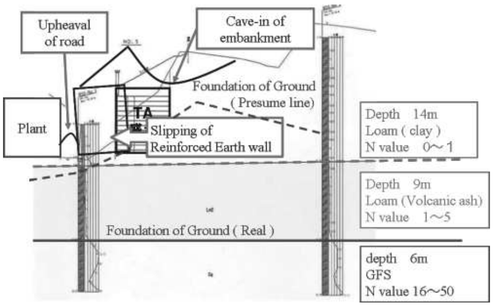

Figure 5. Result of boring survey

Since the earth levee was washed away, the bottoms of the walls along the levee were exposed and subjected to severe erosion. It can be presumed that this strong scouring caused the Reinforced Earth fill to wash away and panels to fall down. Also, at some locations, there were lower panels that may have been removed because the foundation structure near the intersection with the earth levee was exposed by the tsunami that washed away earth fill from this point, which certainly further increased the local water flow rate.

The noted phenomenon of erosion seems to have occurred due to the shallow depth of wall embedment at 0.5 m, which was similar to the standard depth provision for support of local road sections. Another wall situated at a different point on the same peninsula, with a 1.5m depth embedment, was subjected to the same magnitude of tsunami waves and only rated Damage Rank I.

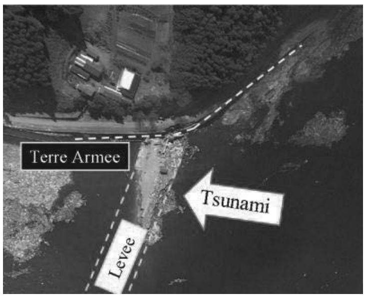

Photo 5. Upper view around wall and direction of the tsunami

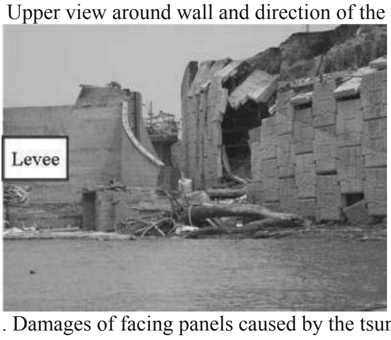

Photo 6 . Damages of facing panels caused by the tsunami

2.4 *Example of damaged structure due to combined factors (frost heave phenomenon)*

2.4.1 *< Case 4.1 wall H_{max} = 13.0 m, bank h = 5.0 m, L = 900 m, A = 7,600 m^2>*

At a site where panels covering a Reinforced Earth wall deformed and collapsed (Photo 7) because of frost heave phenomenon while the structure was being constructed, part of the structure suffered further damage as a result of being hit by the 2008 Iwate-Miyagi Inland Earthquake, which registered a seismic intensity of upper 6. As a countermeasure against frost heave, it was decided to install a backside filter layer (non-susceptible to frost heave) and to substitute the existing earth fill with superior-quality earth fill (these measures are in accordance with the current standard1) for locations where deformation exists). While these measures were being implemented, the structure was subjected again to tremors from the 2011 Tohoku Earthquake, registering a seismic intensity of upper 5 at that location. The survey carried out this time revealed that sections of the wall where anti-frost heave measures were implemented, only rated Damage Rank I (Photo 8). On the other hand, sections where the measures had not yet been implemented resulted in Damage Rank VI (Photo 9). In the latter sections, it is likely that the connections between reinforcing strips and panels had already been damaged due to accumulated displacement brought about by prior frost heave.

Photo 7. Collapse of facing panels by frost heaving of backfill.(Before 2008 the Iwate Miyagi Nairiku Earthquake)

Photo 8. No damage Section of Anti-frost heaving (After the 2011 Tohoku Earthquake)

Photo 9. Collapse of facing panels in the sections where no fill substitution had taken place (After the 2011 Tohoku Earthquake`)

3 EVALUATION OF EARTHQUAKE RESISTANCE PERFORMANCE

The earthquake resistance performance of Reinforced Earth (Terre Armee) walls was evaluated based upon the probability of deformation/failure observed in the earthquake together with survey results of damage inflicted by past earthquakes. Distress that could be classified as Damage Rank VI was observed for the first time in Japan with the Tohoku Earthquake. With the probability of failure (Pf), which was the ratio of fractured structures among the surveyed number of structures, the limit state of damage suffered was calculated through safety index (β) under the assumption that distributions of both seismic force and seismic resistance follow normal distributions. Damage rankings were determined from required structural performance levels shown in Table 2. The probability of deformation (Pd) for Damage Rank V or higher cases (at which the possibility of repairing the damage becomes more than that for slight damage), together with the values of this probability for past earthquakes, are shown in Table 3. Although this Tohoku Earthquake caused damage more severe than that inflicted by past quakes, the value of safety index $\beta_f = 2.77$ indicates that a comparatively high level of safety was maintained; particularly when considering that β_f usually falls between 2.0 and 3.5 for general civil engineering structures4.

Table 2. Demand for damage rank

Damage Rank	Serviceability	Structural stability	Safety
VI	L	L	M
V	M	M	H
IV	M	H	H
III	M	H	H
II	H	H	H
I	H	H	H

* H: High M: Middle L: Low

Table 3. Evaluation of seismic performance

Earthquake		Pf, Pd (%)	ß
Off the coast of Tohoku Eq. 2011 Mw9.0	VI	0.28	2.77
	V over	0.63	2.49
Iwate Miyagi Nairiku Eq.2008 Mw7.2 Noto HantoEq.2007 Mw6.9 Niigataken Chuetsu oki Eq.2007 Mw6.8 Mid Niigata Pref. Eq.2004 Mw6.8, The Southern Hyogo Pref. Eq. 1995 Mw7.2	V over	0.46	2.60

4 CONCLUSIONS

Some 40 years have passed since the Reinforced Earth technique was introduced in Japan. Structures built with this method have been subjected to many large-scale earthquakes including the Tohoku Earthquake of March 2011 in which the rate of high structural damage was quite small. Over 98% of the numerous local Reinforced Earth walls examined after the Tohoku Earthquake had only light to non-existent damage. As demonstrated in this and many other earthquake-related disasters, the seismic resistance of these structures has proven that the technique is outstanding in terms of its operational reliability and safety.

5 REFERENCES

1). Public Works Research Center. 2003. *Reinforced Earth Wall (Terre Armee) Method-Based Design and Construction, 3rd Edition.*

2). Public Works Research Center, 2005. *Damage Level Evaluation and Report of Basic Policy Reviewing Committee for Restoration of Disaster Damages.*

3). Japan Terre Armee Association. 2011. *2nd Investigation of the 2011 Off the Pacific Coast of Tohoku Earthquake*.

4). Masaru Hoshiya, 1986. *Reliability Based Design for Structures*. Kajima Institute Publishing.