Seismic design of reinforced soil walls in Japan: A case study on the 2016 Kumamoto earthquake

Yoshihisa Miyata
National Defense Academy, Japan

Kenji Watanabe
University of Tokyo, Japan

Tomohiro Fujita
Public Works Research Institute, Japan

ABSTRACT: Soil reinforcement technology has greatly contributed to solving seismic stability problems in soil structures. Japan has accumulated many seismic experiences, and has developed seismic technology for reinforced soil structures. This paper first introduces the concept of performance-based seismic design methods for reinforced soil walls for roads and railways in Japan. Then, in a case study of reinforced soil walls after the 2016 Kumamoto earthquake, it is shown that reinforced soil walls exhibited high performance during the earthquake. Finally, future developments in seismic design are summarized. The necessity of developing super large deformation analysis, stability analysis methods for damaged walls, and seismic risk assessments are discussed.

Keywords: seismic design, reinforced wall, case study, performance-based design

1 INTRODUCTION

Seismic stability of soil structures is a common problem across the globe. It can be very difficult to respond effectively to questions such as how large a seismic action should be estimated, what target performance level should be considered for the estimated seismic action, and how to select countermeasures to achieve the target performance. Considering the answers to these questions exposes the limitations of classical techniques for evaluating soil structures. Soil reinforcement technology can contribute significantly to solving this problem. Japan has accumulated many earthquake experiences, and has developed seismic technology based on reinforced soil structures in response. This paper introduces the seismic design methods for reinforced soil walls in Japan, and considers future tasks based on a case study of the 2016 Kumamoto earthquake.

2 SEISMIC DESIGN METHODS FOR REINFORCED SOIL WALLS IN JAPAN

2.1 *General direction of Japanese seismic design for soil structures*

After the Great Hanshin Earthquake, the necessity of estimating a large seismic action exceeding the scope of the seismic intensity method has increased for soil structures. On the other hand, it has also been noted that the target performance of soil structures should vary depending on the importance of the structure. When those discussions began after 1995, Japan had to ensure the consistency of their design methods with international standards such as ISO 2394 for the design principles of structures. Based on technical and procedural necessity, Japanese seismic design has improved since the 2000s (Honjo et al., 2010). In designing for seismic action, consideration of two action levels has been required. Level 1 (L1) seismic action represents a probable strong earthquake action during the service life of the structure, whereas Level 2 (L2) seismic action represents the strongest possible earthquake with an extremely low probability of occurrence. The L2 seismic action can be estimated by considering large-scale plate boundary earthquakes or fault earthquakes inland.

For the target performances considered in seismic design, three performance levels have been defined. Performance Level 1 (PL1) is the highest level, and represents performance that can maintain the function of the structure without repair after an earthquake. Performance Level 2 (PL2) is in the middle, and represents performance which requires repair after the event, but the function of the structure can be restored quickly. Performance Level 3 (PL3) is the lowest level, and represents performance which is not a total collapse, but cannot be repaired. In the practice of seismic design, based on the basic concept of the performance matrix developed in United States, the basic idea is that the target performance for an L1 seismic action should be PL1, while the target for an L2 seismic action should be PL2 or PL3, depending on the importance of the structure.

Movement towards performance design in Japan is based on the "Basis of Structural Design for Buildings and Public Works" published by the Ministry of Land, Infrastructure, and Transport in 2002. This design principle is based on the idea that common items should be subjected to the same standards, regardless of differences in application field (e.g., civil or architectural engineering), and has been applied to systems such as steel, concrete, and soil structures. Since this principle has been enacted, the transition to performance-based design has progressed rapidly. As a result, the seismic design of reinforced soil walls has also made significant progress. Below, points of the current design methods for roads and railways will be discussed.

2.2 *Seismic design of reinforced soil walls for road applications*

For roads, steel strip reinforced soil walls, multi-anchor reinforced soil walls, and geosynthetic reinforced soil walls are primarily used. The cumulative area of facing reached 20 million m^2 in 2014, and it is now recognized as a general construction technology for soil structures. The designs have been developed in accord with technical manuals published by the Public Works Research Center (PWRC 2013a, 2013b, 2014). These conform to the technical guidelines for road earthworks issued by the Japan Road Association (JRA, 2012). The basic concept of the seismic design is to determine the soil reinforcement conditions needed so that the safety factor calculated by the seismic intensity method will achieve the target value. The seismic intensity considered was based on the seismic record, and it is different for high and low seismic zones. However, the target safety is the same for any design situation. In 2015, a new technical standard was developed based on the Road Law, which is a general law in Japan (MLIT, 2015).

Table 1. Required performance and seismic action for reinforced soil walls constructed as road structures in Japan (MLIT, 2017)

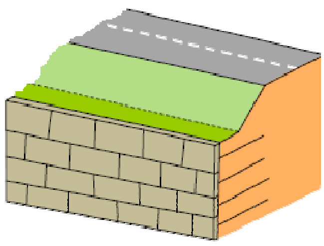
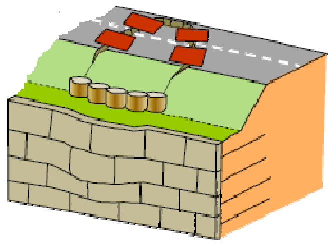
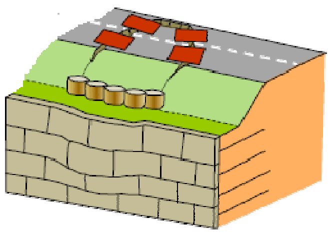
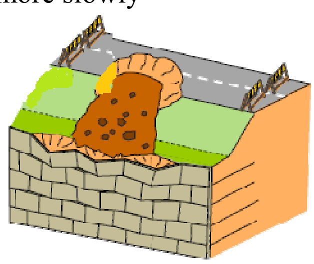
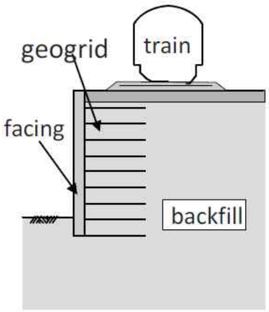
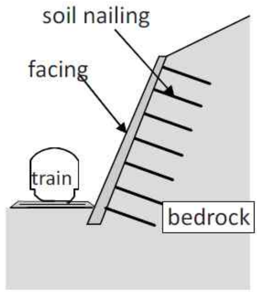
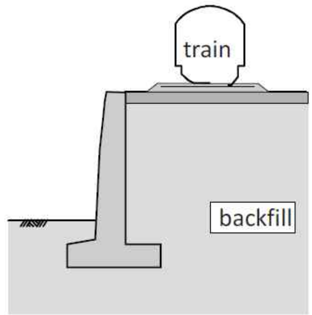
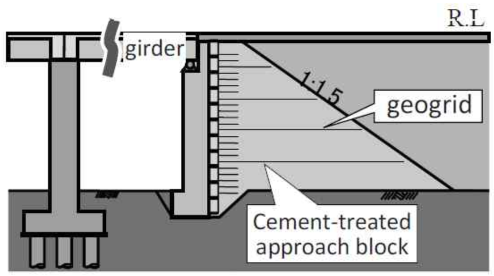
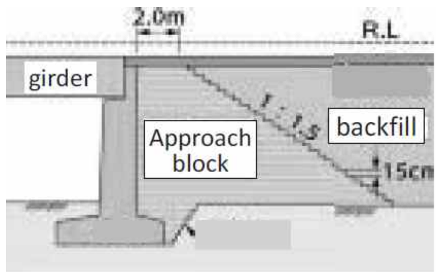
<table>
<tr><td colspan="2" rowspan="2">Importance of structure / Actions</td><td rowspan="2">High</td><td colspan="2">Normal</td></tr>
<tr><td>H > 8m</td><td>H ≤ 8m</td></tr>
<tr><td colspan="2">Permanent</td><td colspan="2" rowspan="2">Performance Level (PL) 1
To maintain normal operation
</td><td></td></tr>
<tr><td rowspan="2">Seismic</td><td>L1: Frequently</td><td>Performance Level (PL) 2
To recover quickly
</td></tr>
<tr><td>L2: Accidental</td><td>Performance Level (PL) 2
To recover quickly
</td><td colspan="2">Performance Level (PL) 3
To recover more slowly
</td></tr>
</table>

Table 2. Classification of earth retaining structures for railways (RTRI, 2012)

	Type of structure	
	Reinforced soil structure	Conventional soil structure
Retaining wall	 	
Bridge abutment		

Two years later, in 2017, the reference manual for the new standard was published, and reorganization of the design specifications for various structures, such as embankments, culverts, and retaining walls, is now being advanced. In the commentary on the new technical standards, a combination of action and required performance for reinforced earth walls were described, as summarized in Table 1 (JRA, 2017).

The following four factors are taken into account in judging the importance of the structure:

a) positioning of the structure on a regional disaster prevention plan;
b) impact of collapse of the structure on other structures and facilities;
c) availability of substitutes if the structure collapses; and
d) difficulty of recovering the function of the structure.

Regarding point a), it is necessary to considered whether the structures are designated as emergency transportation roads in the regional disaster prevention plan, and their role in securing emergency transport during emergency activities and disaster recovery responses. With point b), it is considered whether the damage to the structure will affect other structures or adjacent facilities. For point c), it is considered whether the traffic volume can be secured on an alternative road if the structure is damaged and the network loses its passage function. In point d), the required time to restore function is considered.

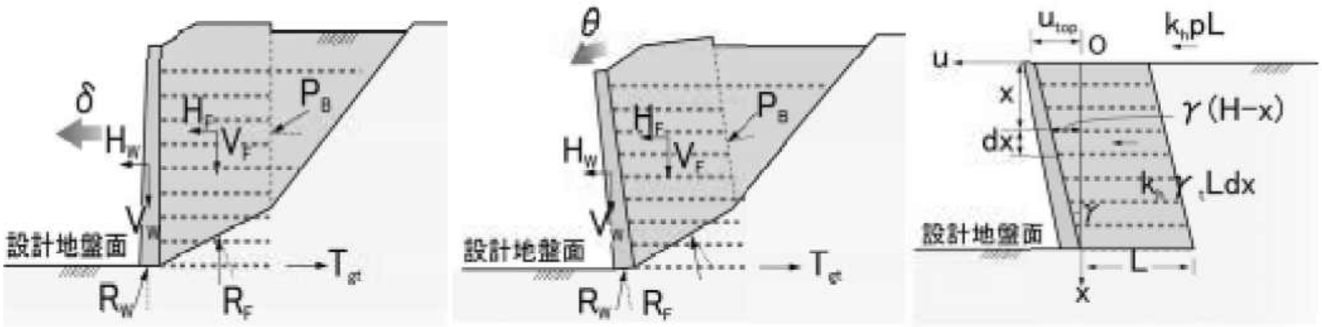
2.3 *Seismic design of reinforced soil walls for railway applications*

For railways, two types of geosynthetic reinforced soil walls with rigid facing are primarily used. One is for retaining structures, and the other is for bridge abutments. A comparison between reinforced soil structures and conventional soil structures is given in Table 2. The cumulative wall length reached 27 km in 2015 (Watanabe et al, 2017). The seismic performance of the reinforced soil system has been recognized as being much better than conventional systems through several seismic events (Tatsuoka et al., 1997). This system plays an important role for high-level operation of trains.

The design of reinforced structures in the 1990s was done so that the safety factor calculated by the seismic intensity method would achieve the target value. It was based on technical specifications for embankments, not for retaining structures. In 2002, the Technical Regulatory Standards on Japanese Railways were revised (MLIT, 2002). With this, the basic concept of design was updated from specification-based to performance-based design.

Table 3. Allowable deformation level for each track type based on the required performance of railway structure in Japan (RTRI, 2012)

Deformation level		Settlement, S, or Differential settlement, Sd		
		Slab track	Ballast track	
			Embankment/ Backfill of retaining wall	Transmission zone (backfill of bridge abutment, box culvert)
1	Almost no deformation (functionality can be used without repair)	No settlement / No residual settlement		
2	Some deformation (functionality can be restored in a short time)	S ≤ 5 cm	S ≤ 20 cm	Sd ≤ 10 cm
3	Large residual deformation (functionality can be restored with partial rebuilding)	5 cm < S ≤ 15 cm	20 cm < S ≤ 50 cm	10 cm < S ≤ 20 cm
4	Extremely large residual deformation (functionality cannot be restored without a total rebuild)	15 cm < S	50 cm < S	20 cm < S



(a) Sliding deformation mode (b) Overturing deformation mode (c) Shear deformation mode

Figure 1. Classification of earth retaining structures covered under the new soil retaining structure standard (RTRI, 2012)

In 2012, the technical specifications for the design of soil structures for railways were also revised based on the technical regulatory standards, and technical specifications for conventional retaining structures and reinforced soil structures were included in the design of retaining soil structures (RTRT, 2012). By following the revised specifications, it is possible for the designer to select a conventional or geosynthetic reinforced soil structure by comparing their performance with an equivalent index, such as stability against traffic load or residual displacement caused by severe earthquake, as summarized in Table 3 and Figure 1.

3 CASE STUDY ON THE 2016 KUMAMOTO EARTHQUAKE

3.1 *The 2016 Kumamoto earthquake*

Two earthquakes hit Kumamoto, Japan within two days in April, 2016. The first earthquake was Mw6.2 on April 14, 2016 at 21:26 (JST). This was designated as the "fore shock." Considerable structural damage and human casualties, including 9 deaths, were reported. The second earthquake was Mw7.0 on April 16, 2016 at 01:25 (JST), approximately 28 hours after the first quake. This was designated as the "main shock." The epicenters of both earthquakes were located in same town, and they were separated by only 4.5 km. Many aftershocks followed the two earthquakes. The total number of aftershocks (larger than magnitude 3.5) had reached 200 by one week after the foreshock.

Table 4. Performance of reinforced soil walls during the 2016 Kumamoto earthquake

Application		Roads			Railways
Reinforced wall type		Steel Strip walls	Geosynthetic walls	Multi-anchor walls	Geosynthetic walls
Number of structures		736			70
Performance Level	Collapse	0.7%	0%	0%	0%
	PL3	0.3%	0%	0%	0%
	PL2	1.0%	1.5%	3.0%	0%
	PL1	98.0%	98.5%	97.0%	100%

3.2 *Investigation results*

After the earthquake, the Japan Geotechnical Society (JGS) organized a team to support the recovery of the damaged sites and to study the potential for secondary disasters.

They quickly investigated slope failures and landslides, liquefaction, and damage to river dikes, and provided the results to the public (Mukunoki et al., 2016). In another investigation, the Public Work Research Center investigated the level of damage to reinforced soil walls constructed as road structures. From their structure database, walls in seismic areas were identified, and investigation teams were sent. The Japanese Railway Company also sent investigation teams to the sites to explore the damage level of reinforced soil structures.

The limit states of the reinforced soil walls were classified as four different levels depending on the damage: collapse, restorability limit state (equivalent to PL3 in Table 1), serviceability limit state (PL2), and no damage (PL1). Table 4 summarizes the damage statistics of the investigated reinforced soil walls. Similar statistics during Tohoku earthquake were reported by an author and his colleagues (Miyata 2014, Kuwano et al., 2014). Although the seismic motion was much greater than the design value across a wide area, the ultimate limit state represents less than 1% for all three types of investigated walls. More than 95% of the walls exhibited no damage. The 2016 Kumamoto Earthquake was huge, and its aftershocks were also very strong. Such a strong seismic load was not considered in the design of these reinforced soil walls. However, most of the walls showed very high seismic resistance during the earthquake. This implies that the actual seismic performance of reinforced soil walls is considerably higher than the design target.

3.3 *Tasks for future development*

Through studying the Kumamoto earthquake, the authors believe that the importance of the following items should be reaffirmed:

a) Analysis of super large deformation: super large deformation analysis is needed to evaluate the impact of collapse of a structure on other structures and facilities.

b) Analysis of damaged walls due to seismic actions: after the main shock, there may be many aftershocks and rain action. Analysis of damaged walls is important for the recovery time of the damage area.

c) Estimation of seismic risk: determination of the amount of investment required for earthquake resistance should be based on the result of risk assessments. It is necessary to standardize these methods to evaluate risk fairly and quickly.

4 SUMMARY

Seismic design methods for reinforced soil structures in Japan have been introduced. In general, these are based on the concept of performance-based design; however, they differ between road and railway applications. In the 2016 Kumamoto earthquake, reinforced soil walls exhibited high seismic performance. To develop further rational seismic design, continuous efforts are required. In particular, development of a seismic stability analysis method considering large deformations and combined actions may be important.

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