Landmarks in Earth Reinforcement, Ochiai et al. (eds),
© 2001 Swets & Zeitlinger, ISBN 90 2651 863 3

Evaluation of seismic performance in Mechanically Stabilized Earth structures

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ABSTRACT: Recent earthquake events have brought about renewed interest in the response of a variety of structures to seismic loads. In the case of mechanically stabilized earth structures, such as Reinforced Earth®, current seismic design codes do not appear to fully incorporate their inherent flexibility. A brief catalogue of major earthquakes and corresponding descriptions regarding the condition of local Reinforced Earth structures is provided to demonstrate the realistic flexibility of the structures. A call for better consideration of the ductile response of Reinforced Earth is recommended based on its flexible composition of discrete steel reinforcements and select soil matrix.

1 BACKGROUND

In the last decade there have been major earthquake events in the United States (Northridge, California, 1994, 6.7 Richter magnitude), Japan (Great Hanshin, Kobe, 1995, 7.2 Richter magnitude), and Turkey (North Anatolian, Izmit, 1999, 7.4 Richter magnitude). The Northridge Earthquake was responsible for 57 deaths, 11,000 injuries and $20 billion US in damages. The Kobe Earthquake was a terrible tragedy that killed more than 5,000 people, injured 27,000 more and destroyed over 150,000 structures (houses, buildings, bridges, elevated roads, port works and utility services). The even more tragic Izmit Earthquake resulted in 16,000 deaths, 30,000 injuries and over $16 billion US in damage.

In the three earthquakes cited, there were numerous Reinforced Earth structures constructed near the respective epicenters of the seismic events. The relative flexibility of Reinforced Earth walls and their ability to withstand distress in the face of large horizontal and vertical accelerations appears to set these structures apart from the more rigid structures where significant damage occurred under seismic action. Yet by most building codes, Reinforced Earth structures are routinely required to be designed using the same quasi-static design loads as those given for rigid structures. The use of quasi-static analysis, though simple, neglects the fact that Reinforced Earth can displace to a certain extent without showing significant damage. Resulting designs may extend the reinforcements to unreasonable lengths.

The purpose of this paper is to briefly catalogue the condition of Reinforced Earth structures subjected to seismic events in the Northridge, Kobe and Izmit Earthquakes. The actual physical condition will then be compared to the criteria used in design for the walls. Even in cases where the seismic accelerations exceeded the design accelerations, it will be shown that little if any distress resulted. The rationale shall be presented that the ductility of the Reinforced Earth may allow minor permanent deflections to occur without distress that would affect service life. Although methods of calculation could be presented to predict the allowable deflections, it is instead suggested that a monitoring program be established to better assess stability versus deflection in seismic events. Suggestions for the future monitoring program will be discussed at the conclusion of this paper with an eye toward establishing a displacement criterion in design of Reinforced Earth.

2 REINFORCED EARTH SEISMIC DESIGN

French engineer and architect Henri Vidal invented Reinforced Earth over 30 years ago. The most common system is a composite material formed by the placement of granular soil and steel reinforcements as shown on the section in Figure 1. The linear steel reinforcements are connected in turn to individual concrete facing panels. The panels are held into place by the interfriction that results between the reinforcements and granular soil. Reinforced Earth is simply a coherent gravity mass engineered to be internally stable while at the same time resisting externally applied loads.

Under seismic conditions, Reinforced Earth is usually designed considering quasi-static design loads. The design method is intended to proportion structures on the basis of horizontal accelerations given in seismic areas with appropriate factors of

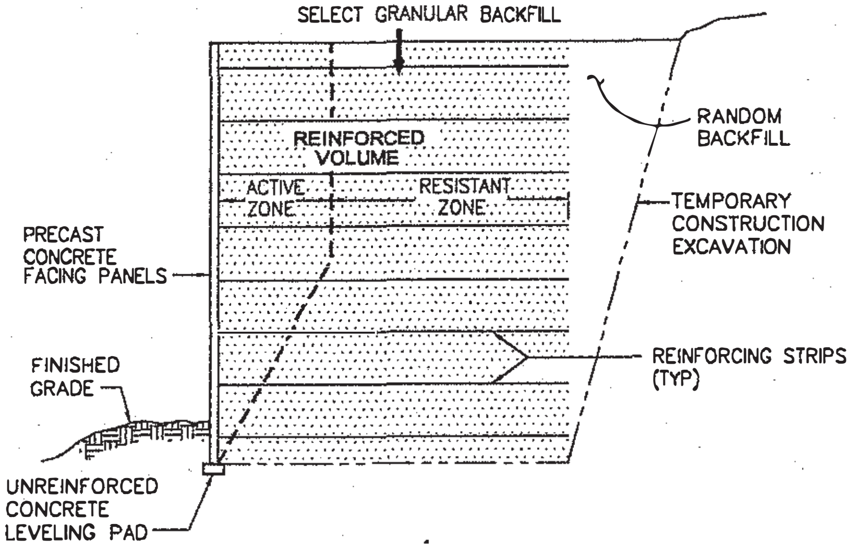

Figure 1. Typical section of a Reinforced Earth Structure.

safety for internal and external stability. A summary of the seismic design procedure for Reinforced Earth follows.

2.1 *Internal stability*

The flexibility of Reinforced Earth is fairly well addressed in internationally recognized design codes, which mirror pseudo-static numerical or reduced-scale models. The reinforcements found in Reinforced Earth are designed to withstand a combination of static forces and horizontal dynamic forces generated by the inertia of the retained soil in the active zone. The inertia force is distributed to the individual reinforcements proportionally to the available resistance of the reinforcements (resistant zone) at each level within the structure.

Under seismic loading conditions, it is understood that pullout resistance of the earth reinforcements can be reduced as much as 20% for accelerations as high as 0.4 g. Therefore, pullout resistance is conservatively taken at 80% of the resistance used in static only conditions. Factors of safety against pullout and tensile rupture of the reinforcements under combined static and seismic loading may be reduced to 75% of the factors of safety required in static only conditions.

2.2 *External stability*

The Mononobe-Okabe pseudo-static method is used in external stability computations of Reinforced Earth. However, the static force is only combined with ½ of the dynamic earth pressure and 50% of the full inertial force of the wall. Factors of safety against sliding and overturning may be reduced to 75% of the factors of safety required in static only conditions.

3 PERFORMANCE OF REINFORCED EARTH STRUCTURES

A review of the Reinforced Earth structures near the epicenters of the Northridge, Kobe and Izmit earthquakes indicated very little damage occurred to any of the structures. Of significant interest are the design-versus-actual horizontal accelerations and resulting permanent wall deflections recorded.

3.1 *Northridge earthquake*

A total of 23 Reinforced Earth structures were located within the affected area of the earthquake. Of these, over 65% were higher than 5 m and over 25% are higher than 10 m (Frankenberger, Bloomfield & Anderson 1997). The distance of the Reinforced Earth structures from the earthquake epicenter ranged from 13 to 83 km. The estimated ground accelerations varied horizontally from 0.07 g to 0.91 g and varied vertically from 0.04 g to 0.62 g. The only damage that appeared was minor spalling of concrete panels in some of the walls. It is interesting to note that adjacent structures to the Reinforced Earth structures, such as buildings, suffered much more severe damage and in some instances were posted as unsafe. Of even more interest is the fact that over 75% of the Reinforced Earth structures were designed using lesser horizontal ground accelerations than actually occurred, and over 50% of the Reinforced Earth structures were designed using no consideration for horizontal ground accelerations at all.

3.2 *Kobe earthquake*

Of the 120 Reinforced Earth structures inspected after the earthquake, 70% were over 5 m high and 15% were over 10 m high. The structures were designed using estimated ground accelerations of 0.15 to 0.2 g. The actual ground acceleration was 0.27 g. Ground movement was evident above or next to 22 of the structures, with 10 walls showing minor cracking of isolated concrete panels and 3 walls exhibiting significant lateral movement (Tatsuoka 1995 and Kobayashi, et.al., 1997). Deformations recorded in walls at Awaji Island and Hosiga-oka Park varied between 4 mm to 113 mm (displacement relative to bottom of the panel at mid-height and top of walls). All of the walls remained functional after the earthquake.

3.3 *Izmit earthquake*

A full evaluation of the Reinforced Earth structures for this particular earthquake area has not yet been completed. However, one bridge and ramp structure was surveyed at Arifiye, almost immediately adjacent to the epicenter (Segrestin 2000 and Asheim & Mander, 2000). Although the bridge itself collapsed, the Reinforced Earth ramp walls sustained only nominal damage and remained stable (Figures 2). Shear deformations from differential settlements propagated upward through the panels, separating some by as much as 75 mm. The Reinforced Earth walls were designed for a ground acceleration of 0.10 g. This resulted in only a minor increase in the amount of reinforcing strips compared to static design. Yet the actual ground acceleration was measured at 0.4 g. It is interesting to note that if the full effect of ground acceleration were considered in design under current practice, then at least 40% more reinforcement would have been added. The fact that the increased reinforcement did not prove to be needed is a good indication of the safety of the technology and conservative nature of current design principles.

4 MODIFICATIONS TO SEISMIC DESIGN PRACTICE

Design of Reinforced Earth structures under seismic conditions is based upon the concept of a rigid-plastic mechanism. However, reports of favorable deformation behavior of Reinforced Earth during recent seismic events in the United States, Japan and Turkey suggest that plastic deformation evaluation of the soil-reinforcement system should be admissible. The extent of deformation is dependent somewhat on the height of the structure and length of reinforcement. The Reinforced Earth Company is contemplating a survey of its structures in seismic areas to further the concept of plastic deformation and its evaluation. It is noted that the plastic deformation model is relevant only as far as the soil-reinforcement interaction is concerned. It may not be enough in itself to take into account the potential brittle failure of corroded strips, which would require separate consideration.

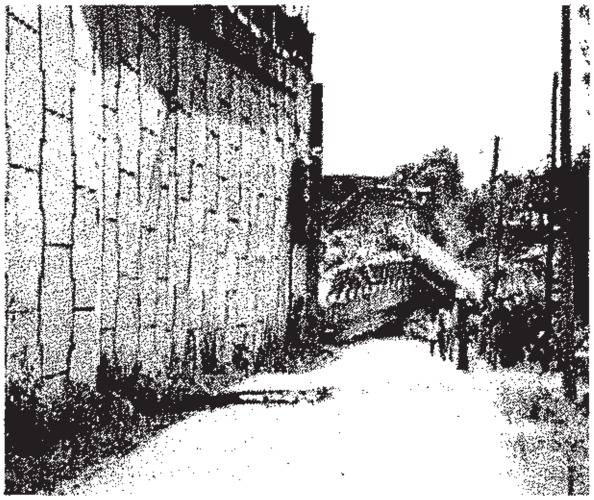

Figure 2. Arifiye Reinforced Earth ramp wall. Photo Asheim & Mander, EERI.

Finite element analyses (Segrestin & Bastick 1988) indicate that the zone of maximum stress moves out only slightly with the addition of dynamic forces and may essentially be ignored. Shake table studies (Bathurst, et. al., 1996, and Sakaguchi, et. al., 1992 and 1996) suggest that lateral wall displacements only tended to increase with decreasing reinforcement length if the reinforcement length was less than 0.7H, where "H" is the total height of wall. The reinforcement length of 0.7H is the minimum basis for design of Reinforced Earth structures. Adding to the minimum length for purposes of seismic external stability alone should not be necessary and the requirements of the static mode of design (sliding and overturning) should generally govern.

The height of a Reinforced Earth structure affects the amplification of acceleration found in the structure, i.e., fundamental frequency of the wall versus predominant frequency of the earthquake motion. It is noted that strong motion earthquakes typically have predominant frequencies of 3 Hz or less. Compare this predominant frequency to the fundamental frequencies of short walls at 10 Hz and tall walls at 3 Hz. It is not surprising that short walls, even if not designed for horizontal ground accelerations, are more or less unaffected by seismic events. It is recommended that seismic design consider the height of the Reinforced Earth structure when making evaluations, and de-emphasize the reliance on ground acceleration.

Finally, design codes should introduce a plastic deformation model in the evaluation of Reinforced Earth structures. Displacement-based design is suggested here primarily as a means to justify the reduction of reinforcement length (Michalowski & You 2000). Current design relies on no deflections to occur, as would be calculated in a steel frame structure. Instead, a deformation-based design is suggested for Reinforced earth structures that applies a safety factor to the true soil-reinforcement strength parameters, and by indirect means to the displacements calculated.

5 CONCLUSIONS

Reinforced Earth structures have proven to be safe and flexible in the presence of seismic events throughout the world. Current design codes apply a very conservative approach, especially in the determination of external stability. This paper suggests that a plastic deformation approach be taken instead in the design of Reinforced Earth structures; whereby consideration for seismic design will be based on wall height, ground acceleration, and allowable deformation. The wall height will determine how much reliance needs to be paid to seismic design, with lower height walls being less restrictive than moderate to tall walls.

Recognizing that Reinforced Earth walls can deflect and remain stable means that establishing an inventory of wall deflections after seismic events and corresponding wall heights will be important. It is recommended that a survey of Reinforced Earth structures be undertaken. To be reliable, the location of the relationship of the base of the walls with respect to the upper portions of the walls needs to be established, preferably in seismically active cities where a number of these walls would be concentrated. When significant seismic events occur in the cities where base line surveys have been completed, then follow up measurements should be undertaken. It is anticipated that actual deformation readings may be used to tailor better design models and establish more realistic and economical reinforcement lengths in safe design.

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