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Reinforced earth walls withstand Northridge Earthquake

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ABSTRACT: The Northridge Earthquake occurred in Los Angeles, California on January 17, 1994 causing severe damage and collapse of significant highway and commercial structures. There are 23 Reinforced Earth structures within the affected area of the earthquake. There was no structural damage to any of these walls and only one was found to have minor concrete spalling.

1 BACKGROUND

The 6.7 Richter magnitude Northridge Earthquake which occurred on January 17, 1994, caused severe structural damage to buildings and freeways. The earthquake occurred in the densely populated San Fernando Valley in Northridge, California, 30 km northwest of downtown Los Angeles. The earthquake was responsible for 57 deaths, 11,000 injuries and $20 billion in damages. The Northridge Earthquake was reported as the most costly natural disaster in U.S. history.

The Northridge earthquake occurred on a previously unknown thrust fault generating the highest vertical ground accelerations ever recorded in California. Ground accelerations were recorded as high as 1.93 g horizontal and 1.15 g vertical 5 km from the epicenter. The extensive structural damage within the Los Angeles metropolitan area included the collapse of 5 major freeway bridges (See Figure 1), 18 parking structures and 40 buildings.

Figure 1. Collapsed Bridge on Interstate 5 at Gavin Canyon 2 km from Lyons Avenue Reinforced Earth Wall (Civil Engineering, March 1994)

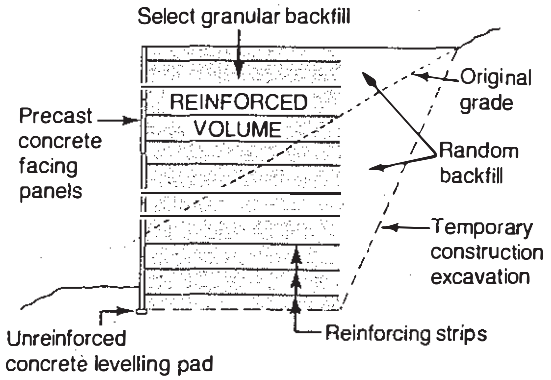

Figure 2. Typical Section of a Reinforced Earth Structure

2 REINFORCED EARTH

Reinforced Earth structures have been built and are in service in sixty (60) countries around the world. Originally invented more than 30 years ago by French engineer and architect, Henry Vidal, Reinforced Earth is a composite material formed by the association of granular soil and reinforcements. Through friction, the mechanical properties of the soil are improved by inclusion of linear galvanized steel earth reinforcements. The wall facing typically consists of articulated concrete facing panels. A Reinforced Earth structure is simply a coherent gravity mass engineered to resist the externally applied loads. A typical section of a Reinforced Earth is as shown in Figure 2.

3 PERFORMANCE OF REINFORCED EARTH STRUCTURES DURING THE EARTHQUAKE

A review of the Reinforced Earth structures near the epicenter was conducted by engineers from The Reinforced Earth Company. Many of these structures are owned by the California Department of Transportation (CalTrans) and were also reviewed by engineers of CalTrans. A total of 23 Reinforced Earth structures are located within the affected area of the Northridge Earthquake. Of these, over 65% are higher than 5 m and over 25% are higher than 10m.

The structures include 21 Reinforced Earth walls supporting rail line, highways, freeways and on/off ramps, city streets in San Pedro and Los Angeles, Chevron refinery oil storage tanks, a housing development in Los Angeles and two Reinforced Earth bridge abutments in Corona. One of the walls (Route 39) is the first Reinforced Earth structure constructed in the United States in 1972.

The distance of the Reinforced Earth structures from the earthquake epicenter range from 13 to 83 km (See Table 1). Three Reinforced Earth structures are located less than 14 km from the epicenter. In this area, ground accelerations ranged from 0.46 to 0.66 g horizontal and from 0.1 to 0.29 g vertical. Regardless of wall location relative to the epicenter, all structures have performed as intended and are fully intact and structurally sound.

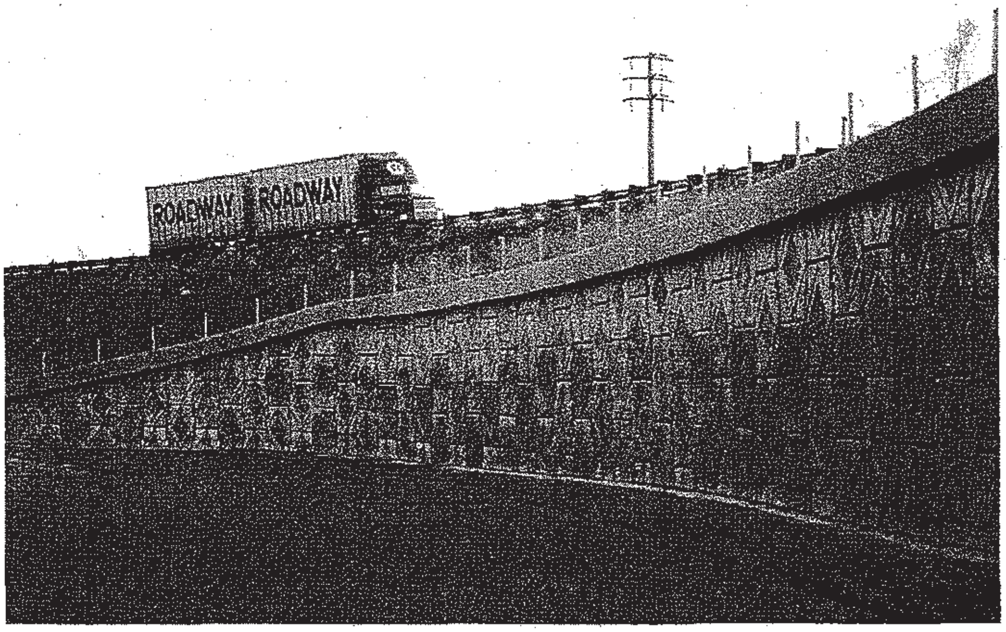

Figure 3. View of Reinforced Earth Wall at Lyons Avenue after the Northridge Earthquake

Table 1. Reinforced Earth Wall Locations and Northridge Earthquake Seismic Accelerations (California Division of Mines and Geology, 1994)

REINFORCED EARTH PROJECTS	DISTANCE FROM EPICENTER(km)	ESTIMATED GROUND ACCELERATION HORZ	ESTIMATED GROUND ACCELERATION VERT
Lyons Avenue Wall	16	.63-.91	.34-.62
Calabasas Wall	13	.46-.66	.18-.29
Berkeley Hall School Wall	13	.46-.66	.18-.29
Mountaingate Subdivision Wall	14	.46-.66	.18-.29
Metro Green Line Walls	37	.13	.04
San Diego Freeway Wall	37	.13	.04
Chevron Refinery Wall	35	.13	.04
I-110 Walls in Wilmington	51	.12-.25	.06-.08
San Pedro Beach Wall	58	.11-.25	.07-.08
I-605 Wall in Norwalk	51	.23	.14
Corona Bridge Abutments	83	.12	.03
Route 2 Mountain Wall	32	.23-.35	.11-.15
Route 39 Mountain Wall	61	.07-.15	.04-.07

The area located 10 to 20 km north of the epicenter (in the direction of the rupture propagation) recorded high ground displacements and long durations of movement. The result was a number of localized areas of significant damage to roads, bridges and buildings. One Reinforced Earth wall is located in this area at Lyons Avenue, 16 km from the epicenter. The Lyons Avenue wall shown in Figure 3, supports the southbound exit ramp from Interstate 5. Nearby collapsed structures include 3 freeway bridges on Interstate 5 at Gavin Canyon (2 km from the Lyons Avenue wall) as shown in Figure 1 and the Interstate 5/Route 14 Interchange (6 km from the Lyons Avenue wall).

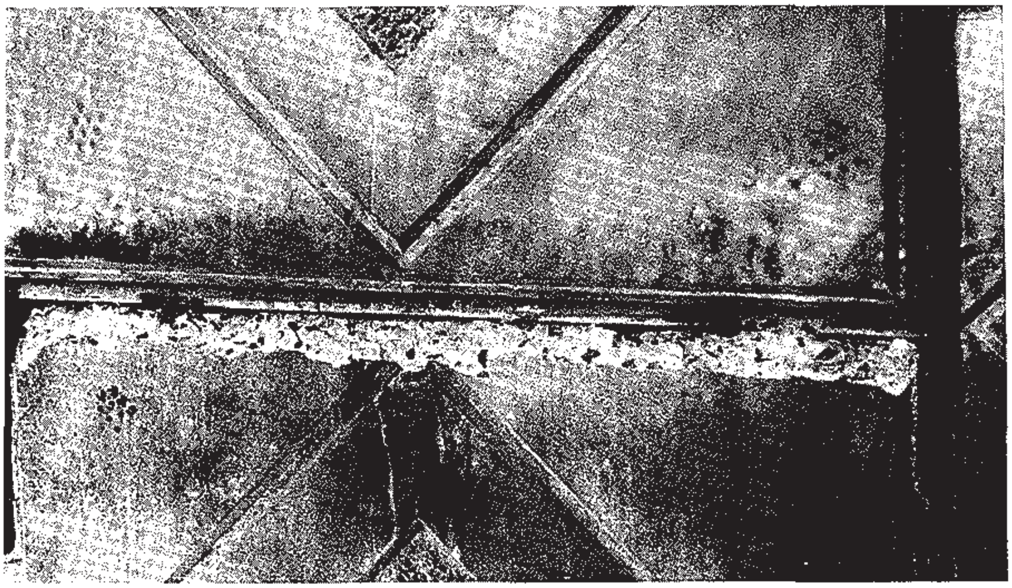

Figure 4. Spalling of bottom panel restrained from movement by embedment (Lyons Avenue)

The Lyons Avenue Reinforced Earth wall suffered superficial damage (concrete spalling) of some of the lowermost panels as shown in Figure 4.

The panels are 1.5 m wide x 1.5 m high, 14 cm in thickness and consist of 28 MPa (4000 psi) reinforced concrete. The 2 cm thick EDPM Rubber Bearing Pads located between each of the panels appeared to be flattened by seismic motions at the spalled panel locations. Recorded ground accelerations, ranging from 0.63 to 0.91 g horizontal and 0.35 to 0.62 g vertical, were high enough to cause the wall panels to move up and down. The duration of strong shaking is recorded to be 10 seconds within this area. It appears that since movement of the bottom panels was restricted by embedment, the second row of panels literally "bounced" against the top of the lower panels causing the spalling. Although enough movement occurred to cause spalling in some panels, the wall panels remain in alignment. The building next to the wall suffered severe structural damage and was posted "Unsafe" to enter after the earthquake.

Reinforced Earth structures have already been tested numerous times by actual earthquakes in seismically active regions throughout the world before the Northridge Earthquake. In Fruili, Italy, four Reinforced Earth walls were located at the epicenter of the 1976, 6.4 Richter magnitude earthquake. No damage occurred to these walls. In 1983, a serious 7.7 Richter magnitude earthquake occurred in the Akita area of Japan, causing considerable damage to buildings, bridges and port installations. None of the 24 Reinforced Earth structures in the affected area suffered any damage. In 1989, the Loma Prieta earthquake, a severe 7.1 Richter magnitude event, shook the San Francisco area causing serious damage to roadways, bridges and buildings. All 20 of the Reinforced Earth structures near the epicenter of this earthquake performed without any damage.

4 SEISMIC DESIGN

Researchers have been involved in extensive studies of Reinforced Earth structures subjected to seismic motion since 1970. The studies confirm that the current standard design for static loading allows these walls to resist earthquakes. Because of their inherent strength and flexibility, Reinforced Earth structures historically have performed without structural damage whether they were specifically designed for earthquake resistance or not. In order to conform to strict application of seismic codes a practical seismic design method was developed from the research. The design method is intended to proportion structures in seismically active areas with appropriate factors of safety with regard to external and internal stability. Based on Owner's specifications, some of the Reinforced Earth walls in this report were designed for seismic loads. For example, the Lyons Avenue wall was designed using a maximum horizontal acceleration of 0.5 g. As usual, vertical accelerations were not considered in the design. A summary of the seismic design procedure for Reinforced Earth structures is as follows.

4.1 External Stability

External stability computations are made by considering in addition to static forces, the horizontal inertia force, P_{IR} of the effective reinforced soil mass acting simultaneously with fifty (50) percent of the dynamic horizontal thrust, P_{AE}, as determined by the pseudo-static Mononabe-Okabe method. One-half of the resultant (0.5 P_{AE}) is applied to the back surface of the effective reinforced soil mass at a height equal to 0.6 times the height of the back surface of the effective soil mass, H_2. The inertia force, P_{IR}, is applied simultaneously at a height concentric with the centroid of the effective reinforced soil mass as shown in Figure 5. For a vertical wall with a horizonal backfill and a retained soil having an angle of internal friction of 30°, a free field acceleration, A, of 0.4 g, the values of A_m (the average maximum horizontal acceleration), P_{IR} (the inertia of the effective reinforced soil mass) and P_{AE} (the dynamic horizontal thrust) may be determined by the following equations:

$$A_m = (1.45-A)A$$
$$P_{IR} = 0.5\ A_m\ \gamma H^2$$
$$P_{AE} = 0.375\ A_m\ \gamma H^2$$

For other accelerations and for soils with shear strength other than 30°, the Mononabe-Okabe equations must be used to determine P_{AE}.

For structures with sloping backfills, the inertia force, P_{IR}, is based on an effective reinforced soil mass having a height, H_2, and a base width equal to 0.5H_2 determined as follows:

$$H_2 = H \frac{Tan\beta x 0.5H}{1-0.5\ Tan\beta}$$

Note: The reinforcement length, L, may need to be increased for stability, however, the applied thrusts do NOT increase and remain applied to their respective imaginary vertical boundaries as shown.

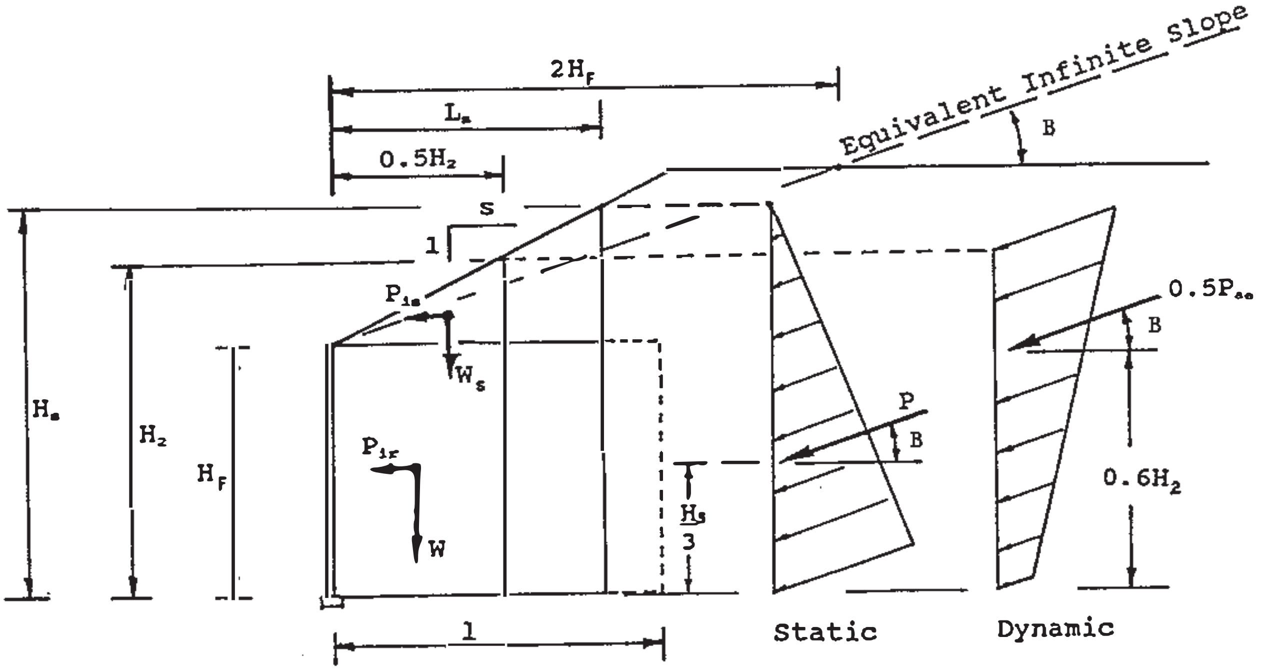

Figure 5. External Stability - Broken Back Slope Condition

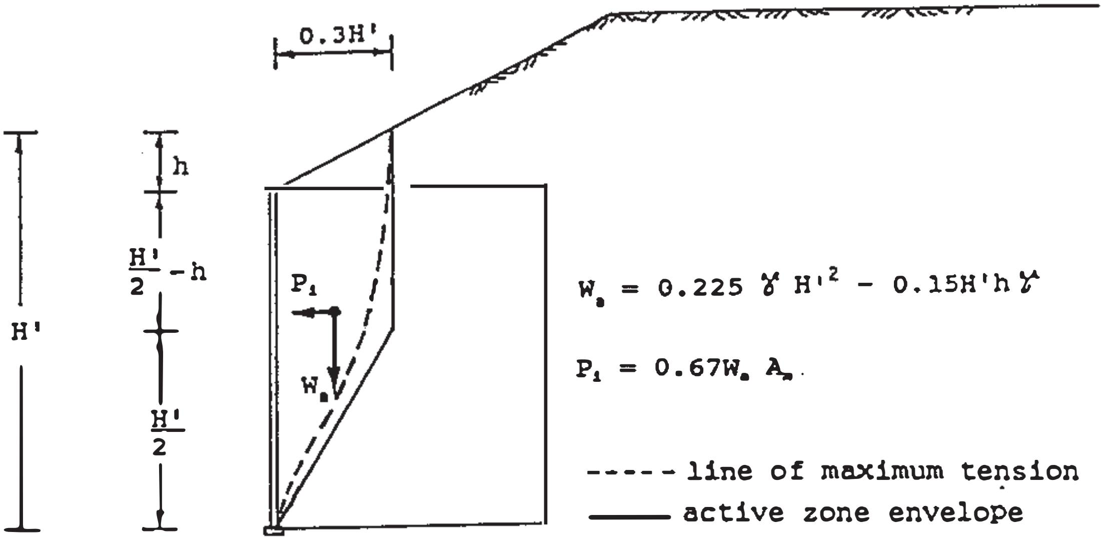

Figure 6. Internal Stability - Sloping Condition

Under combined static and dynamic loads, factors of safety against sliding and overturning may be reduced to seventy-five (75) percent of the factors of safety customary for static only conditions.

4.2 Internal Stability

The earth reinforcements are designed to withstand, in addition to static forces, the horizontal dynamic forces generated by the inertia of the soil being retained by the earth reinforcements.

The inertia force, P_i, per unit length of wall, is equal to the force generated by the inertia of the soil between the actual line of maximum tension and the facing. This equates to two-thirds (2/3) of the weight of soil within the idealized active zone envelope shown in Figure 6, multiplied by the average maximum horizontal acceleration A_m.

Within a Reinforced Earth wall reinforced with discrete linear metallic reinforcing strips, the inertia force, P_i per unit length of structure has been confirmed by F.E.M. modeling to be less than or equal to the following:

$$P_i = 0.15 \gamma H^2 A_m$$

The inertia force, P_i is distributed to the reinforcements proportionally to the available resistance of the reinforcements at each level within the structure.

For the seismic loading condition, the pullout resistance of the earth reinforcements is conservatively taken as eighty (80) percent of the resistance used for the static only condition in recognition that vertical accelerations during a seismic event can reduce pullout resistance by up to twenty (20) percent when accelerations are as high as 0.4 g.

Factors of safety against pullout and rupture of the earth reinforcements, under combined static and seismic loads, may be reduced to seventy-five (75) percent of the factors of safety required for static only conditions.

Generally, traffic surcharge is omitted from the determination of the combined static and seismic loads.

5 CONCLUSION

The superior performance of Reinforced Earth structures during seismic events can be attributed to the following factors: Reinforced Earth is a flexible structure, allowing significant differential movement to occur within the reinforced soil mass without adversely effecting the integrity of the wall panels or their supporting structure. The Reinforced Earth granular backfill serves as an excellent damping medium. Panel joints are open allowing movement of the facing panels and pore pressures (if any) to dissipate. Regarding strength, the high adherence galvanized steel earth reinforcements are designed to be in an allowable stress condition at the end of the service life of the structure. This feature ensures a minimum factor of safety against rupture of 2.2 for static loads and at least 1.65 for combined static and dynamic loads. In addition, the connection of reinforcements to the facing panels provides a factor of safety greater than 2.2 against pullout or rupture for static loads, and at least 1.65 for combined static and dynamic loads. Undisputedly, Reinforced Earth is the strongest and safest retaining wall system available in the industry. The unique combination of high adherence steel strips and flexible articulated concrete facing panels allows Reinforced Earth structures to withstand seismic events many times greater than the 6.7 Richter magnitude Northridge earthquake.

REFERENCES

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