Field observations of reinforced soil structures under seismic loading

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ABSTRACT: Design considerations for the stability of reinforced soil structures when subjected to seismic loadings is briefly reviewed. Because of the flexible nature of these structures, they are generally believed to perform well when subjected to horizontal ground accelerations. The performance of five reinforced slopes and walls that experienced the Loma Prieta earthquake of 1989 are evaluated. The observed performance of these structures demonstrates the ability of reinforced soil to withstand large ground motions.

INTRODUCTION

Steepened soil slopes and walls reinforced with high density polyethylene (HDPE) geogrids have been in use in seismically active regions of the United States for over a decade. The state-of-practice for the design of these structures is to perform a conventional pseudo-static analysis. During an earthquake, the retained fill exerts a dynamic horizontal thrust on the reinforced earth mass in addition to the static force.

Reinforced soil structures have performed well during past seismic events. This was most recently demonstrated in 1989 with the Loma Prieta earthquake near San Francisco, California. Several reinforced slopes and walls were subjected to this earthquake without experiencing distress. The performance of five reinforced slopes and walls located in the San Francisco Bay area will be reviewed and compared to the design criteria and methodology used in the original design of these structures.

DESIGN METHODOLOGY - REINFORCED SOIL WALLS

Mechanically Stabilized Earth (MSE) walls using polymeric reinforcement have been traditionally designed in seismically active areas using the Mononabe-Okabe pseudo-static approach. External stability, the ability of the reinforced soil mass to withstand driving forces exerted by the retained soil and any surcharge loads without sliding, overturning or exhibiting bearing failure, must be maintained.` The seismic forces that are exerted on the reinforced soil structure are modelled as per Mononabe-Okabe, as static forces. The design methodology considers the added static forces both within and outside the reinforced soil mass when considering external stability (Figure 1). Internal stability is the ability of the reinforced soil mass to behave as a coherent mass and be self supporting under the action of its own weight and any externally applied forces (i.e. seismic forces). This is accomplished through stress transfer from soil to geogrid reinforcement. The reinforcement is

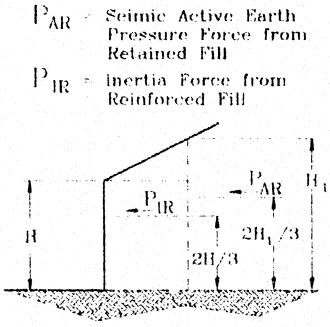

Figure 1. Mononode-Okabe Psuedo-Static Forces

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selected and placed to preclude tension rupture and to prevent pullout from the soil mass beyond the assumed failure plane. The inertia force caused by the seismic excitation of the reinforced fill, in addition to the static forces caused by a potential failure of the reinforced soil mass must be resisted by the reinforcement without rupture or pullout failure. A tieback wedge analysis is used to determine the forces in the reinforcement (Mitchell and Villet, 1986).

DESIGN METHODOLOGY GEOGRID REINFORCED SLOPES

The seismic analysis for reinforced earth slopes is conventionally performed using a pseudo-static analysis with a slope stability computer program (Tenslo1). A horizontal pseudo-static force, which is some percentage of the slice weight, is applied to the center of each slice in the analysis. A vertical force may also be simultaneously applied. Internal, external and compound failure modes should be analyzed with the additional pseudo-static acceleration force included (Berg, 1991).

A retaining wall Mononabe-Okabe approach has recently been recommended for design of reinforced slopes (Christopher et.al., 1989). However, applicability of this approach on slopes has not been demonstrated in the authors' opinion. Influence of the angle of slope face and backslope angle on applicability of the Mononabe-Okabe approach has been discussed by Seed and Whitman (1970).

The application of a pseudo-static load, either for a reinforced soil wall or slope, assumes that the load is sustained indefinitely unlike the transitory oscillation type load actually caused by an earthquake. For this reason, Seed (1983) recommends that a pseudo-static acceleration of 0.15g be set as the maximum level ascribable to limit equilibrium analyses regardless of the predicted maximum ground motion.

REINFORCEMENT STRENGTH

Polymer reinforcements, HDPE and polypropylene (PP), exhibit visco-elastic behavior and rate-dependent load strain response. Long term design strengths are therefore based on long-term creep testing. Seismic loading conditions (10-15 seconds) will induce reinforcement strain rates much higher than those used in determining the allowable strength of the reinforcement. Thus, under seismic loading the allowable long-term design strength will be higher than under static conditions (Bonaparte el.al., 1986).

LOMA PRIETA EARTHQUAKE

On October 17, 1989 at 5:04 pm (Pacific Daylight Time) an earthquake registering 7.1 (Richter) occurred along the San Andreas Fault in Northern California. The epicenter of the earthquake was 16 kilometers Northeast of Santa Cruz, California. The earthquake occurred at a depth of approximately 19 kilometers, and the fault rupture terminated before it reached the ground surface. The duration of the shaking was ten to fifteen seconds. The strongest ground shaking, accelerations of 0.64g horizontal and 0.60g vertical, were recorded near the epicenter.

This was the fourth largest earthquake in the United States since the 1906 earthquake in San Francisco. The estimated direct cost of damage from Loma Prieta was as high as $10 billion. Thousands of people were injured and major structural damage occurred to bridges, roads, commercial office buildings, houses and apartments.

The Loma Prieta earthquake was the most severe seismic event to occur since the first (1982) use of structural geogrids to reinforce steep slopes. On November 13 and 14, 1989, less than a month after Loma Prieta a group of Tensar technical specialists visited several reinforced soil structures in Northern California (Figure 2) to investigate the effects that Loma Prieta had on these structures. The following is a brief summary of the observations made during this visit.

WATSONVILLE WALL

This reinforced soil structure consists of a 3 m high, geogrid wrap face wall with a 4H:IV sloping backfill above the top of the wall. Highway 152 (a 4 lane highway) is located directly behind the slope. The project was constructed in 1986 using HDPE uniaxial (UX1200) and PP biaxial geogrids (Table 1). The uniaxial geogrids were used as primary reinforcement with the biaxial grids used to retain the soil between primary geogrid layers, at the wall face. An wood fiber mat was used on the inside of the wrap to prevent material eroding

GEOGRID DESIGNATION	STRUCTURE	POLYMER TYPE	APERTURE SIZE (mm)		THICKNESS (mm)		ULTIMATE SINGLE RIB STRENGTH (kN/m)
			MD	XD	at rib	at junct.	
UX1200	extruded, punched & drawn sheet	HDPE	99	15	1.2	4.5	78
UX1500	extruded, punched & drawn sheet	HDPE	145	15	1.3	4.3	86
UX1600	extruded, punched & drawn sheet	HDPE	137	15	1.8	5.8	117
BX1200	extruded, punched, & drawn sheet	PP	25	33	1.0	3.8	17.5

MD= machine direction
XD= cross machine direction

Table 1

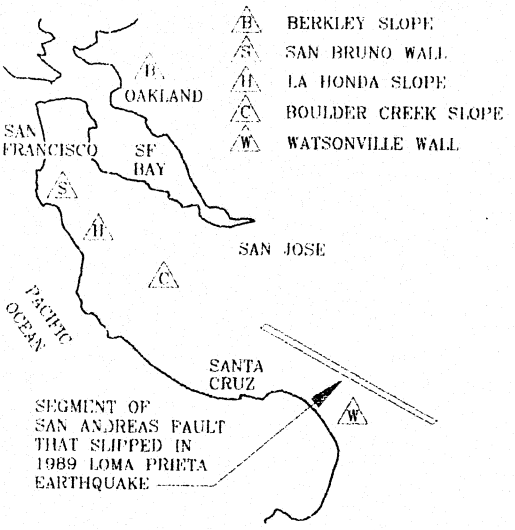
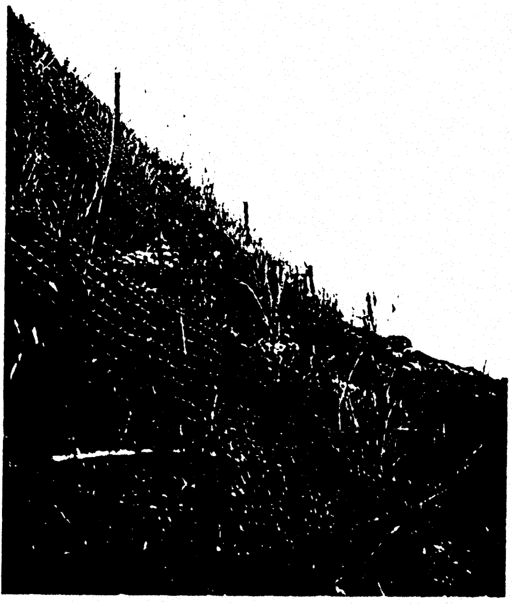


Figure 2. Location Map



Photograph 1: Watsonville Wall

through the biaxial geogrid.

This wall is located approximately 11 km from the epicenter of the earthquake. The original design for this structure incorporated a maximum horizontal acceleration of 0.1-0.2g. Estimated horizontal acceleration at the site based on data from selected stations of the California Strong Motion Instrumentation Program was 0.4g. No cracks were observed on top of this wall at the time of the inspection. Vegetation at the face of the wall was sparse which allowed for close observation of wall face movements. However, no indication of movements were observed (Photograph 1).

SAN BRUNO RETAINING WALL

This 5.5 m high structural geogrid reinforced retaining wall was constructed in the summer of 1989. It is located on a hillside directly on top of an existing steep, 1H:1V, well vegetated reinforced slope. HDPE uniaxial geogrids (UX1600 and UX1500) were used to reinforce the soil wall. The wall facing consisted of segmental concrete units. The backfill above the top of the wall slopes at an angle of 2H:1V. An access road and apartment complex are located on top of the sloping backfill (Figure 3).

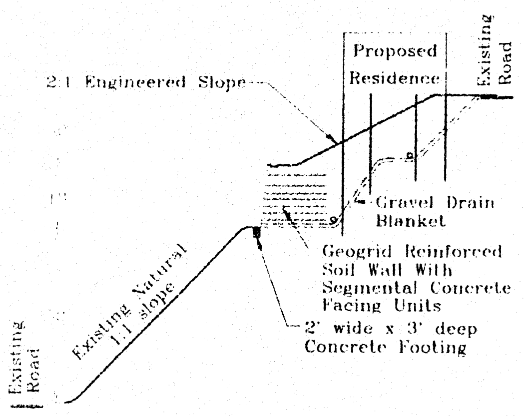
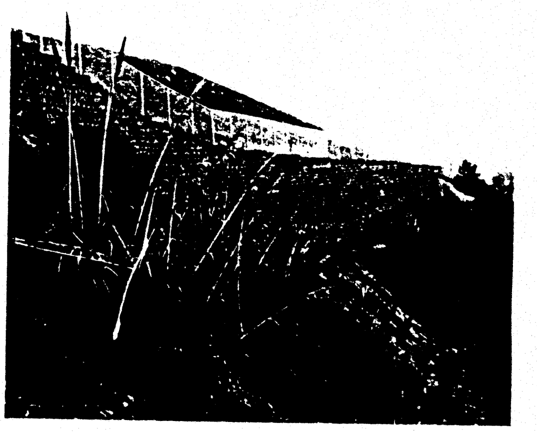


Figure 3. Typical Cross Section San Bruno Retaining Wall



Photograph 2: San Bruno Wall

The site is located along the San Andreas Fault approximately 89 km from the epicenter. The wall was designed for a maximum horizontal acceleration of 0.1-0.2g. The estimated horizontal acceleration from Loma Prieta was 0.1g. Based on visual observations there was no apparent indication of wall movement. Segmental concrete facing units were intact and in good condition. There were no apparent cracks above the wall (Photograph 2). However, a small section of the unreinforced slope below the wall had recently been repaired from a landslide failure.

BOULDER CREEK SLOPE

This structural geogrid reinforced slope is 15 m high with a maximum slope angle of 1H:1V. Uniaxial geogrids were used for primary reinforcement with biaxial geogrids used to wrap the face to prevent sloughing and erosion. The site is located approximately 26 km from the epicenter.

After the Loma Prieta earthquake the reinforced slope appeared in good condition. The estimated horizontal acceleration at this site was 0.4g. The face of the slope showed no signs of sloughing or damage. However, at the crest of the slope some minor cracking was observed. Due to the location of these cracks, it is believed that they existed prior to the earthquake.

LAWRENCE BERKELEY LABORATORY SLOPE

The Lawrence Berkeley Laboratory is located in the Berkeley Hills on the campus of the University of California. In 1985 a reinforced steepened slope was constructed to create additional parking. The reinforced slope had a maximum angle of 0.75H:lV and was approximately 24.5 m high.

The reinforced slope consists of uniaxial (UX1200) geogrids used as primary reinforcement to stabilize the slope against internal and external failures. Intermediate reinforcement using biaxial (BX1200) geogrids was placed at approximately 0.3 m intervals between primary geogrid layers, to prevent sloughing and erosion at the face of the slope. Figure 4 shows a typical cross-section of the reinforced slope including typical geogrid layout.

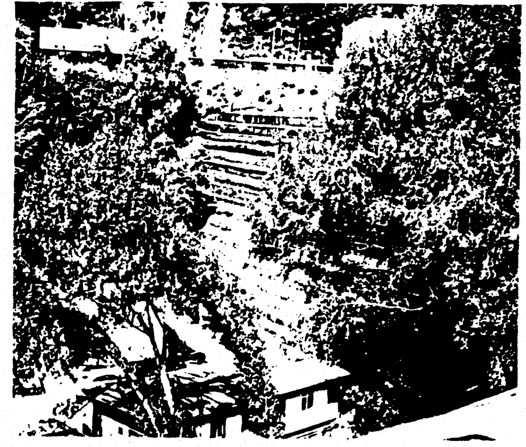
This reinforced soil structure is located approximately 130 km from the epicenter and experienced an approximate horizontal ground acceleration of 0.1g. After the earthquake, visual observations indicated that there was no apparent movement of the slope. No cracks were observed in the paved surface above the slope. The face of this slope was well vegetated near the bottom making detection of potential movement difficult. However, at the top of the slope vegetation was less dense and no indication of sloughing or cracks were observed (Photograph 3).

LA HONDA SLOPE

Following a series of heavy storms of intense duration that started in the early part of 1982 and continued throughout that year, two large landslides occurred south of San Francisco on Route 84 near La Honda, California. The landslides were the result of severe undercutting by La Honda Creek, that eroded the toe of the highway embankment. Restrictions on altering the stream bed, right of way restrictions, site geometry and traffic flow requirements prevented roadway relocation and required reconstruction of the embankment to steeper side slopes. Figure 5 shows a typical cross-section of the repaired slope which consisted of a 1.5H:IV slope for the bottom 4.5 m with a 1 m wide rock face to prevent scour. The remaining portion of the slope (9 m) had a maximum slope angle of 0.75H:IV and was reinforced with uniaxial geogrid placed 0.7 m on center.

This site is located approximately 63 km from the epicenter of the Loma Prieta earthquake. Estimated horizontal ground acceleration at the site was 0.1g. After the earthquake, visual observations indicated no physical distress, no cracks, sloughing or erosion problems (Photograph 4). In addition to visual observation of the site, movement of the slope has been monitored by Caltrans with a slope inclinometer.

The inclinometer data clearly shows movement of the upper (steeper) portion of the slope after the earthquake (Figure 6). This movement is less than 2 cm, which is approximately 0.2% of the slope height.



Photograph 3: Lawrence Berkeley Slope

Photograph 4: La Honda Slope

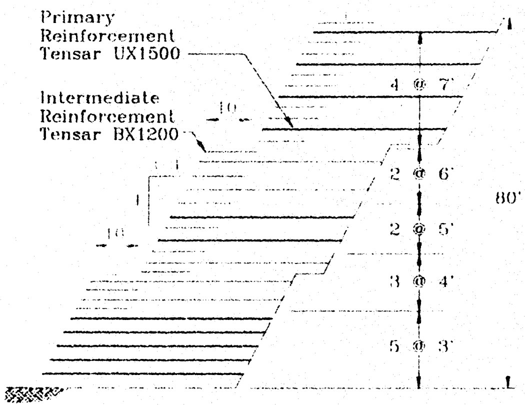


Figure 4. Typical Section Lawrence Berkeley Laboratory Reinforced Slope

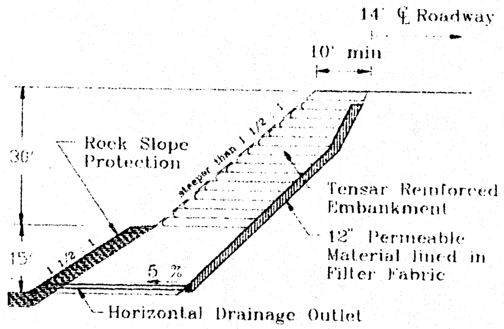


Figure 5. Typical Section La Honda Reinforced Slope

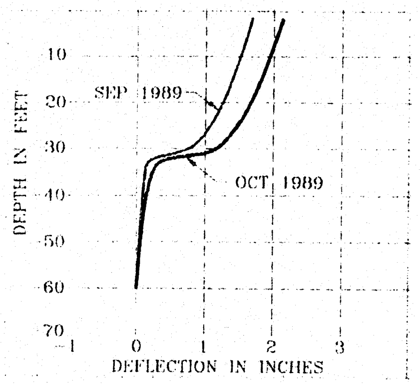


Figure 6. La Honda Inclinometer Data

CONCLUSIONS

Reinforced soil walls and steepened slopes using HDPE geogrids have been used in seismically active regions of the United States for over a decade. The performance of five reinforced soil structures subjected to the Loma Prieta earthquake has shown that these structures can withstand severe ground motions. In fact, very little if any distress was visually observed at any of the structures reviewed.

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