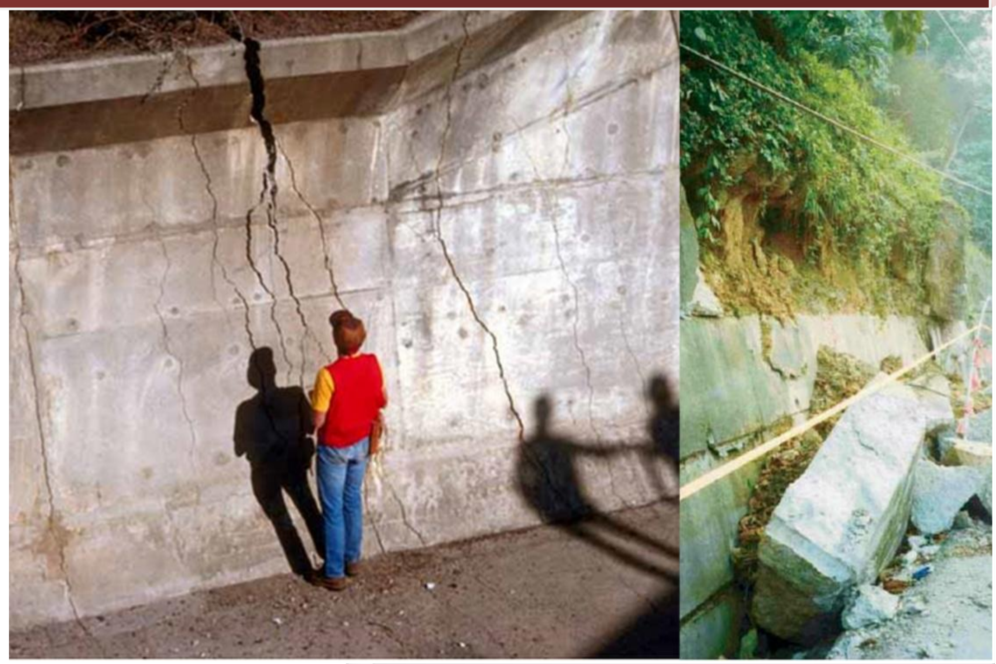
2009

Assessment of the modes of failure of retaining structures from previous major earthquakes:

Caltrans Seismic Design Analysis of Retaining Walls Project



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9/4/2009

Abstract

The report herein is part of a larger project; the objective of the larger project is to improve the seismic design guidelines for highway retaining walls. For the large project, two specimens of full-scale, reinforced concrete gravity retaining walls were constructed according to the current building code of The California Department of Transportation (Caltrans). The specimens will undergo shake table test at NEESinc's Englekirk Center for Structural Engineering facility. The testing protocols to be used are the 1994 California Northridge (Mw= 6.7) and the 1999 Turkey Izmit/Kocaeli (Mw=7.4) earthquakes. The structural performance of the retaining walls after testing will thus be analyzed and used to make changes to the current design code.

For this secondary project, assessment of the modes of failure of retaining walls from previous significant earthquake is done. A discussion is given regarding the correlations between the modes of failure and earthquake characteristics. Finally, recommendations as to which types of reinforcing techniques are most effective in resisting seismic loads are given.

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1 INTRODUCTION

1.1

What is this project about?

The main objective of the *overall* project is to develop experimentally validated seismic design guidelines for retaining walls. The *purpose* of this NEES-REU research is to analyze the modes of failure of retaining structures from previous significant earthquakes.

1.2

Motivation

The *overall* project was pursued in order to develop guidelines which will *improve* the designing of retaining walls which are able to withstand seismic loads. Developing new guidelines is essential in order to prevent significant economic losses from earthquake damage. The California Department of Transportation (Caltrans) currently uses design techniques which have not been validated by full scale models, and which also contain drawbacks. In addition to this, Caltrans wants to know the structural performance of its current retaining wall design code after been subjected to earthquakes.

2 METHODOLOGY

2.1

Setup

The experimental setup involves constructing two, full-scale models of gravity cantilever RC walls, with one of the walls fitted with a reinforced infill sound wall barrier. Multiple sensors for measuring deformations were attached to each wall including strain gauges, flexiforce sensors, MEMS sensors, linear potentiometers, and pressure cells. Each wall will be placed inside a large steel soil box and filled with silt backfill. The testing protocols for the shake table motion include the 1994 Northridge (US-Ca) and the Kocaeli (1999 Turkey) earthquakes. The walls will also be tested to failure, and the data collected will be used to improve numerical seismic design guidelines.

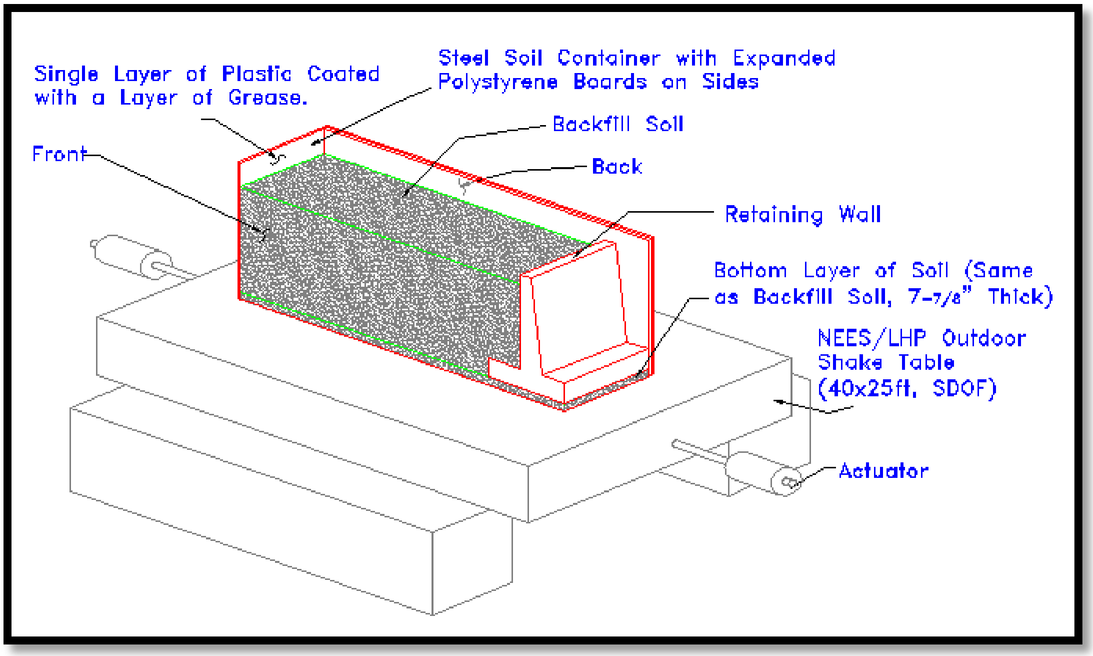

Figure 3: Shake table setup for the retaining wall specimen without a sound wall barrier.

Figure 4: Photo of the retaining walls with strain gauges attached. Note the rebars for the infill sound barrier on top of the nearest wall.

3 NUMERICAL METHODS OF RETAINING WALL DESIGN

3.1

Current methods

Currently, Caltrans employs the Mononobe-Okabe and the Newmark methods for the numerical analysis of retaining walls carrying sound walls. However, these methods do not account for all of the important parameters which affect the performance of walls during seismic excitation. The next two sections give a background of the two methods.

3.1.1

Mononobe-Okabe (Force-based) Method

This method involves assuming that the wall and the backfill soil act like a rigid object (Caltrans BDS 2004). It is only applicable where the backfill soil is homogeneous and cohesionless (NCHRP 2008 X-59). It has complexities because "the significance of various parameters is not obvious, it gives unreliable estimate for the seismic earth pressures for large ground motions and high back slope angles," and does not take the wall inertia into account (Caltrans BDS 2004).

3.1.2

Newmark (Displacement-based) Method

Also known as the *Newmark sliding block* method, this method was sought in order to overcome the drawbacks of the Mononobe-Okabe method (Cheng, unpublished internal report). It involves using a retaining wall's *yield acceleration* to compute the actual lateral displacement of the wall due to seismic excitation (NCHRP 12-70, 8-5). However, the computations for the yield acceleration are based on the Mononobe-Okabe method (NCHRP 12-70, 8-10).

4 QUALITATIVE ANALYSIS OF RETAINING WALL DAMAGES FROM PREVIOUS EARTHQUAKES

Retaining wall damages are ubiquitous throughout previous earthquakes such as the Northridge, Sichuan, Loma Prieta, Chi-Chi and L'Aquila in Central Italy. Although the failures of retaining structures take up a significant portion of transportation infrastructures, they are customarily not studied or reported since they are not of the highest priority during times of disaster. Typically however, damages range from major cracks to complete failures, depending on a number of earthquake parameters.

Just as it is important to do visual analysis of the damages suffered by commercial and residential buildings, it is essential to perform a qualitative analysis of retaining structures from various earthquakes. The following sections highlight the modes of failure from seven earthquakes. It does not seek to determine which type of retaining wall exhibits the best performance. Rather it highlights and assesses the modes and amount of damage incurred by retaining walls.

4.1 Comparison of the numerical characteristics of the earthquakes studied herein

In establishing data for the analyses, a side by side comparison of the parameters of a number of earthquakes is made, as the following table figures and depicts. The peak ground acceleration (PGA) and peak ground velocity (PGV) for the various earthquakes compiled in Table 1 were obtained from the USGS data archive, and the linear approximation of the pseudo-acceleration equation below was used to calculate the frequency of each earthquake.

Equation 1:

$$\boldsymbol{S_a = \omega\, S_v}$$

$$\boldsymbol{T = \frac{2\pi}{\omega}}$$

Where

$S_a = peak\ ground\ acceleration$

$S_v = peak\ ground\ velocity$

$\omega = earthquake\ frequency$ (Rad/s)

T = earthquake period (s)

Table 1: Numerical characteristics and durations of the seven earthquakes which are discussed in the upcoming sections.

Earthquake	Magnitude (Mw)	PGA (m/s^2)	PGV (cm/s)	PGD (cm)	Frequency (Rad/s)	Duration (s)
L'Aquila (2009) Central Italy	6.3	.62g	44.44	3.22	13.8	45.00
Northridge (1994) CA	6.7	.94g	47.83	2.47	19.3	15.00
Loma Prieta (1989) CA	6.9	1.0g	131	17.5	7.48	10.00
Kobe, (1995) Japan	6.9	.83g	82.49	8.32	9.91	20.00
Izmit/Kocaeli (1999) Turkey	7.4	1.14g	114.95	11.8	9.74	45.00
Chi-Chi (1999) Taiwan	7.6	.96g	62.10	4.11	15.1	30.00
Sichuan (2008) China	7.9	1.56g	160.18	16.7	9.58	110.00

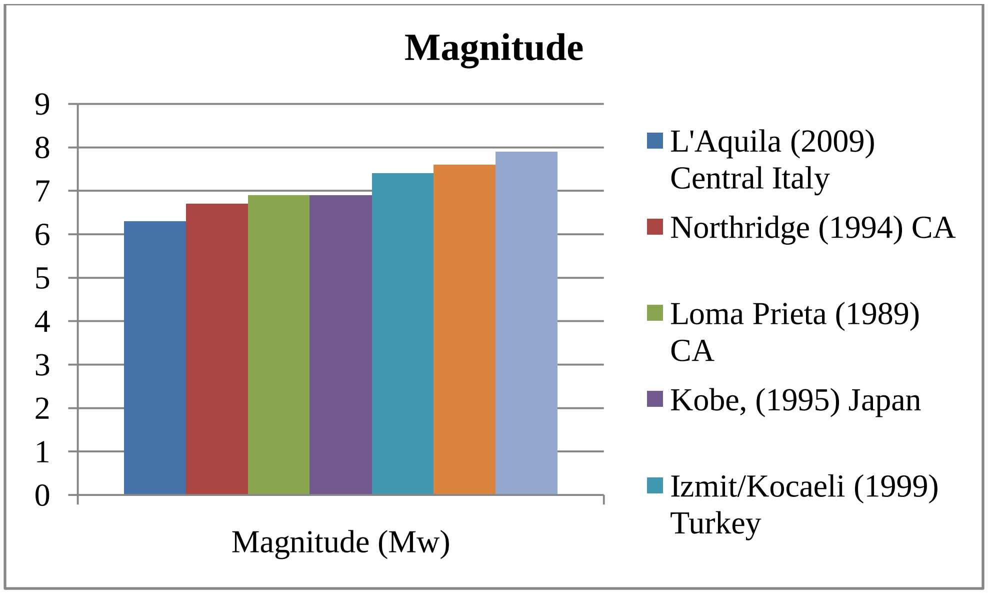

Figure 3: Graph comparing the magnitudes of the seven earthquakes. One unit in the Richter scale magnitude represents a tenfold difference in the earthquake amplitude, but a difference of about 32 times in the amount of energy released compared to the preceding whole number value (USGS Richter Magnitude Scale).

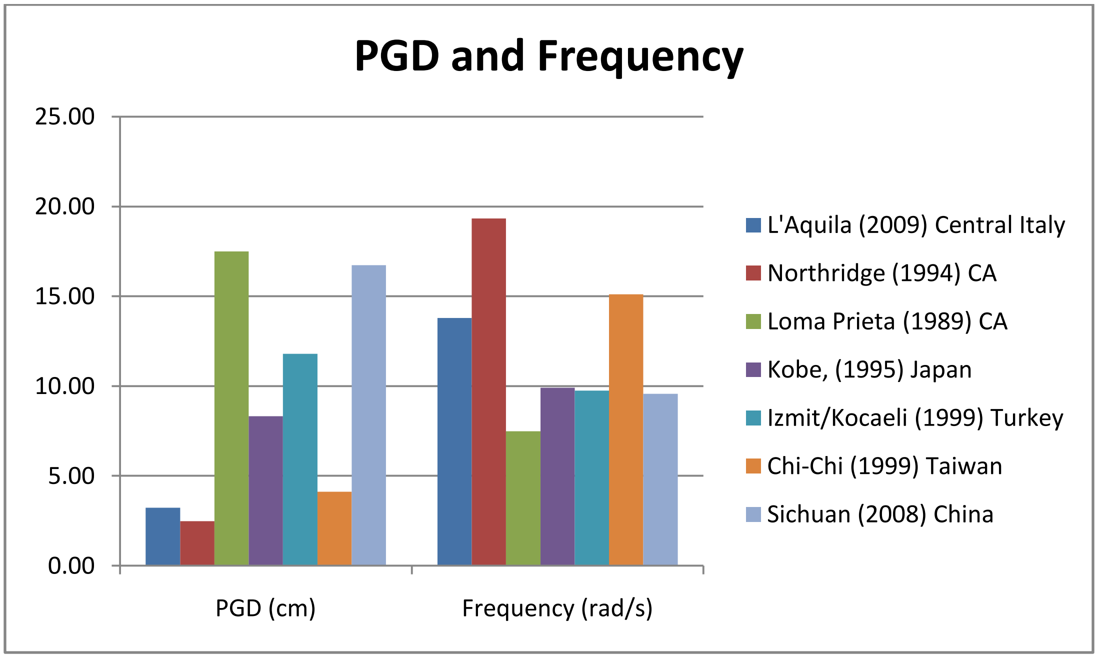

Figure 4: Side by side comparison of the peak ground displacement (PGD) and the frequencies of the earthquakes.

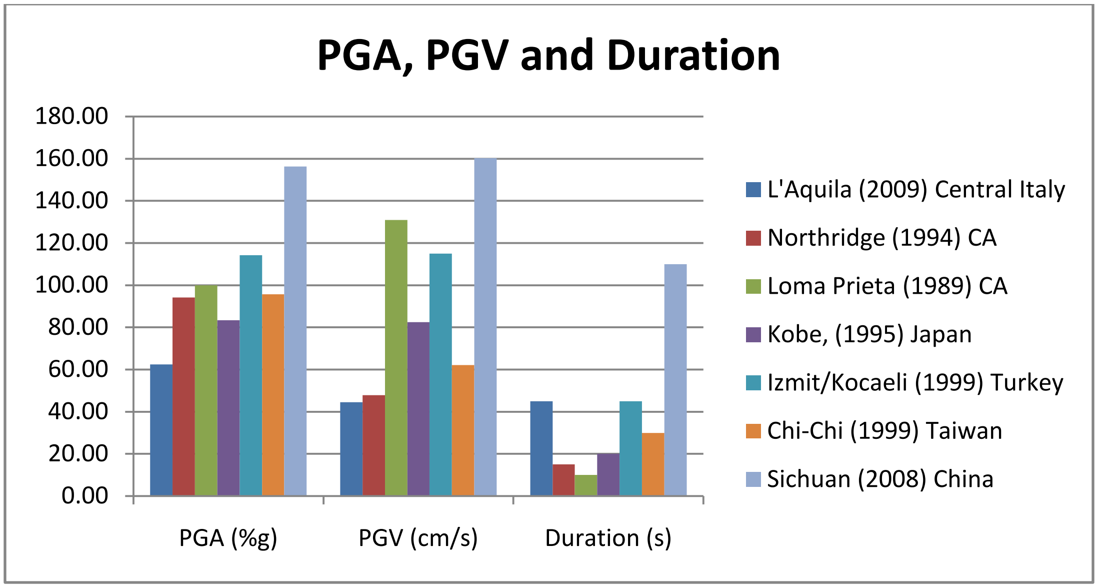

Figure 5: Side by side comparison of the peak ground acceleration (PGA), peak ground velocity (PGV) and the *duration* of each earthquake**.**

4.2

Schematics of the three types of Retaining Walls discussed in the upcoming sections:

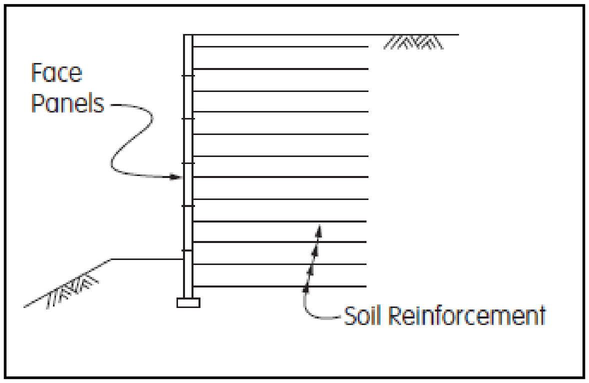

Figure 6: Mechanically Stabilized Earth (MSE) wall with panels. These types of retaining structures are designed for large wall heights and are capable of very high performances (Reinforced Earth Company®).

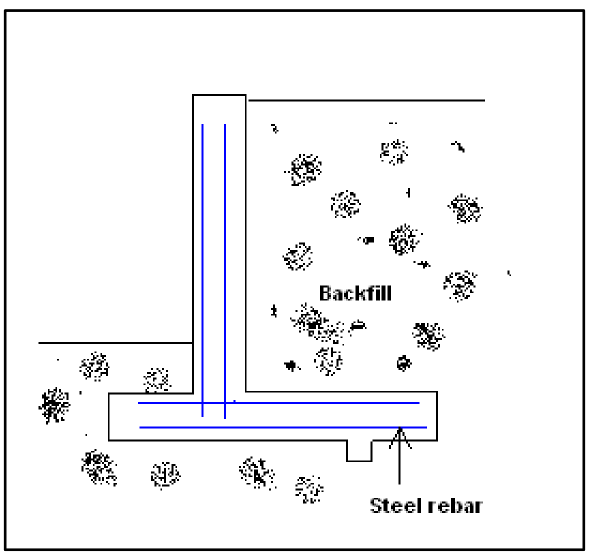

Figure 7: Reinforced concrete gravity-cantilever wall.

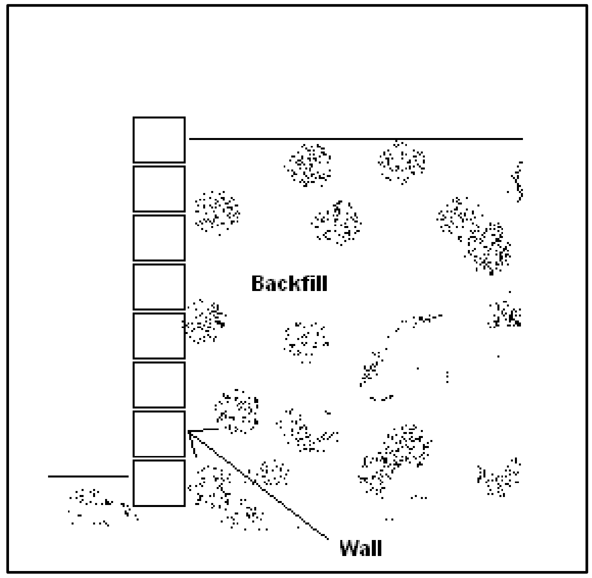

Figure 8: Block and mortar wall (no reinforcements).

4.3

Retaining Wall Damage Analyses

4.3.1

L'Aquila

Figure 9: The masonry infill of this wall failed from the L'Aquila earthquake (GEER).

Figure 10: Cracks due to the L'Aquila earthquake (GEER).

Figure 11: Total collapse of a wall from the L'Aquila earthquake (GEER).

Observations:

The magnitude 6.3 quake in L'Aquila caused significant damage to masonry infill-type retaining walls, as can be seen in the photos on this page. However, it was observed that some walls incurred only major cracks but did not undergo total collapse. The significant contrast seen here (some walls collapsing while others only failing through cracking) can best be attributed to the type of construction used for the various retaining walls. This is because the L'Aquila earthquake had the smallest magnitude, PGA and PGD. The collapse of the masonry infill was also caused by the high frequency exhibited by this quake as compared to the other earthquakes mentioned in the graphs.

4.3.2

Chi-Chi

Figure 12: This retaining wall was not reinforced; it failed at the mortar joints (Fang 1144).

Figure 13: This wall sank into the earth due to insufficient pressure support at its toe (Fang 1148).

Figure 14: Shih-Kang dam spillway failure (USBR 2009).

Observations:

The soil which the wall in **Figure 12** was supporting was used for a plantation. This being so, one sees that liquefaction might have occurred underneath the wall (Fang 1148). *This combined with the soft characteristic of the soil, are primarily what caused the wall to sink into the ground.*

The Chi-Chi quake had a ground displacement comparable to the 1994 Northridge and the 2009 L'Aquila earthquakes. It also had a frequency similar to that of the L'Aquila one. A quick observation of the photos of retaining structures from the Chi-Chi and the L'Aquila earthquakes show a *striking similarity* in the type of damages incurred by retaining walls. The walls share the same type of block construction, and in both earthquakes, the top half of the walls collapsed.

Thus, it appears that retaining walls built with unreinforced masonry infill will suffer considerable damage on earthquakes with magnitudes similar to those of the Northridge and the L'Aquila earthquakes (6.3-6.7) and with similar frequencies as well.

4.3.3

Loma Prieta

Figure 15: Loma Prieta: this retaining wall sustained major cracks (Wikipedia).

Observations:

This earthquake produced significant damage to transportation structures such as bridges, commercial and residential buildings (Irvine). In particular a span of the Bay Bridge collapsed, and many buildings built out of unreinforced blocks suffered a high degree of structural damage (Irvine).

The mechanism of this earthquake was a reverse thrust fault. This being so, much of ground motion was in the vertical direction. Liquefaction was observed on numerous buildings as well as significant damage to masonry infill structures (Irvine).

As can be seen in **Figure 13**, that section of the retaining wall only incurred major cracks, but remained in good structural condition to perform its function. According to a 1995 report published by the AASHTO, 20 reinforced earth retaining structures in the San Francisco area did not suffer damage during the 1989 Loma Prieta earthquake. Out of these twenty, only three were designed to withstand some amount of seismic activity.
As is indicated in the bar charts, the relatively *short* duration of this quake is the most appealing characteristic which favored this small amount of damage.

4.3.4

Sichuan (Wenchuan)

Figure 16: Stone and concrete retaining wall. (Source unknown).

Figure 17: Photo of another retaining wall. (Source unknown).

Although the 2008 Sichuan quake had the largest magnitude, PGA, PGV, PGD, as well as the longest duration of ground shaking, it caused the least amount of damage to retaining walls. Retaining walls such as the ones shown in the photos above performed very well even though they are not reinforced.

This fact can best be explained by the soil structure around the pertaining retaining walls. Previous analysis reports of this earthquake state that there was not much liquefaction in the soil (Mageau 12).

Figure 18: Photo of a reinforced concrete retaining wall.

Note: Reinforce concrete retaining walls are not popular in this area; however, this wall performed well and only had cracks.

Figure 19: Embankment which had a small settlement at the middle.
Note: Two reinforced soil embankments were observed; the other one (not shown) was not damaged at all because it contained more reinforcement (anchors and concrete lattice structure) which were added during a previous repair (landslide-gib.blogsot.com).

4.3.5

Kobe

Although photos of retaining walls from the Kobe earthquakes are difficult to find, one report states that 120 structures constructed from reinforced earth remained usable after the earthquake (Sankey 3). These walls were designed for horizontal accelerations of about 0.20g but nevertheless withstood the actual earthquake accelerations of 0.27g (Sankey 3).

Figure 20: Reinforced earth wall after earthquake (Sankey 3).

This retaining wall remained sound after the Kocaeli earthquake even though the bridge next to it collapsed (Sankey 3). This particular wall was designed to resist horizontal accelerations of up to 0.20g (Sankey 3). However, the reported peak acceleration around the location of this wall was 0.40g, yet the wall remained practical (Sankey 3). According to Sankey, if this wall was to be designed to withstand the 0.40g acceleration, it would have required four times the amount of reinforcing rebars compared to the original design for 0.20g. However, since the wall was able to resist seismic loads multiple times of what it was designed for, it is not always necessary to put the full amount of reinforcement in order to meet a certain design criterion (Sankey 3).

4.3.6

Northridge

Observations:

The 1994 Northridge earthquake is documented as the most damaging quake in the U.S. (Heidebrecht 298). The large amount of damage was a result of the epicenter occurring directly below a heavily populated area (Heidebrecht 298). This earthquake was also peculiar in that it produced high vertical ground accelerations (Heidebrecht 298).

Nevertheless, liquefaction was not a problem as the soil was dry (Irvine). The absence of liquefaction decreased the loadings which retaining structures encountered.

Although not many photos of retaining walls from this particular quake are available, a 1995 AASHTO report states that 20 reinforced earth walls (17 of which were owned by Caltrans) as well as two reinforced earth bridge abutments performed very well with only minor damage during the earthquake. This high performance was observed even though ten of the twenty walls were not designed to withstand any seismic loads (AASHTO MSE 9 3).

This is not surprising since reinforced earth retaining walls are constructed from alternating layers of backfill, and reinforcing strips which are parallel to the ground (Reinforced Earth Company ®). This specific design allows these types of walls to withstand very high horizontal accelerations, and hence large lateral forces (Reinforced Earth Company ®).

5 DISCUSSION

5.1

Overall Visual Analysis of RW Damages

The amount of damage incurred by retaining structures depends on a number of factors. Although the intensity of an earthquake is a good indicator of the extent of damage, the duration of the earthquake as well as the relative orientation of a structure with respect to the ground motion are more significant. The type of materials used for the construction and whether or not reinforcing techniques were used are particularly important.

One general trend from the photos depicting failure in retaining walls is that most of the walls were not reinforced and as a result suffered extensive damage. Moreover, the structures which incurred the most damage were the ones composed of masonry concrete units (MCUs). This type of construction is thus not effective in resisting seismic loads because mortar joints fail from high shear.

In looking at the observations during the Loma Prieta, Northridge and Kobe earthquakes, it is clear that *reinforced earth* walls are *very effective* in resisting seismic loads.

5.2

Frequency & Duration vs. Damage Incurred

As can be related to natural experience, the frequency of the ground motion is a major predictor of the amount of structural damage. For structures which are fixed to the earth and without seismic mitigation systems, low frequency quakes cause little damage to structures which are short in the vertical direction and vice versa. High frequency ground motion result in more damage to retaining structures than low frequency. Because reinforced earth retaining walls are made for high walls, high frequency earthquakes are even less likely to cause significant damage.

6 CONCLUSION

In analyzing the performance of the retaining structures during previous significant earthquakes, *there is stronger evidence of high performance with reinforced earth* techniques than with either masonry infill or unreinforced concrete. There is also *strong evidence of major failure of infill* walls in seismic events similar to those of the L'Aquila and Chi-Chi earthquakes.

There are some discrepancies with regards to earthquake characteristics and corresponding behaviors of failure. For instance, the L'Aquila quake had the smallest magnitude compared to Chi-Chi, Northridge, Kocaeli and Sichuan. Yet some retaining structures sustained a lot of damage. The Chi-Chi earthquake caused significant damage to as well as induced rotation and sinking to retaining walls composed of CMUs. Also, although Sichuan produced the longest shake duration, it did not cause damage to infill or unreinforced concrete type RWs. *Thus, all in all, whether or not reinforcements are implemented into retaining structures is more important than the intensity of an earthquake.* Furthermore, *the exact amount of reinforcing material need not be met in order to ensure resistance to a certain performance criterion,* as was evidenced by the bridge abutment which survived the Kocaeli/Izmit earthquake.

7 Shortcoming of this study

This study did not include the effects of backfill properties such as soil density and cohesion. However, it included the effects of saturation and found out that soil liquefaction poses more damage to retaining structures than unsaturated soil.

8 RECOMMENDATIONS

Based on the statistics of the performance of the retaining structures studied in this report, mechanically stabilized earth structures are the most ideal solution for mitigating damage due to seismic events.

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ACKNOWLEDGMENTS

This project was funded by The California Department of Transportation (**Caltrans**). Special thanks to the PI and Co PI **Prof. Dawn Cheng** and **Prof. Boris Jeremić**, respectively, as well as graduate student mentor **Erin Mock**. Also thanks to the REU Coordinators **Alicia Lyman-Holt**, **Kate Normandin**, REU Advisors from NEESit; **Lelli Van Den Einde**, **Tess Kinderman**, **Tez Tadepalli**, and the employees at the Englekirk Center for Structural Engineering.