A Tale of Two Bridges: Comparison between the Seismic Performance of Flexible and Rigid Abutments

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ABSTRACT

The number of bridges constructed on geosynthetic-reinforced soil (GRS) abutments has greatly increased over the past decade, largely because of their good performance and comparatively low costs. While significant emphasis has been placed on understanding the behaviour of GRS bridge abutments under static loading conditions, many aspects of their potential use in seismic-susceptible areas should still be investigated. This study provides a field condition survey conducted on two similar bridges constructed in a highly seismic region in Chile after being hit by the 27 February 2010 Maule Earthquake. The bridges surveyed include a bridge supported by GRS abutments and a conventional bridge supported by piled concrete abutments. It was concluded that GRS bridge abutments would likely mitigate the dynamic horizontal forces induced by bridge superstructures. Overall, based on this comparative field evaluation, GRS bridge abutments were found to provide a better response for bridges located in highly seismic-susceptible areas.

1. INTRODUCTION

The number of bridges constructed on geosynthetic-reinforced soil (GRS) abutments has greatly increased over the past decade, largely because of their good performance and comparatively low costs. In such bridges, the superstructure load is directly conveyed to a geosynthetic-reinforced backfill through bearing seats (i.e. no deep foundation). This technology has proven to be cost-effective, save time and effectively alleviate differential settlements between the bridge deck and approaching roadway (i.e. the “bump at the end of the bridge”). Reinforced soil walls have shown good performance under seismic conditions, particularly when compared to the performance of conventional retaining structures. However, since the use of soil-reinforcement in bridge abutments is deemed an emerging technology, limited research has been conducted on the seismic performance of GRS bridge abutments. While significant emphasis has been placed on understanding the behaviour of GRS bridge abutments under static loading conditions, many aspects of their potential use in seismic-susceptible areas should still be investigated. This study provides a field condition survey conducted on two similar bridges constructed in a highly seismic region in Chile after being hit by the 27 February 2010 Maule Earthquake. The bridges surveyed include a bridge supported by GRS abutments (San Francisco Bridge) and a conventional bridge supported by piled concrete abutments (Las Mercedes Bridge). They are located approximately 6.5 km apart and oriented in an approximate east-west direction. The study involves a comparison between the distresses observed in the two bridges after the earthquake. The deformations exhibited by the GRS bridge were found to be significantly smaller than those observed in the conventional bridge. It was concluded that GRS bridge abutments would likely mitigate the dynamic horizontal forces induced by bridge superstructures. Overall, based on this comparative field evaluation, GRS bridge abutments were found to provide a better response for bridges located in highly seismic-susceptible areas.

2. BACKGROUND

Reinforced soil walls have consistently shown satisfactory performance under seismic conditions deemed favourable to that of conventional retaining structures. Many research studies have been conducted to assess the behaviour of reinforced soil walls in extreme events and good performance was observed (e.g. Tatsuoka et al. 1998; Sandri 1997; Ling et al. 2001; Ling 2003). However, since the use of soil-reinforcement in bridge abutments is deemed a newly emerging technology, very limited research has been conducted on GRS bridge abutments.

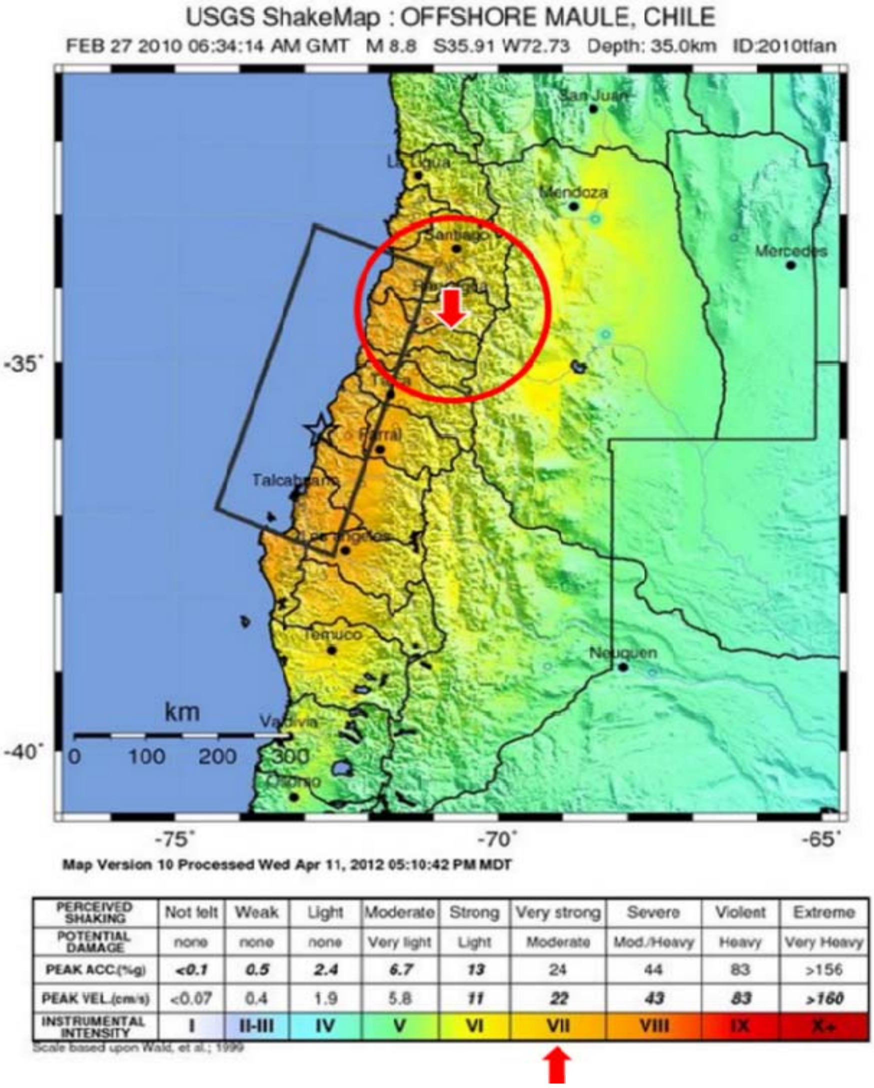
Helwany et al. (2012) conducted a study on the dynamic behaviour of GRS abutments involving a set of large-scale shaking table tests using the Triaxial Earthquake and Shock Simulator. The GRS bridge abutment performed well with small lateral facing displacements and seat settlements during the first sinusoidal motion test. The GRS abutment model withstood the vertical and horizontal loads imposed on it while being shaken by ground accelerations of 0.15 g and 1.0 g at frequencies of 1.5 and 3.0 Hz, respectively. In general, the GRS bridge abutment remained functional (i.e. no significant damage or movement) up to an acceleration of 1.0 g, at which point considerable sliding of the GRS abutment base on foundation soil was observed, though without any structural failure. Adams et al. (2012) commented that this experiment suggested that a GRS abutment is capable of withstanding at least low to medium earthquakes without any special provisions. Helwany et al. (2012) also conducted a numerical simulation of the shaking table tests on the GRS bridge abutment models and concluded that, in extreme events, GRS bridge abutments would generally experience small seat settlements (less than 5 cm) and relatively large lateral deformation (up to 20 cm). However, the study reported that bearing seats might experience sliding if the bearing pads are not properly designed. For instance, elastomeric bearing pads should have a lower natural frequency than the expected high energy frequency range of ground motion anticipated at the construction site. It was also observed that bearing pads with a natural frequency less than the frequency of the ground motion may result in a separation of the horizontal motion of the bridge superstructure and abutments, which significantly mitigates the horizontal forces conveyed to the abutments.

Adams et al. (2012) reported that seismic design for GRS bridge abutments requires an external stability check like other conventional gravity structures. They also reported that design considerations for seismicity include increasing the base width of the abutment, which enhances the bearing capacity and external stability of the abutment. Increasing the length of the reinforcement at the top of the reinforced soil mass increases the stability as well. An integrated approach has been deemed beneficial, as the various components of the structure are founded on the same soil stratum, preventing the development of a failure plane along the cut slope, which may eventually lead to a progressive failure. Adams et al. (2012) reported that no seismic design requirements are necessary for the internal stability of GRS bridge abutments.

Fox et al. (2015) conducted a study to investigate the interaction between GRS abutments and the bridge superstructure under seismic conditions. The study involved numerical simulations of GRS bridges and shaking table tests, which were validated against field and lab monitoring data. They conducted a parametric study to evaluate the effect of several design parameters on the seismic response of GRS abutments in a longitudinal direction: (1) reinforcement vertical spacing; (2) reinforcement stiffness; (3) reinforcement length; (4) friction angle of the backfill; (5) cohesion of the backfill; (6) bridge load; (7) earthquake ground motion record; and (8) bearing pad friction coefficient. It was concluded that GRS bridge abutments may be a feasible alternative for single-span and multi-span bridges in seismic-susceptible areas. The lateral deformation of the abutment facing observed upon shaking in both longitudinal and transverse directions was small and likely acceptable for major earthquakes. The vertical and lateral deformations of the bridge bearing seat observed were also small and acceptable for major earthquakes. Shear keys underneath bridge bearing seats were found to be effective in mitigating potential vertical and lateral deformations of the bearing seats upon ground shaking in a transverse direction.

3. THE 2010 MAULE EARTHQUAKE IN CHILE

The 2010 Maule Earthquake struck central Chile on 17 February 2010 at 03:34:14 AM local time (06:34:14 UTC). The United States Geological Survey (USGS) estimated the magnitude of the earthquake as Mw 8.8 (moment magnitude scale), with the epicentre located at 35.909 degrees S (latitude), 72.733 degrees W (longitude) and the hypocentre located 35 km deep. The epicentre was located 95 km from Chillán, 105 km from Concepción, 115 km from Talca and 335 km from Santiago, which are the major Chilean cities. The earthquake was deemed the fifth strongest earthquake recorded in history worldwide (Elnashai et al. 2010). In a simulation of the fault rupture, Lay et al. (2010) showed that the duration of the earthquake exceeded 3 minutes, while the significant energy was released within the first the 2 minutes. It was also concluded that the fault was bilateral, with the rupture propagating away from the epicentre in north and south directions. Elnashai et al. (2010) reported that the ground uplift movement reached up to 2 m, whereas the ground settlement reached up to 0.4 m. In addition, the Chilean coast moved westward into the ocean, with movement up to 6 m at some locations. The earthquake strongly affected a considerably large area, as shown in Figure 1. The figure shows that at some locations the intensity reached IX, according to the Modified Mercalli Intensity Scale. Note that the bridges assessed in this study were located in a region where the intensity reached VII (denoted by red arrows in Figure 1). As shown in Figure 2, the distance between the bridges and the epicentre was measured as approximately 300 km. According to the USGS, the number of aftershocks recorded after the main shock exceeded 130 by 6 March (13 of which had magnitudes greater than Mw 6.0), and 304 by 26 April of magnitude 5 Mw or more (21 of which had magnitudes greater than Mw 6.0).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1. Instrumental intensity map for the main shock (after USGS 2012).

Figure 2. Geographic distance between the earthquake epicentre and the location of the bridges (plotted on Google maps).

4. CASE STUDY BIDGES

Two bridges were selected with a primary objective of comparing the performance of GRS bridge abutments to conventional bridge abutments in seismic conditions. Among all the bridges exposed to the 2010 Maule earthquake in Chile, only one bridge was identified as having been constructed using GRS abutments. The bridge is referred to herein as the San Francisco Bridge. The writers also identified the bridge closest to the San Francisco Bridge that was constructed using conventional abutments (concrete bearing seats resting on a deep foundation). This bridge is referred to herein as the Las Mercedes Bridge. The geographic location of the two structures was identified and marked on a map, as pictured in Figure 3. The distance between the two structures was estimated at approximately 6.5 km. In addition, both bridges are aligned and oriented approximately east-west, which is perpendicular to the direction of rupture propagation of the earthquake. Yen et al. (2011) observed ground movement in the San Francisco Bridge area due to weak sensitive clays and observed no ground movement in the Las Mercedes Bridge area, but ground motion amplification likely occurred due to liquefaction or weak sensitive clays.

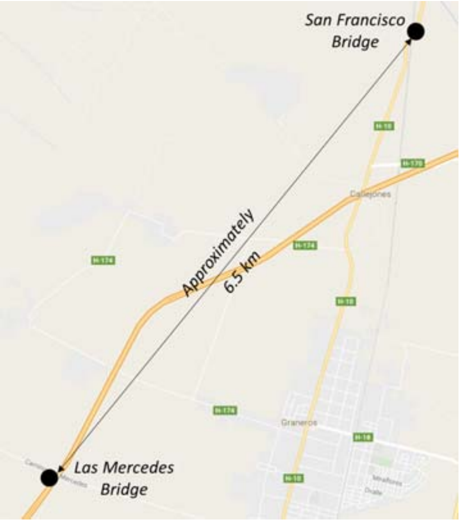


Figure 3. The geographic locations of San Francisco and Las Mercedes Bridges (plotted on Google maps).

4.1 San Francisco Bridge

San Francisco Bridge was constructed in 2001 along Route H-10 overpassing a railway line in Mostazal, O'Higgins Region, Chile. The geographical coordinates of the bridge are approximately -34.03 degrees S (Latitude) and -70.72 degrees W (Longitude), and the orientation is approximately east-west. The superstructure spans over 30 m and rests on bearing seats, which rest directly on the reinforced soil mass. The superstructure consists of four precast, pre-stressed concrete girders skewed at an angle of 39.53 degrees. The heights of the east and west abutments are 7.72 and 8.49 m, respectively, measured from the leveling pads (the base of the reinforced soil mass) up to the foundation level of the bearing seats. The foundation soil on which the abutments were constructed had a unit weight of 20 kN/m^3, a friction angle of 32 degrees and cohesion of 15 kPa. The backfill material used in the abutments was cohesionless material with friction angle of 42 degrees. The reinforcement employed in the abutments was High-Density Polyethylene (HDPE) uniaxial geogrid layers. The vertical spacing in the east abutment was 0.4 m near the top and bottom of the abutments, and 0.6 m near the mid-height of the abutments. The vertical spacing in the west abutment was 0.4 m and 0.2 m near the top. In addition, the reinforcement spacing in the wing-walls (sloping reinforced mass of the abutments) was 0.6 m throughout the height. Three different reinforcements were used with three different ultimate tensile strengths: (1) 144-kN/m reinforcement near the bottom; (2) 114-kN/m near the mid-height; and (3) 70-kN/m near the top.

The load on the footings of each abutment is approximately 210 kPa, which is the typical maximum allowed footing load in AASHTO design specifications (Allen 2012). The abutments were designed using the 2002 AASHTO Standard Specifications (Tensar Earth Technologies 2003). The acceleration coefficient used in seismic design was 0.3g. Note that the actual peak ground acceleration (PGA) measured near the bridge during the 2010 Maule earthquake ranged from 0.3g to 0.5g. However, the abutments performed very well, exhibiting no signs of lateral or vertical movement due to the earthquake. The bridge superstructure suffered some relatively minor damage, as shown in Figure 4 (Yen et al. 2011), but was still functional. The damage was probably due to the large skew angle of the superstructure and longitudinal downward slope. This combination of the large skew and slope caused the bridge superstructure to move downslope toward the acute angle in the bridge skew, resulting in the damage (Allen 2012). Yen et al (2011) reported similar observations of other skewed bridges investigated in Chile after the same earthquake event. In addition, they suggested that the damage could also have been caused by the bridge's tendency to slide downhill, as the bridge was located on a downhill roadway grade.

Figure 4. Damages observed at the San Francisco Bridge: (a) displacement in west abutment; (b) cracks in east abutment (courtesy of Daniel Alzamora).

4.2 Las Mercedes Bridge

Las Mercedes Bridge was constructed in 2001 along Camino Las Mercedes overpassing Route 5 in Graneros, O'Higgins Region, Chile. The geographical coordinates of the bridge are approximately -34.07 degrees S (Latitude) and -70.76 degrees W (Longitude). The bridge superstructure is 54-m long with two spans and oriented approximately east-west. The superstructure consists of three precast, pre-stressed concrete girders skewed at a slight angle of 11 degrees. The superstructure rests on a two-column intermediate bent and two bearing seat abutments, all of which convey the load to drilled shafts (Yen et al. 2011; Buckle et al. 2012). Two seismic bars were installed between the adjacent girders at all supports to provide lateral restraint. However, neither diaphragms nor shear keys were used to laterally restrain the superstructure (Buckle et al. 2012). Instead, the superstructure girders were supported by rubber pad bearings without any stiff connection with the abutments (Unjoh 2011).

Figure 5. Damages observed at Las Mercedes Bridge: (a) side view looking north showing unseating at west abutment; (b) west abutment unseating to the south; (c) damage due to lack of side stoppers and diaphragms; (d) surface cracks at the embankment (courtesy of Daniel Alzamora).

Las Mercedes Bridge twisted significantly in a counter-clockwise direction during the earthquake. This caused the exterior girders to displace significantly off their bearing seats at both ends as seen in Figure 5. Specifically, the superstructure was displaced transversely by approximately 1.0 to 1.4 m at both ends (Unjoh 2011). The exterior girders rotated off the abutment seats at both ends, which resulted in in a longitudinal crack between the exterior and interior girders in the deck slab. A single transverse crack also occurred in the deck slab above the intermediate pier (Yen et al. 2011, Buckle et al. 2012). Side curtain walls were damaged when hit by the superstructure (Yen et al. 2011; Unjoh 2011; Buckle et al. 2012), as shown in Figure 5a. The bridge was weakly restrained in both translational and rotational directions due to the absence of lateral restraints (Kawashima et al. 2010; Buckle et al. 2012) as Figures 5b and 5c show. Figure 5d shows minor damage in one of the bridge embankments as reported by Elnashai et al. (2010).

5. LESSONS LEARNED

- Earthquake forces on the abutments of long and wide bridges can be large and special detailing of the backwall and its foundations is required to resist these forces.
- Approach or friction slabs should be used and well anchored to avoid separation from the abutment during earthquakes (Wood 2015).
- The weight of the superstructure of the San Francisco Bridge (4 girders) was more likely higher than that of the superstructure of the Las Mercedes Bridge (3 girders). This weight difference makes the lateral forces induced by the superstructure during the earthquake on the abutments of the San Francisco Bridge higher than those induced on the abutments of the Las Mercedes Bridge. However, the lateral displacement observed for the Las Mercedes Bridge superstructure was much higher than

that observed for the San Francisco Bridge superstructure. Figure 6 shows a comparison between the lateral deformations of the seismic bars of both bridges. Note that neither bridge had lateral restraints (e.g. shear keys, diaphragms).

- The energy dissipation at bridge abutments has a significant contribution to the overall damping of the bridge under strong ground motions (Lee et al. 2011). Damping from abutment soil-structure interaction can increase the overall damping of the structure to a much higher value (Wood 2015). In this case, the flexible reinforced soil abutments of San Francisco Bridge are more likely to have higher damping compared to that of the rigid concrete abutments of Las Mercedes Bridge.


(a) (b)

Figure 6. Condition of seismic bars: (a) San Francisco Bridge; and (b) Las Mercedes Bridge (courtesy of Daniel Alzamora) (note that diaphragms were not used in either bridge).

6. CONCLUSIONS

This study involved a comparison of the performances of two neighbouring bridges upon their exposure to the 2010 Maule Earthquake in Chile. The following conclusions were made:

- In general, GRS bridge abutments, in which the superstructure load is conveyed directly to the reinforced soil mass through a shallow foundation, are deemed sustainable alternatives for bridges in seismic-susceptible areas.
- GRS bridge abutments are cost-effective and time-saving as compared to alternative conventional abutments. This is because GRS abutments do not use deep foundations.
- GRS bridge abutments can alleviate the differential settlement between bridge superstructures and their approach roadway structures, which significantly reduce maintenance costs.
- Special detailing of abutment backwalls and abutment foundations is required to resist earthquake forces.
- Flexible reinforced soil abutments are more likely to have higher damping compared to that of rigid concrete abutments.
- Although GRS abutments have demonstrated good performance under seismic loading conditions, further research is needed to fully understand their dynamic behaviour before they can be used in highly seismic-susceptible areas.