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COMPARISON OF MEASURED AND COMPUTED LATERAL SPREAD DISPLACEMENTS FOR Mw 8.8 MAULE CHILE CASE HISTORIES

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Abstract

Because earthquakes larger than M_w8.0 are relatively rare, empirical models for predicting lateral spread displacement have generally focused on earthquakes of lesser magnitude. As a result, these models have not been calibrated for larger magnitude events. Nevertheless, engineers are often required to estimate lateral spread displacements for M_w8+ events and some engineers have extrapolated in employing current lateral spreading models for predicting displacements when designing utilities, bridges, and piers. In this paper, two lateral spread case histories from the M_w8.8 Maule Chile earthquake in 2010 are used to help understand the strengths and weaknesses of various empirical models for predicting lateral spread displacements. In addition, recommendations for improving the accuracy of these models are suggested in some cases. In this paper, predictions from five empirical models commonly used in engineering practice are compared with measured displacements. The model that best matched the measured displacements from the Maule Chile case histories uses local attenuation relationships to predict ground motions rather than simple magnitude and distance terms. This approach makes it easier to apply the model to any seismic region. In contrast, models that use magnitude and distance directly are often rather difficult to apply for cases involving subduction zone earthquakes where the closest horizontal distance to the zone of energy release may simply be zero over large area of an affected region producing poor discrimination of ground motion. In addition, appropriate site-to-source distances can vary greatly between different seismic regions and for different faulting mechanisms. For this reason, models that depend on an internal source-to-site distance show less promise with large subduction zone earthquakes throughout the world. Models with site-to-source distances are most accurate in the western United States and Japan because the case histories for these models came from these countries. Nevertheless, soil properties such as the T15 thickness, the fines content, and the mean grain size all seemed to be useful in predicting displacement. Models that use shear strains from lab data typically over-predicted measured displacements but using a strain-reduction factor with depth significantly improved the accuracy of the predictions. Similarly, current CPT-based empirical equations generally over-predicted measured displacements by more than a factor of two and strain reduction factors based on depth were necessary to improve agreement with measured results.

Keywords: lateral spread; liquefaction; lateral displacement prediction

1. Introduction

Empirical models are commonly used for predicting lateral spreading in engineering practice because they are easy to use and require less costly soil investigation. These models use case histories to correlate site characteristics and displacements using multi-linear regression. Since empirical models use case histories, they are dependent upon and limited by past experiences. This has led empirical models to come with recommended input ranges to warn users against extrapolation that may invalidate the model. A variable commonly extrapolated in lateral spreading models is earthquake magnitude. Earthquakes with M_w>8.0 are less common than M_w = 6.0-8.0 earthquakes leading to less case histories for earthquakes with M_w>8.0. Current empirical models have case histories from only one earthquake with M_w>8.0, the 1964 Alaska earthquake with a M_w =9.2. Although some of these models permit the use of earthquake magnitudes up to 9.2, verification of their validity at large magnitudes is needed because of the lack of data in the 8.0-9.2 magnitude range. This research uses case histories from the Maule Chile 2010 earthquake with M_w=8.8 to examine the strengths and weaknesses of empirical lateral spreading models when used for M_w>8.0.

2. Maule Chile Case History Sites

Since Chilean ports are essential to the Chilean economy, many piers were investigated for damage immediately following the Maule Chile earthquake, leading to well documented measurements of lateral spread displacements at these sites. This study focuses on two piers in Coronel, Chile: North Pier, and South Pier, as shown in the Google Earth© image in Figure 1. Lateral spread displacements were measured at these sites following the earthquake [1, 2]. Geotechnical reports for North Pier and South Pier were made available to the research team by the Port of Coronel. After reviewing the available geotechnical information, additional CPT, SPT, and shear wave velocity tests were performed to supplement the data and ensure that quality geotechnical information was obtained at each site for the five empirical models being investigated.

Figure 1 Piers damaged by lateral spreading

2.2 North Pier

The North Pier is a conventional pile-supported pier built in 1996, which was expanded first in 2000 and again in 2004. At the North Pier, several piles supporting the pier were damaged by lateral spreading. The first three rows of piles rotated and two piles broke away from the deck and displaced over a meter as shown in Figure 2 [2]. Piles located farther along the deck were not subject to lateral spreading forces and were supported by the stronger, non-liquefiable layers beneath the sea floor. While lateral spreading caused the piles closer to shore to move out to sea, these seaward piles stayed in place, causing compression forces in the deck. This caused the deck to stay in place while several piles moved seaward.

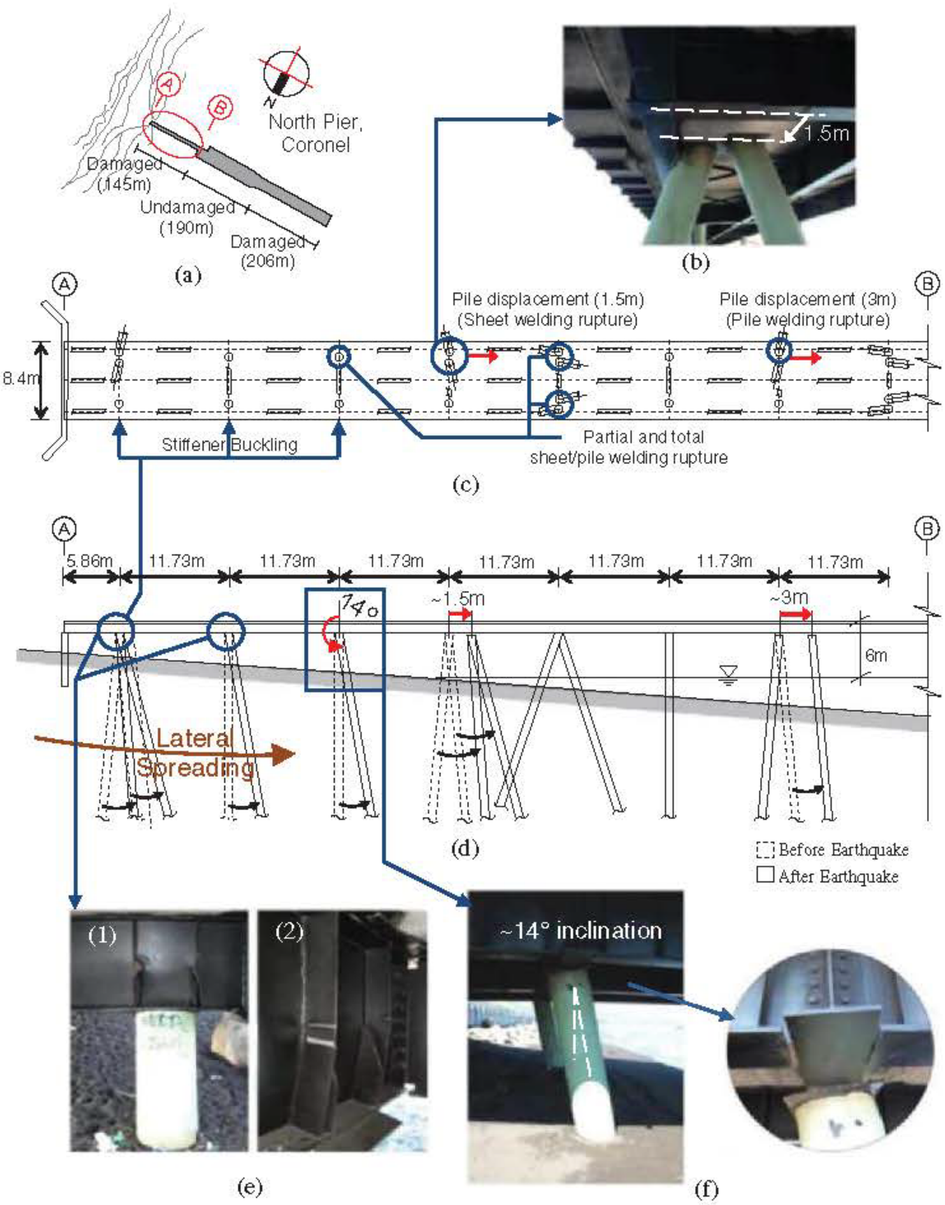

Figure 2 Lateral spread displacements at the North Pier [2]

Three of the displacements measured at the north pier site are included in the case histories. First is the ground displacement of 0.55 meters, NP-PR, that caused the third row of piles to rotate 14 degrees [1, 2]. The other two ground displacements correspond to the piles that displaced in rows 4 and 7, NP-PD1 and NP-PD2, respectively. It should be noted that the pile displacements shown in Figure 2 are measured along the bottom of the pier deck instead of the ground surface. The full 1.5 meters of pile displacement is assumed equal to the ground displacement for row 4 because the portion of exposed pile is small and both of the battered piles moved together with no signs of bending. However, the pile that displaced 3 meters in row 7 has a longer portion of exposed pile length. An analysis in L-pile indicated that the pile would bend under the ground deformations at the transition between liquefiable and non-liquefiable soils, making the displacement at the pier higher than the displacement at the ground surface. Without resistance at the pile head, the pile would freely rotate seaward under the ground deformations. Based on the angle of the bent pile, the displacement at the ground surface is about two-thirds to three quarters of the displacement measured along the deck, or between 2-2.25 meters.

2.3 South Pier

Constructed in 2006, the South Pier uses a combination of base isolated piles and flexible vertical piles to achieve greater earthquake resistance. Although the South Pier is within a half mile of the North Pier, smaller displacements were observed at the South Pier. An offset of 47 cm (SP-M1) was measured at the head of the pier between the sheet pile wall and the pier abutment, as shown in Figure 3, but no cracking patterns or other signs of displacement were observed [1]. In-situ testing at the site confirms that the soils at the South Pier, while still liquefiable, were compacted better than the soils at the North Pier, decreasing the susceptibility to lateral spreading. These denser soils are the major reason less damage was observed at and near the South Pier.

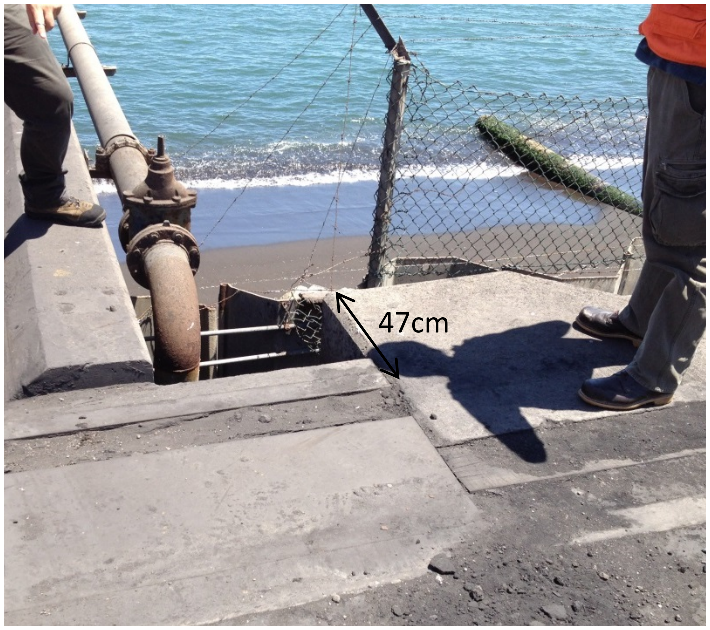

Figure 3 Displacement of ground relative to the South Pier

3. Lateral Spreading Models

Five empirical models commonly used in engineering practice were chosen for comparison of computed and measured lateral displacement values. These models are Youd, Hansen and Bartlett 2002, Bardet et al 2002, Zhang et al 2012, Faris et al. 2006, and Zhang, Robertson and Brachman 2004 [3, 4, 5, 6, 7]. The Youd, Hansen and Bartlett 2002 model was included because it is one of the most well-known and widely used equations for predicting lateral spread displacements. The Bardet et al 2002 model is similar to the Youd, Hansen and Bartlett 2002 model and was included to verify that the results from the Youd, Hansen and Bartlett 2002 model were typical for similar models. The Zhang et al 2012 model is one of the few lateral spreading models designed to be used outside of the western United States and Japan. Both the Faris et al 2006 and Zhang, Robertson and Brachman 2004 models used strain data from cyclic shear tests to develop relationships between in-situ tests, lab data, and case histories for their lateral spread models. The Faris et al 2006 model only has equations for SPT data while the Zhang, Robertson and Brachman 2004 model has equations for SPT and CPT tests. Only the results computed using the Zhang, Robertson and Brachman 2004 CPT equation are presented here.

3.1 Models that use Magnitude and Distance to Predict Ground Motions

The Youd, Hansen and Bartlett 2002 and the Bardet et al. 2002 models use earthquake magnitude and site-to-source distances in their equations to represent the effects of seismic energy on lateral spread displacements at the site. Magnitude is well defined but several methods for determining site-to-source distances exist. Youd, Hansen and Bartlett 2002 defines R as “the horizontal or mapped distance from the site in question to the nearest bound of seismic energy source” [3]. Some confusion has existed over what the nearest bound of seismic energy source means. For strike-slip earthquakes, this distance is the horizontal distance to the closest fault rupture surface because the energy is released beneath the fault as two nearly vertical faults slide past each other. However, in subduction zone earthquakes the energy can be released several kilometers away from the surface fault rupture or trench. The distance between the trench and the zone of energy release becomes more pronounced as the rupture surface between plates approaches horizontal. Youd, Hansen and Bartlett 2002 measured the distance to seismic energy source for the Alaska 1964 earthquake by measuring the closest distance to the zone of uplift [8].

During the Maule Chile 2010 earthquake, energy was released over a large area as the Nazca plate slid under the South American plate. Several rupture models of the earthquake show the plates moving past each other at the Chilean coast line [9, 10, 11]. Since these case history sites are on the shore, the distance R for the sites is zero or the minimum recommended distance for use in the models of 0.5 km. This resulted in large displacement predictions of greater than ten meters for all sites as shown in Table 1**.** Since it is common practice to use the closest distance to the fault as the site-to-source distance when predicting displacements for strike-slip earthquakes, the closest distance of 160 km from the sites to the Atacama trench was also used. However, when this distance was used, it resulted in unreasonably low predictions of lateral displacement, as shown in Table 1.

Table 1 Computed displacements for Youd, Bartlett and Hansen 2002 and Bardet et al. 2002

Site	Measured Values							Predicted Displacement			
	Disp	M_W	S	W	T_{15}	F_{15}	$D50_{15}$	Bardet	Youd	Bardet	Youd
	m		%	%	M	%	mm	0.5km	0.5km	160km	160km
NP-PR	0.55	8.8	--	18.8	4	11	0.5	>10	>10	0	0.18
NP-PD1	1.5	8.8	--	21	4	11	0.5	>10	>10	0	0.19
NP-PD2	2.0-2.25	8.8	--	37.3	3	11	0.5	>10	>10	0	0.23
SP-M1	0.47	8.8	--	12.5	1.4	43	0.1	>10	>10	0	0.04

There are several reasons that the internal site-to-source distance, R, did not provide good predictions for the Maule Chile 2010 earthquake. First, the zone of energy release for a subduction zone is so large that the value of the site-to-source distance, R, is nearly zero over a large area, leading to a poor discrimination of ground motion values. Second, the majority of site-to-source distances used in the development of the model came from case histories with a different faulting mechanism (strike-slip), and a different seismic region (the western United States and Japan). These models are inaccurate because the relationship between magnitude, site-to-source distance and ground motion is not calibrated for the Chilean seismic region or subduction zones. Therefore, these models are not recommended for use for earthquakes with M_w>8.0.

3.2 Zhang et al 2012

The Zhang et al 2012 model was developed to create a lateral spreading model that is accurate in all seismic regions, not just Japan and the western United States. This model is similar to the Youd, Bartlett, and Hansen 2002 model but replaces the site-to-source distance variable, R, with the pseudo displacement at a period of 0.5 seconds, SD. Local attenuation models are used to calculate the pseudo displacement expected in a particular seismic region. By using a local attenuation relationship to account for the characteristics of a particular seismic region and faulting mechanisms, this model seeks to predict more accurately the displacements in countries outside of the western United States and Japan [5] and it was generally successful in Chile.

For the Maule Chile 2010 sites, the Chilean attenuation relationship developed by Contreas and Boroschek 2012 [12] was used. The Zhang et al. 2012 model predicted the displacements for the Maule Chile 2010 case histories with much greater accuracy than the models with site-to-source distance as shown in Figure 4 and Table 2. However, one of the predictions fell just outside the factor of two accuracy range common for lateral spread models. Models such as the Faris et al 2006 and Zhang, Robertson and Brachman 2004 models only predict the maximum displacement at a site. When only the maximum displacement at each site was used, all of the computed values were within the typical accuracy range for the model, as shown in Figure 5.

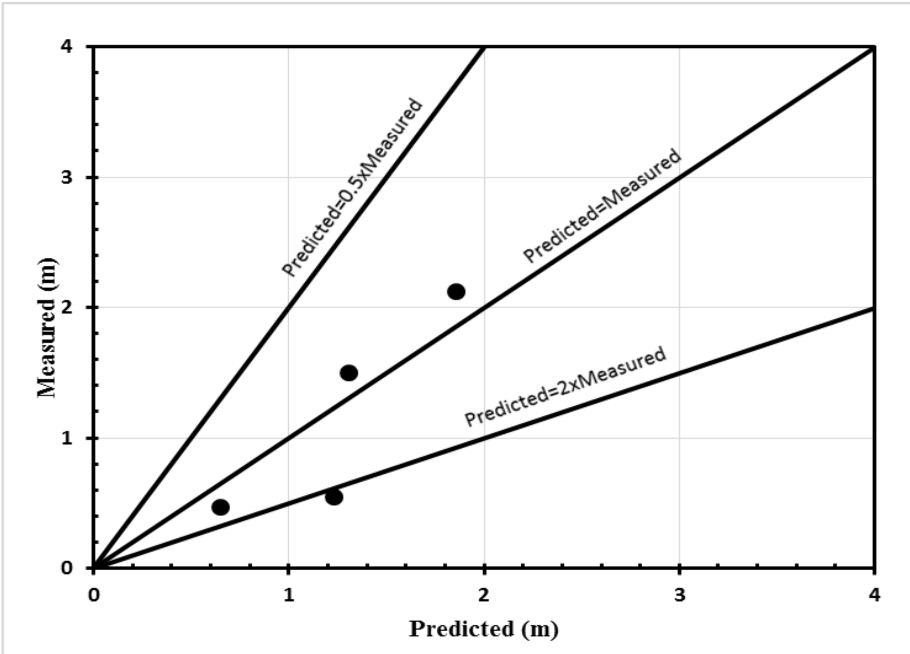

Figure 4 Predicted verses measured displacements for Zhang et al. 2012

Table 2 Computed displacement for Zhang et al. 2012

Site	Disp (m)	SD	DH(m)	Pred/Meas
NP-PR	0.55	0.054	1.23	2.24
NP-PD1	1.5	0.054	1.31	0.87
NP-PD2	2.0-2.25	0.054	1.86	0.88
SP-M1	0.47	0.054	0.65	1.38

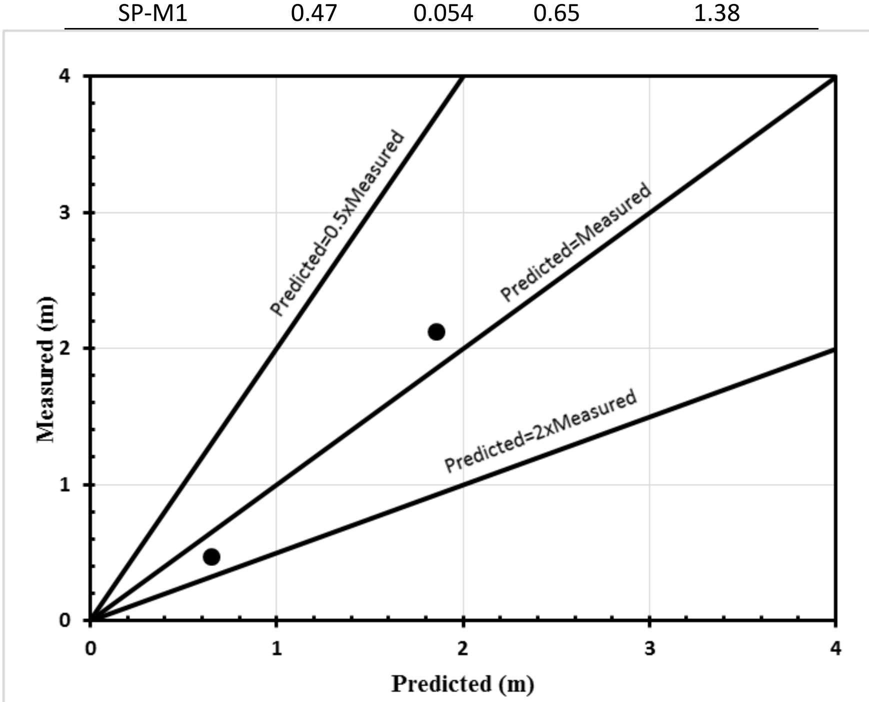

Figure 5 Zhang et al 2012 with the maximum displacement for each site

3.3 Zhang Robertson and Brachman 2004

Zhang, Robertson and Brachman [7] used a combination of laboratory data and lateral spread case histories to create their model. The model uses the strain potential of soil based on cyclic shear strain tests to develop a prediction for how much the soil will move. Displacements for the Zhang, Robertson and Brachman 2004 model were calculated by using the CPT analysis program within Cliq [13] that uses this approach. The maximum displacement at each site was over-predicted by more than a factor of two, as shown in Table 3 and Figure 6. Cliq has an option to apply the strain reduction factor from Cetin et al 2004 [14] to gently sloping cases to account for the effect of depth on strain. This reduction factor was originally developed to account for the decrease in liquefaction settlement with depth. When the Cetin et al 2004 strain reduction factor was also used on the free-face sites, the accuracy of computed displacements increased dramatically. The error for both the North and South Pier decreased to below a factor of two as shown in Table 3 and Figure 7. CPT data was not available at every case history site used to develop this model, so correlations between SPT and CPT data were used to fill in missing data. This lack of CPT data and use of correlations may have contributed to the increased error within this method.

Table 3 Computed Displacements for Zhang, Robertson and Brachman 2004

				Original		With Cetin et al 2004	
Site	Max Disp (m)	S (%)	W (%)	D_H(m)	Pred/Meas	D_H(m)	Pred/Meas
NP-PD2	2.0-2.25	--	37.3	5.10	2.40	2.14	1.00
SP-M1	0.47	--	12.5	1.93	4.11	0.89	1.89

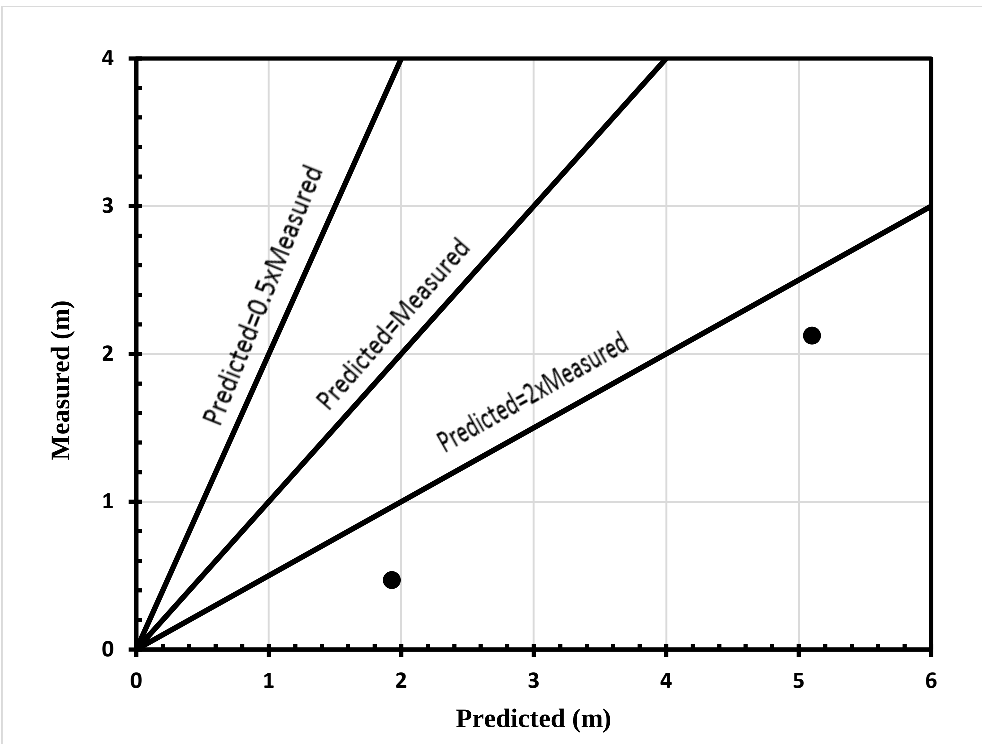

Figure 6 Predicted versus measured displacements for Zhang, Robertson and Brachman 2004

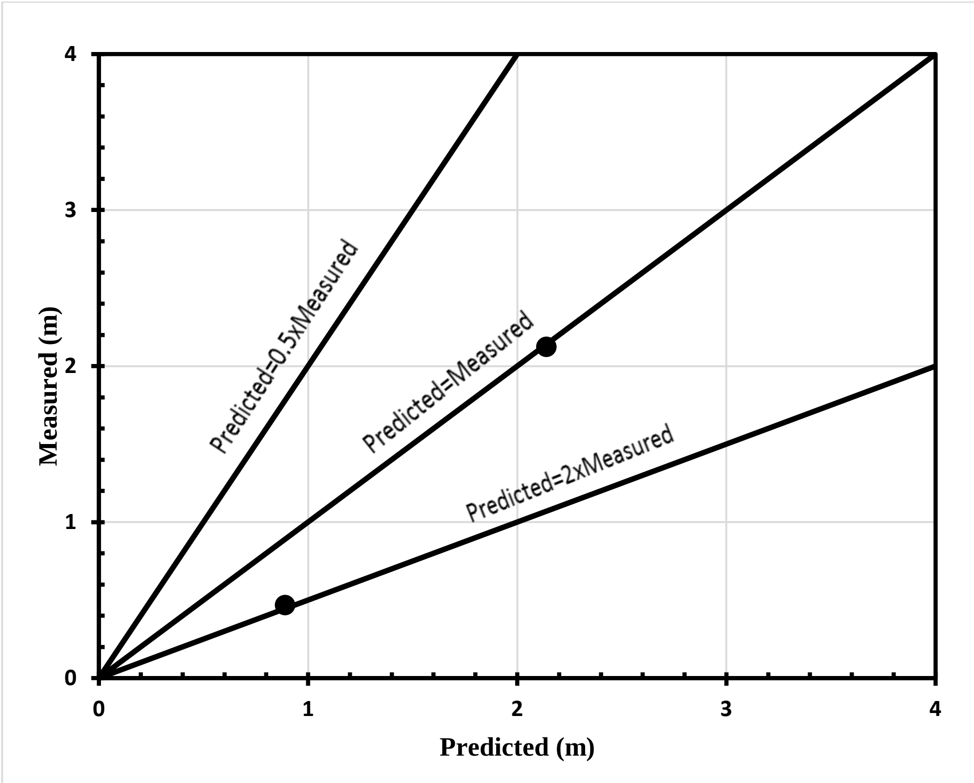

Figure 7 Zhang, Robertson and Brachman 2004 with Cetin et al 2004 correction factor

3.4 Faris et al 2006

The Faris et al 2006 model is similar to the Zhang, Robertson and Brachman 2004 model, but was solely developed for SPT data. A special characteristic of the Faris et al 2006 model is the way that the geometry is calculated. The geometry can be calculated using a free-face geometry, slope geometry, or a combination of both. Computed displacements using the Faris et al 2006 model were all greater than the measured displacements for the case history sites in Chile, as shown in Figure 8. However, the computed values were significantly better than the values calculated with the Zhang, Robertson and Brachman 2004 CPT model. The Cetin et al 2004 strain reduction factor was also combined with this model, as shown in Figure 9 and Table 4. For the Faris et al 2006 model, the benefit of using the Cetin et al 2004 reduction factor is less clear than with the Zhang, Robertson and Brachman 2004 model. However, the use of the strain reduction factor may be helpful to avoid overly conservative estimates, when large displacements are calculated and it is planned to use a safety factor of two.

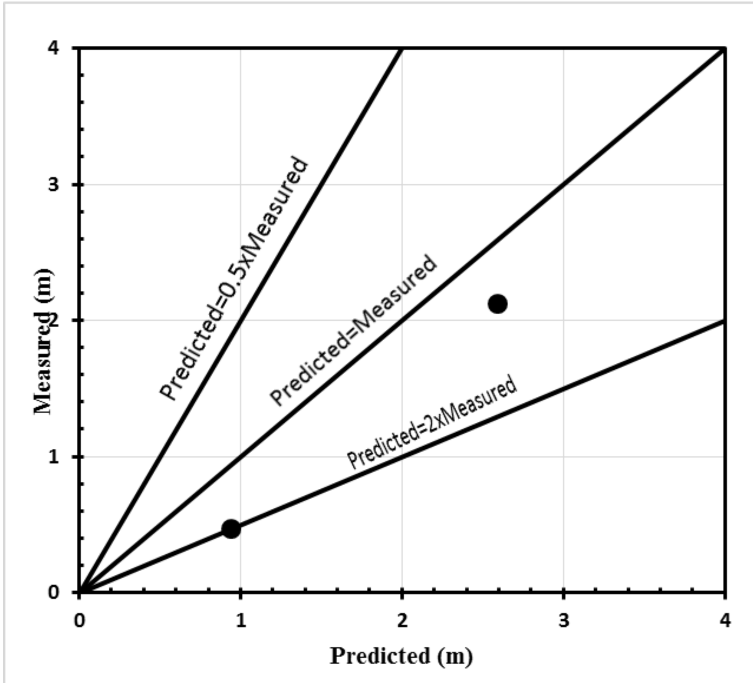

Figure 8 Comparison of measured and computed displacements using Faris et al 2006

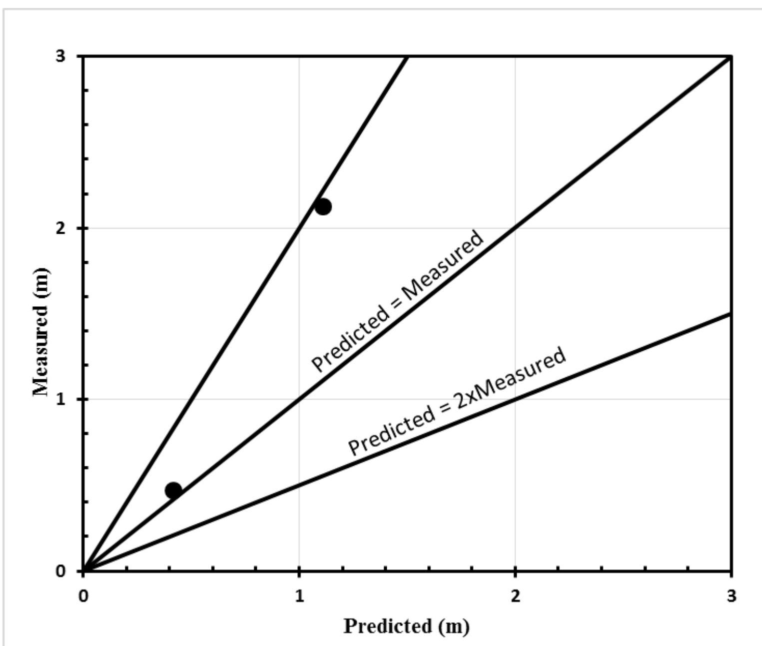

Figure 9 Comparison of measured and computed displacements for Faris et al 2006 with strain reduction factor

Table 4 Computed displacements for Faris et al 2006

				Orginial		W/ Cetin et al 2004	
Site	Disp (m)	∑DPI	α	DH(m)	% Error	DH(m)	% Error
NP-PD2	2.0-2.25	2.38	58.1	2.59	17%	1.11	-52%
SP-M1	0.47	0.9	54.6	0.94	100%	0.42	-11%

5. Conclusion

1. The Maule Chile 2010 case histories provide important additional insights to predicting lateral spread displacements for M_w 8+ earthquake events.
2. Empirical lateral spreading models with an internal site-to-source distance such as Youd, Hansen and Bartlett 2002 and Bardet et. al 2002 are not recommended for predicting lateral spread displacements for subduction zone earthquake events.
3. The Zhang, et al. 2012 model predictions for the maximum displacements at the case histories was within the factor of two accuracy range without a trend towards over or under prediction. This model is considered the best match for the case history sites.
4. Both the Faris et al 2006 and Zhang, Robertson and Brachman 2004 models have a trend towards over prediction of the case history sites.
5. The Cetin et al 2004 depth reduction factor should be used with the Zhang, Robertson and Brachman 2004 model for M_w 8+ earthquake events because the model tends to over-predict the displacements for the sites by more than a factor of two.

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