PERFORMANCE OF BRIDGES IN LIQUEFIED GROUND DURING 1999 CHI-CHI EARTHQUAKE

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ABSTRACT :

The 1999 Chi-Chi, Taiwan Earthquake is one of the best-documented seismic events in history. Numerous cases of ground failure were caused by liquefaction and cyclic failure of young, saturated loose sediments. Reconnaissance efforts aimed at documenting these cases of ground failure were often near bridges, many of which exhibited no adverse effects from liquefaction and were therefore not systematically studied after the earthquake. This paper presents cases of bridges that were founded in soils that exhibited evidence of liquefaction and lateral spreading near the bridges, but had little adverse impact on performance of the bridges. These case histories provide an opportunity to evaluate how well our engineering calculation procedures can predict good performance.

KEYWORDS: Bridge, Liquefaction, Lateral Spreading, Foundation, Pinning

1. INTRODUCTION

The September 21, 1999 Chi Chi earthquake (M_w = 7.6) was one of the best-documented earthquakes in history. Extensive liquefaction and ground failure of natural sediments occurred in near-fault regions (Stewart 2001), providing ample opportunity to validate engineering evaluation procedures against valuable case history information. Chu et al. (2006) performed site investigations at sites where liquefaction-induced lateral spreading had occurred, and some of these sites were near bridges that were not adversely affected by the observed ground failure. While the goal of their study was to evaluate methodologies for estimating lateral spreading displacements, the proximity of their sites to bridges is fortuitous for also validating engineering evaluation procedures for bridges in liquefied ground. Case histories involving good performance of bridges are often overlooked due to the understandably sharp focus on cases of failure. However, cases of good performance are just as important as cases of poor performance for validation of engineering evaluation procedures. Therefore, the cases of good bridge performance observed at lateral spread sites in Taiwan are important to document so that they may be used in validation studies. This paper presents a fairly detailed documentation of soil conditions and structural performance of four bridges near sites studied by Chu et al. (2006), and a more cursory discussion of five other bridges documented by Lin and Suen (2000) in a report in Chinese. Presented first is the Leuw-Mei bridge, which is a multi-span bridge that suffered some shaking-induced damage to bearings, but no measurable foundation deformation despite lateral spreading on both river banks upstream and downstream of the bridge. Presented second are three short single-span bridges whose superstructure acted as a strut to hold back the river banks that would have otherwise spread toward the channel. Finally, implications of the observed performance of these bridges are discussed.

2. LEUW-MEI BRIDGE

The Leuw-Mei Bridge in Nantou is a 7-span curved bridge with six short reinforced concrete box girder spans ranging from 21*m* to 28*m* long, and one 140*m*-long cable stay steel span over the Miao-Lo River (Fig. 1). The bridge was constructed in 1998 as a replacement for a previous bridge, and was within a kilometer of surface rupture of the Chelungpu Fault. The superstructure spans are simply-supported on reinforced concrete bearings atop the 2*m* diameter reinforced concrete piers (Fig. 2). The bearings were crushed by inertia forces due to strong ground shaking, and lateral displacements of nearly a meter were measured in the transverse direction after the earthquake (Lin and Suen 2000). A 20 cm vertical offset was observed at the pier supporting one side of the steel cable stay span because the steel span was supported on taller bearings than the reinforced concrete span, and therefore settled more when the bearings crushed. No damage or permanent deformations of the foundations were observed after the earthquake, hence the cause of damage to the bearings was attributed to inertia loads.

The abutments of the Leuw-Mei Bridge were founded on spread footings, while the pier columns were founded on large 5*m* diameter reinforced concrete caissons embedded to depths of 17 *m* (Fig. 3). The caissons consist of an 80-cm-thick reinforced concrete ring with the center backfilled with soil, except in the bottom 3*m*, which was filled with unreinforced concrete, and the upper 2*m*, which comprised a reinforced concrete cap. The caisson detailing in Fig. 3 is for the middle portion of the caisson at the location where the arrows are pointing in the figure. A total of 100 19ϕ bars ran in the longitudinal direction around the perimeter of the wall, with 50 bars near the inside of the caisson and 50 near the outside. The lower portion near the tip of the caisson was more heavily reinforced presumably due to stresses anticipated during construction of the foundation. However, large demands near the tip of the caisson due to earthquake loading (either inertia or lateral spreading)

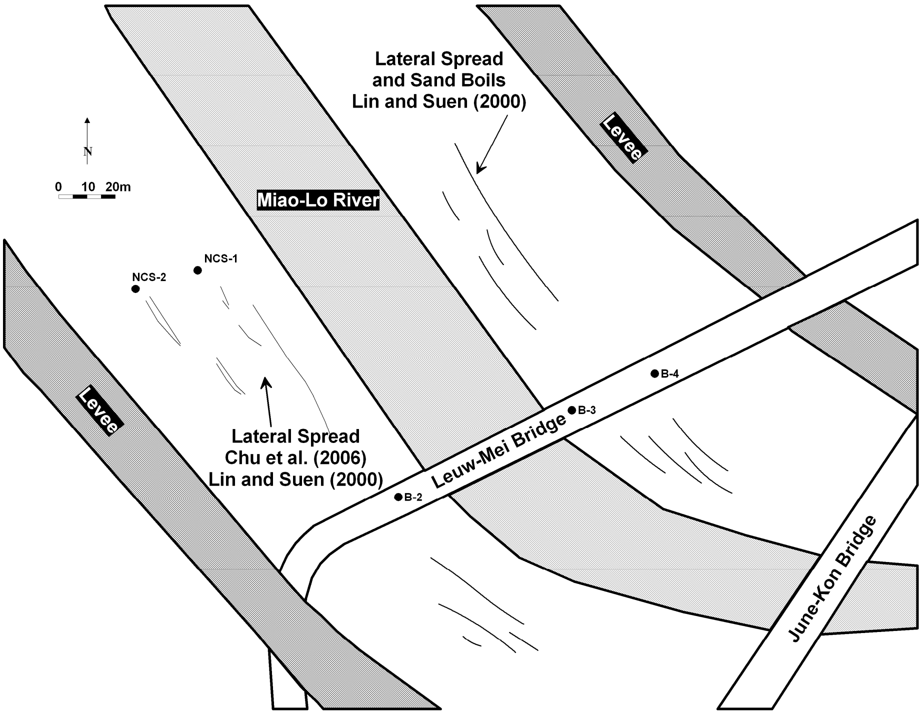

Figure 1: Plan view of Leuw-Mei Bridge, observed lateral spreading, and locations of soil site investigations.

Figure 2: Photo of Leuw-Mei Bridge (Courtesy of Rob Kayen).

would not be anticipated since the caissons were embedded deeply in competent soil. Hence, the heavy reinforcing in this region is expected to have little impact on the seismic performance of the caisson.

While the bridge damage was attributed to strong shaking and resulting inertia loads, surface evidence of liquefaction and lateral spreading was also observed near the bridge. The young alluvial river bank deposits on both sides of the river liquefied and spread laterally (Lin and Suen 2000, Chu et al. 2006), with displacements as large as 25*cm* measured by Chu et al. (2006). Surface evidence of lateral spreading was not apparent in the soils along the bridge axis, but was apparent on both banks of the Miao-Lo River both upstream and downstream of the bridge. The presence of lateral spreading all around the bridge, but not along the axis of the bridge, leaves two possibilities: (1) the soil was stronger near the bridge, and therefore not as susceptible to lateral spreading as the soils upstream and downstream, and/or (2) the bridge components imposed forces on the soil that restrained downslope displacements, thereby reducing the observed lateral spreading amplitude. Possibility (1) will be explored first.

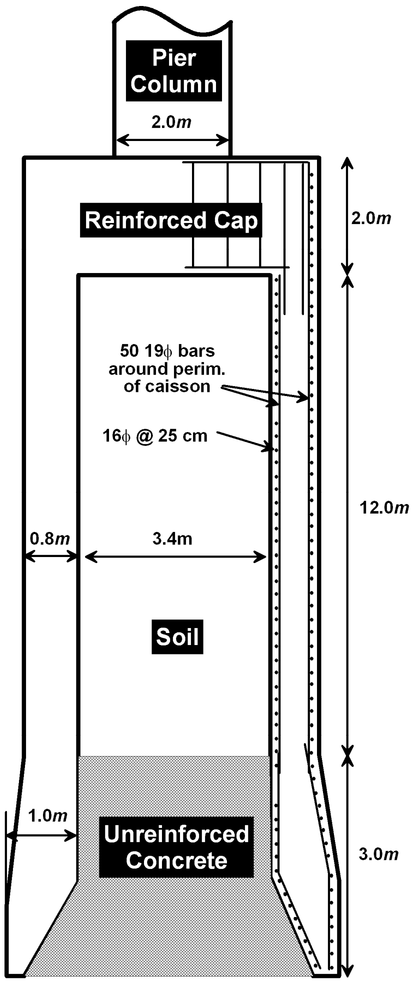

Figure 3: Construction detail of reinforced concrete caisson supporting pier columns of Leuw-Mei Bridge.

Liquefiable deposits were observed about 100 m north of the bridge by Chu et al. (2006) at a lateral spread site they referred to as "Nantou Site N" (see points NCS-1 and NCS-2 in Fig. 1). A saturated silty sand deposit with $(N_1)_{60}$ values ranging from 10 to 20 blows per foot was determined to have liquefied and caused the observed lateral spreading deformations of as much as 25 cm toward the Miao-Lo River. The water table was at a depth of only one meter at the time of their investigation. A similar deposit was encountered in the site investigation conducted prior to construction of the bridge (Foo-Ting Engineering Corporation, 1995) along the bridge axis about 100 m south of Nantou Site N (see points B-2, B-3 and B-4 in Fig. 1). The soils encountered at these two locations had high content of non-plastic fines and classification ranged from SP to ML. Uncorrected SPT blow counts are presented in Fig. 4 for the two different site investigations. The reason for using uncorrected blow counts is that insufficient information is provided in the report by Foo-Ting to correct those blow counts, and uncorrected blow counts likely provide a more direct comparison of soil conditions assuming that similar drilling methods were used for the two site investigations. The upper 5*m* of the soils on the east side of the river (B-3 and B-4) exhibit higher blow counts than the soils on the west side of the river (B-2, NCS-1 and NCS-2), though lateral spreading was observed on both sides of the river. Soils on the west side of the river exhibit similar blow counts whether encountered along the bridge axis (B-2) or 100*m* north of the bridge (NCS -1 and NCS-2). The similarity in blow counts encountered at these locations does not support the conclusion that the observed ground deformations can be attributed solely to differences in soil properties. Hence, it is reasonable to expect that the soil along the bridge axis would also have spread in the absence of restraining forces provided by the bridge components.

Recent research has shown that deep foundations can reduce lateral spreading displacements (Boulanger et al. 2007, Brandenberg et al. 2007). Engineering evaluation procedures have been developed to quantify the pinning effect that bridge components can have on lateral spreading displacements (e.g., Martin et al. 2002, Boulanger et al. 2007), but these procedures have not been validated with any field case histories. Hence, uncertainties remain regarding the accuracy of the methods. In particular, it is not yet clear whether free-field soil displacements are an appropriate demand to impose on the foundations of bridge piers when the out-of-plane soil thickness is large. There is generally agreement that soil displacements smaller than the free-field displacements should be imposed when finite-width bridge abutments spread laterally because the restrained soil

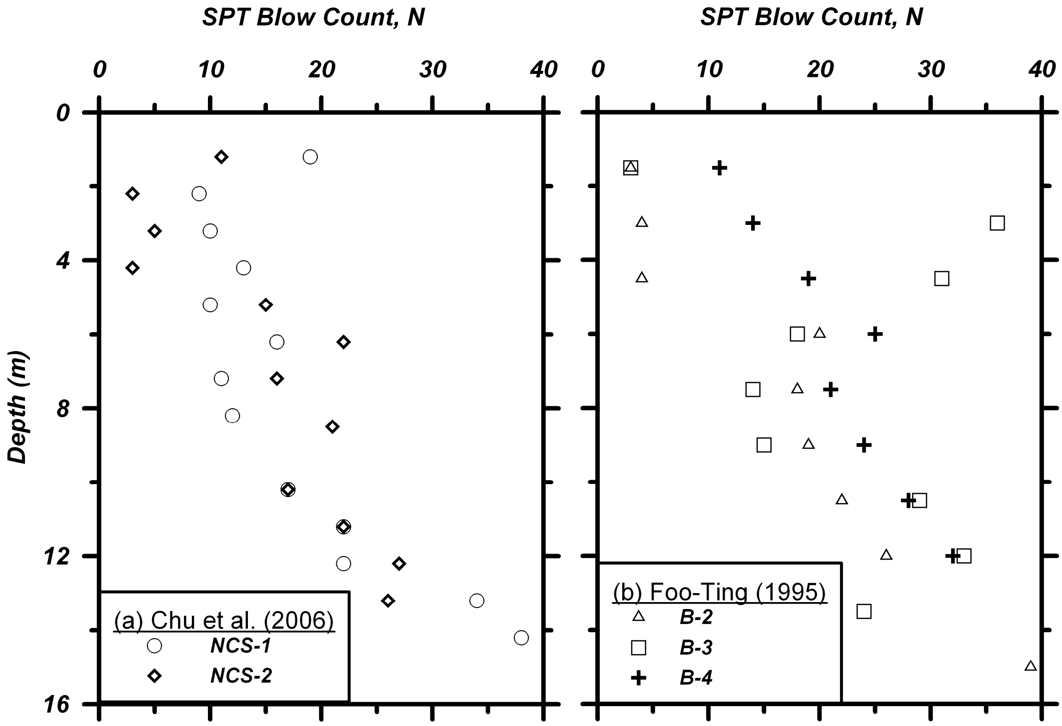

Figure 4: Soil borings near the Leuw-Mei Bridge by (a) Chu et al. (2006) and Foo-Ting (1995).

mass is small. This field case history is an excellent opportunity to identify whether free-field soil displacements would predict worse performance than the observed performance, thereby helping to clarify some uncertainties in existing methodologies. Whether the stresses exerted on the spreading soils by the bridge components were responsible for the lack of lateral spreading along the bridge axis cannot be established until more detailed analysis is performed.

3. SINGLE-SPAN BRIDGES

Chu et al. (2006) documented lateral spread features in the vicinity of three short single span bridges crossing creeks, and none of the bridges suffered structural damage in the earthquake. The Min-Yee (Fig. 5), Zen-Ho, and Lin-Shen bridges in Wufeng were in fact utilized for drill rigs and cone penetrometer equipment during reconnaissance efforts and site investigations of the lateral spread sites. The structural properties, including foundation properties, of these bridges is unknown by the authors, but the bridge abutments most likely rest on spread footings simply because deep foundations would be unlikely for such short spans. A typical pattern of ground deformation involved lateral spreading of the banks toward the creek at some distance from the bridge, with diminishing displacement amplitude approaching the bridge and no signs of deformation behind the abutments (Fig. 6). A likely explanation for this displacement profile is that the bridge acted as a strut that resisted lateral spreading demands via mobilization of compressive stresses in the bridge deck. Without bearings, simple supports, or connections to intermediate piers, the only possible mode of damage to the single span bridges would arise from excessive compressive stresses being mobilized in the deck. In the case of the three bridges documented here, the compressive stresses were in the tolerable range. However, liquefaction-induced settlement at the approach of a bridge may cause a vertical offset that must be re-graded to return the bridge to service. Hence, a bridge that is structurally undamaged may still fail to meet a performance criterion of immediate service when liquefiable soil deposits are present. Such cases were observed in the 2007 Niigata Chuetsu-Oki earthquake (Kayen et al. 2007). Immediate service may be necessary, for example, for emergency vehicles following an earthquake.

Figure 5: Photo of Min-Yee Bridge (right side of photo) and creek showing signs of liquefaction and lateral spreading (Courtesy of Raymond Seed).

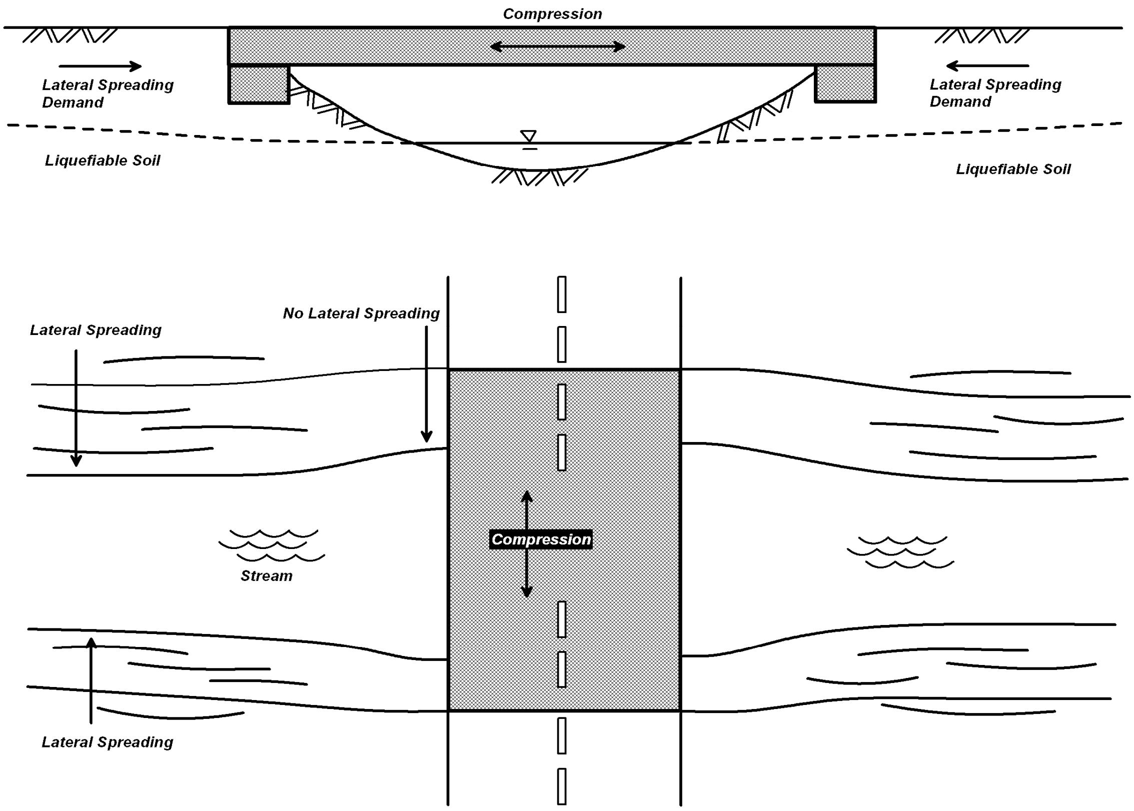

Figure 6: Schematic of short single-span bridges that restrained lateral spreading displacement.

4. SUMMARY OF BRIDGE PERFORMANCE

A total of nine bridges in lateral spreads during the 1999 Chi-Chi earthquake were documented by Chu et al. (2006) and by Lin and Suen (2000). Four of the bridges were near lateral spread sites documented in detail by Chu et al. (2006), and this paper has focused primarily on those bridges. However, six bridges documented by Lin and Suen (2000) (Leuw-Mei Bridge was documented by both studies) were in the vicinity of liquefaction and lateral spreading, and were not damaged by ground failure. These bridges have therefore been included in this paper in Table 1 as part of a database of bridge performance in liquefied ground. Some of the bridges were damaged by strong ground shaking, but none suffered damage clearly caused by liquefaction and ground deformation. The bridge lengths ranged from 60*m* to more than 500*m* with 4 to 24 spans and widths of 8*m* to 20*m*. Superstructures were typically reinforced concrete or pre-stressed concrete I- or T-girders. Abutments typically rested on shallow foundations while pier columns were founded on caissons. Soil data is likely available from site investigations prior to construction of these bridges, though soil information has only been presented for Leuw-Mei Bridge in this paper. Evidence of liquefaction at the sites of these bridges ranged from

Table 1: Summary of documented bridges in lateral spreads during 1999 Chi-Chi Earthquake.

Name	Location	Length (m)	Number of Spans	Width (m)	Year completion	Superstructure	Foundation	investigation informations	Ground failure
Leuw-Mei Bridge	Nantou City: crossing Miao-Lo-Chi River	420	7	10.1	1998	RC I-beam, simple support	Abutments on Spread footings; Pier Columns on Caissons	Foo-Ting Engineering Co. (1995) 4 borings up to 30m deep; Chu et al. (2006), 2 borings + 3 CPT	Lateral spreads; Displacement up to 25 cm (Chu et al. 2006)
June-Kon Bridge	Nantou City: crossing Miao-Lo-Chi River	240	8	20.3	1998	RC I-beam, simple support	Abutments on Spread footings; Pier Columns on Caissons		Sand boils (Lin and Suen, 2000)
Hsiao-Chi Bridge	Nantou City: crossing Chang-Ping-Chi River	60	4	15.1	1986	RC T-beam, simple support	Abutments on Spread footings; Pier Columns on Caissons		Lateral spreads/landsliding of river banks (Lin and Suen, 2000)
Yee-Chiang Bridge	Taiping City: crossing Tou-Pan-Kun-Chi River	288	24	8	1950~1962; 1972 widened	Prestress concrete (PC) Double-Tee beam, simple support	Abutments on Spread footings; Pier Columns on Caissons		Sand boils and ground cracking at the upstream east side (Lin and Suen, 2000)
Shin-Chi-Nan Bridge	Taichung County: crossing Da-Lee-Chi River	502	11	19	1997	PC box, continuous	Abutments on Spread footings; Pier Columns on Spread Footings and Caissons		Sand boils around P4 pier (Lin and Suen, 2000)
Yam-Foam Bridge	Tsao-Tum Zen: crossing Wu-Chi River	455	13	16	1984	PC I-beam, simple support	Abutments on Spread footings		Sand boils around P2~P4 piers, piers displaced up to 55 cm (Lin and Suen, 2000)
Zen-Ho Bridge	Wufeng Sean: crossing Kuo-Neal-Kun-Chi River	20	1	30	unknown		Unknown, but most likely spread footings	Chu et al. (2006) 13 CPTs and 4 borings	Lateral spreads; Displacement up to 125 cm adjacent to abutment, but none apparent behind abutment (Chu et al., 2006)
Min-Yee Bridge	Wufeng Sean: crossing Kuo-Neal-Kun-Chi River	17	1	11.3	unknown		Unknown, but most likely spread footings	Chu et al. (2006) 5 CPTs and 1 boring	Lateral spreads; Displacement up to 300 cm adjacent to abutment, but none apparent behind abutment (Chu et al., 2006)
Lin-Shen Bridge	Wufeng Sean: crossing Lai-Yuan-Creek River	16	1	30	unknown		Unknown, but most likely spread footings	Chu et al. (2006) 1 CPTs and 2 borings	Lateral spreads; Displacement up to 160 cm adjacent to abutment, but none apparent behind abutment (Chu et al., 2006)

sand boils observed on the ground surface to as much as 55*cm* of lateral spreading deformation. The cause of the good performance of these bridges in response to liquefaction is currently unclear, and the bridges should be investigated in more detail to assess whether our engineering evaluation procedures would predict the observed performance.

5. IMPLICATIONS FOR DESIGN PRACTICE

Liquefaction and lateral spreading has affected many bridges throughout the world, causing various levels of damage. For example, Showa Bridge collapsed during the 1964 Niigata earthquake (Hamada 1992) and Nishinomiya Bridge collapsed during the 1995 Kobe earthquake, whereas Landing Road Bridge was only moderately damaged in spite of 2 meters of lateral spreading near the bridge induced by the 1987 Edgecumbe earthquake (Berrill et al. 2001) and a number of bridges in Japan were lightly damaged during the 2007 Niigata Chuetsu-Oki earthquake (Kayen et al. 2007). Our engineering evaluation procedures have largely been validated against case histories of poor performance because we understandably desire to prevent collapse. However, the advent of performance-based earthquake engineering requires accurate prediction of bridge performance at many levels ranging from no damage to collapse. Therefore, the bridges documented in this paper provide an excellent opportunity to assess whether engineering evaluation procedures can predict good performance, which in turn will enhance the reliability of our decision-making tools within a performance-based design framework.

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