Bridge pile−abutment−deck interaction in laterally spreading ground: Lessons from Christchurch

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SUMMARY:
Liquefaction-induced lateral spreading caused extensive damage to bridges during September 2010 Darfield and the following February 2011 Christchurch earthquake. The majority of bridges in the Central Business District (CBD) and the eastern/southern suburbs crossing Avon riverconsists of single to three−span continuous concrete deck and is founded on piles. Bridge damage assessment sheds light to the deformation mechanism, initiated by the riverward displacement of abutment−pile and pier−pilesystems along with the spreading ground. This typical deformation pattern comprises the back rotation of abutments around their contact point with the deck, accompanied by subsequent settlement of the fill behind the abutment and additional distress of the piles. Despite the localized damage, the deck remained intact acting like a strut, thus reducing the displacement demand imposed on the bridge. Therefore, most of these bridges were repairable and held open to traffic after the earthquake events. Three characteristic case histories (Ferrymead Bridge, South Bridge Road Bridge and Anzac Bridge)are described to obtain a deeper insight on how the axial stiffness of the deck controls the overall performance of the bridge by restraining the movement of abutment-pile system. An analytical estimation of the contribution of the superstructure constraint on the stiffness of the abutment−pile system is attempted.

Keywords: bridge, abutment, piles, soil-structure interaction, lateral spreading, Christchurch earthquake

1. INTRODUCTION

The city of Christchurch, New Zealand, was hit by a severe earthquake in February 2011 (Christchurch Earthquake) following Darfield earthquake in September 2010. The predominant geotechnical characteristic of both shaking events was liquefaction and lateral spreading (Smyrou et al., 2011). The Darfield earthquake caused significant liquefaction with evident signs of surface manifestation mostly in the eastern suburbs of Christchurch along the Avon river such as Avonside, Dallington, New Brighton and Bexley (Cubrinovsky et al., 2010). The CBD (Central Business District)was much less affected by liquefaction. The subsequent Christchurch earthquake did not only re-liquefy the previously mentioned areas, but caused a more widespread liquefaction thatalso affected the southern suburbs along Heathcote river and the CBD.

After Darfield earthquake several borehole tests were conducted covering a broad area of the eastern suburbs of Christchurch in order to investigate in detail the properties and the layering of the soil (Tonkin & Taylor LTD, 2011). The soil practically consists of layers of non-plastic silt with low content of fines and clean fine to medium sand (Rees, 2010), combined with high ground water level (0 - 3 m deep). The SPT and CPT values indicated very low cyclic shear resistance especially for at least the first 10 - 15 m of soil (Tonkin & Taylor LTD, 2011). This suggests that the upper layers are highly susceptible to liquefaction and explains why so large amount of sand reached the ground surface.

Liquefaction along Avon and Heathcote river caused significant lateral spreading of the ground in the order of 2 m or more in the free field. Bridges were the structures mostly affected by lateral spreading.

As both rivers form several meanders through the city, there is a large number of bridges connecting the opposite river coasts. Typically, most of them are concrete bridges with small to moderate spans, none to two column bents, continuous deck and seat type abutments founded on piles. Damage assessment of 7 such bridges was performed in the field (Tasiopoulou et al., 2011), resulting in the conclusion that all bridges had repairable structural damage despite sustaining large displacements due to lateral spreading. It should be noted that the bridges performed so well compared to the magnitude of kinematic load from the laterally spreading ground which were subjected to, that they were open to traffic within hours after the seismic events—basically once the settled backfills behind the abutment walls were repaired. Herein, three characteristic cases are described with emphasis to the developed deflection mechanism due to deck−abutment−pile interaction against lateral spreading.

2. BRIDGE PERFORMANCE IN CHRISTCHURCH

2.1. Ferrymead Bridge over Heathcote River

Ferrymead Bridge, built in 1967, runs in EW direction crossing Heathcote river close to Avon-Heathcote estuary. It consists of a three-span prestressed reinforced concrete deck, one solid rigid unit, supported by seat-type wall abutments with two sections (front attached to the deck and rear block) and two bents of four piers. The abutments and the piers are founded on piles. The east abutment and pier are on piles fixed on engineering bedrock, while the west abutment and pier are on floating piles. The soil overlying the bedrock consists of clayey and silty sand, characterized as recent Christchurch formation by Brown and Weeber (1992). During the February 2011 seismic event, the soil liquefied inducing lateral spreading, in contrast to the September 2010 event when no traces of liquefaction were present and the bridge was undamaged.

Ferrymead Bridge was being widened and strengthened when Christchurch earthquake occurred in order to accommodate the increase in users and meet the current earthquake resistance standards. In particular, at the time of the earthquake, only a new abutment had been constructed in the east coast adjacent to the old one. The new abutment was founded on a shaft drilled half a meter in the bedrock and was not yet attached to deck.

Symmetric lateral spreading of the ground towards the center of the bridge proved to be the main kinematic load applied to the bridge pile−foundation and abutments, apart from the uplift by 10 m due to tectonics of the east abutment that is founded on pile fixed on the bedrock. After the damage assessment of the bridge was completed, the deck was the only structural element of the bridge remaining intact.

The abutment tended to move laterally following the soil deformation but the deck restrained the horizontal displacement at top due to its high axial stiffness in compression. Thus, the abutments, being pinned to the deck, back rotated. The piers, on which the deck is seated on bearing pads back rotated in a similar way. The sketch of Fig.2.1. illustrates the deformation of all structural members of the bridge. The difference of the deflection pattern between the old east abutment and the new abutment, located in front of the old one being unattached to the deck, should be noticed and attributed to the presence of the deck constraint. In particular, considering that the old east abutment is 4 m high, it back rotated by 5°, resulting in a riverward displacement of 35 cm at its base (and top of the piles). The horizontal shear crack on the abutment wall at the height of the lower part of the deck, shown in Fig.2.2.a, is indicative of the degree of constraint applied by the deck to the abutment wall through a high axial reaction force. In contrast, the new abutment forward rotated and moved horizontally by 50 cm approximately (Figs.2.2.b and 2.2.c), a movement greater than that of the old one.

Moreover, the piers also moved riverwards, back rotating and forming a gap between their top and the deck. The west pier sustained larger horizontal displacement than the east one most probably due its embedded pile-cap, which transmitted additional load from the laterally spreading ground to the pier-pile system. After damage assessment was performed, the base of the piers was tied to the nearest edges of the firm deck, so as to restrain any further movement of the piers due to aftershocks and/or creep phenomena.
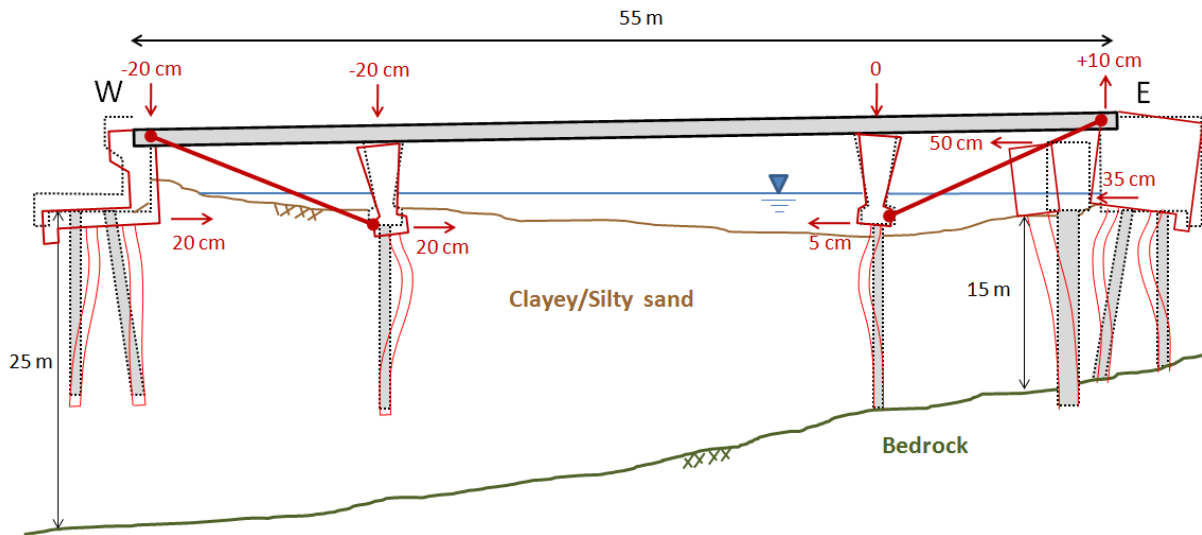
Figure 2.1. Sketch of deflection pattern of Ferrymead Bridge. The base of the piers has been tied to the deck edges after Christchurch earthquake in order to keep them in place and restrain any further inward movement until the strengthening project of the bridge is completed.

Figure 2.2. a) The front section of the east abutment has back rotated and moved upwards by 10 cm. A major horizontal crack was formed at the height of the lower part of the deck, b) The new east abutment has inclined towards the center of the bridge, c) A gap opening at the back side of the shaft due to riverward movement of the new abutment.

2.2. South Bridge Road Bridge over Avon River

South Bridge Road Bridge, built in 1980, runs in the EW direction, crossing Avon river at the Avon-Heathcote estuary. It consists of a three-span skewed reinforced concrete deck supported on two piers and seat-type abutments, founded on two rows of 5 octagonal precast prestressed concrete piles of 40 cm diameter with 3.4 m spacing.

The bridge suffered significant damage during Darfield earthquake due to lateral spreading. The soil in the wetland is very prone to liquefaction (Fig.2.3.). Thus, the ground deformation induced by liquefaction caused back rotation of the abutments, slumping of the approach fills, settlement underneath the abutments and exposure of the pile heads. During Christchurch earthquake, lateral spreading was even more severe, forming cracks in the ground which expanded several meters inland. The initiated damage by Darfield earthquake was extended with evidence of plastic hinging at the top of piles, cracks and concrete spalling in the abutments, as well as even greater subsidence of the backfill(Fig.2.4.). However, in overall, the rotation and horizontal displacement of the abutments only slightly increased compared to how much larger was the soil movement in Christchurch earthquake (Fig.2.5.). This is due to the deck restraining and increase of the pile bending resistance. Thus, the main damage of the bridge is attributed to the first earthquake.

Figure 2.3. Large lateral spreading cracks in the ground parallel to the coast and adjacent to the abutments of South Bridge Road Bridge extending at a great distance inland (left). Back rotation of the west abutment around the deck and slump of the approach fill. The soil underneath the abutments has moved riverwards opening large cracks in the superficial crust and crating gaps in the front side of the piles (right).

Figure 2.4. Back rotation of the west abutment of South Bridge Road Bridge around the deck and slump of the approach fill (left). Concrete spalling exposing the pile reinforcement and flexural cracks developed at the top of the piles indicating initiation of plastic hinging (right).

Figure 2.5. West abutment of South Bridge Road Bridge after Darfield (left) and Christchurch (right) shaking events. During Christchurch earthquake, the bridge sustained additional settlement and lateral displacements indicated by the greater exposure of the top of the pile foundation and the abutment cracks (yellow circle) in comparison to its state after Darfield earthquake (Source of left photo: NHP- Bridge Research Group).

2.3. Anzac Bridge over Avon River

Anzac Bridge is one of the most recent bridges in Christchurch, built in 2000. It is a totally precast structure, with a three-span deck supported on two bents of three columns and concrete abutments with wingwalls on vertical piles. The bridge was almost undamaged in Darfield earthquake. However, severe liquefaction and subsequent lateral spreading occurred during Christchurch earthquake, as illustrated by the large cracks on the ground surface in the near field (Fig. 2.6.). The significant riverward soil movement (about 2 m in the free field) combined with the rigid continuous deck led to back rotation of the abutments and horizontal displacements of the base of abutments in the order of 50 cm which may imply potential plastic hinging of the piles. The deck was undamaged and once again it proved to prevent the bridge failure.

The liquefaction potential analysis of the soil profile (Tasiopoulou et al., 2011), obtained from a borehole between the southern abutment of the Anzac Bridge and the HPSC seismic station (located at a distance of 100m approximately) using the PGA records of the aforementioned station, indicates that liquefaction is certain during Christchurch earthquake (0.29g) and definitely more extensive than the one during Darfield earthquake (0.17g), causing larger soil lateral movement and at a greater depth (10 m). This can reasonably justify why the Anzac bridge sustained no damage during Darfield, but 50cm horizontal displacement, plus rotation of abutments during Christchurch earthquake.

Figure 2.6. Back rotation of the abutments of Anzac Bridge and slump of the backfill. Large lateral spreading cracks in the ground parallel to Avon river coast extending in a great distance from the abutments indicating horizontal ground displacement in the free field more than 1 m.

3. THE EFFECT OF SUPERSTUCTURE ON PILE RESISTANCE

Evidently, the deflection pattern of the bridges points out lateral spreading as the prevailing source of load. The continuous deck was the only intact structural member after the seismic events, acting as a strut against the symmetric lateral movement of the abutment−pile systems towards the centre of the bridge. The abutments were pinned to the edges of the deck; thus, they back rotated, forcing the piles to develop the same rotation at top due to their rigid connection with the abutment wall. Subsequently, the additional kinematic constraint at the top of the piles, attributed to the axially stiff deck, increased the pile resistance to lateral spreading. On the other hand, the piles are subjected to extra bending moment at the top which intensifies the potential of plastic hinging. In overall, the continuous rigid deck was the key feature in the performance of bridges resulting in the reduction of the displacement demand imposed on the bridge and the increase of the effectiveness of the pile "pinning" against lateral spreading.

An attempt to quantify the contribution of the superstructure (deck−abutment) to the pile−foundation performance is based on the simplified method proposed by Tasiopoulou et al.(2012).The piles are subjected to strong kinematic load within the liquefied zone, where the surrounding soil loses its strength and develops large strains. The laterally moving soil "carries" the overlying layers and provides the driving force displacing the pile only a certain amount depending on the relative stiffnesses between piles (K) and soil (G_L). The magnitude of soil movement, the stiffness degradation of the liquefiable zone and the rigidity of pile-superstructure system are the major parameters controlling the pile response and determining the ratio of the pile displacement, δ_p, over the free field one, δ_{fp}, within the liquefied layer, called ratio α (Fig.3.1.).
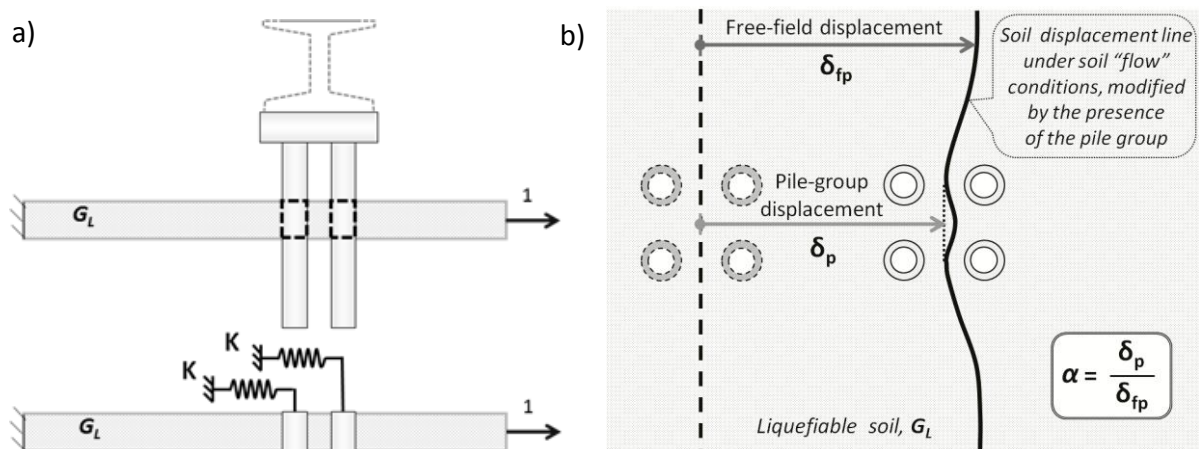

Figure 3.1. a) The pile−foundation can be replaced by an out of plane spring, representing the horizontal stiffness of the pile−superstructure system within the liquefied soil, b) Definition of ratio α as the pile group displacement over the free-field soil displacement due to liquefaction induced soil "flow" (plan view).

In the following, the rigidity of the deck−abutment−pile system is explored. Initially, three characteristic pile deflection patterns are shown in Fig.3.2, depending on the rotation at the pile-top imposed by the superstructure system.
- Case 1 (lower stiffness): No deck constraint is applied to the pile−foundation. Thus, the pile forward rotated in a similar way as a cantilever beam. This deflection pattern is dominant in cases where the deck is not continuous and parts of the seated deck have fallen due to differential movement of consecutive bents.
- Case 2 (higher stiffness): No rotation is allowed to the pile top, only horizontal movement parallel to the deck. This deflection can apply to bridge decks seated on rubber pads.
- Case 3 (high stiffness): The abutment−pile system is pinned around the edge of a continuous deck and the pile top back rotates following the abutment wall. This deflection was observed

to all case histories from Christchurch described above.

It is assumed that there are numerous intermediate cases, especially between Cases 1 and 2. The pile stiffness, K, can be estimated as the equivalent concentrated load to cause unit displacement of piles in the middle of the liquefied zone. The pile stiffness for each case is given:

- Case 1 (cantilever beam):

$$K = \frac{3EI}{h^3\left(4-3\frac{h}{L}\right)} \tag{3.1}$$

where E is the elastic modulus of pile material, I is the moment of inertia, L is the pile "active length" and h is the depth from the middle of liquefied zone to effective fixity (Fig.3.3.a).

- Case 2:

$$K = \frac{12EI}{h^3\left(4-3\frac{h}{L}\right)} \tag{5.2}$$

- Case 3: The back rotation of the pile head, θ is considered to be equal to ratio of the pile−head displacement, δ_3, over the distance H from the pile top to the pinned edge of the abutment. Thus, every time the pile head displaces, the displacement is followed by back rotation equal to $\theta = \delta_3/H$. The pile stiffness, K, is thus, deduced as a function of H.

$$K = \frac{12EI}{h^3\left(4-3\frac{h}{L}\right)+\frac{h^4}{L}\left(\frac{3L-2h}{H+L}\right)\left(-2+\frac{h}{L}\right)} \tag{5.3}$$

It is worth mentioning that if H→∞ (θ→0), the pile stiffness becomes equal to that of case 2. On the other hand, in the extreme case when H→0, meaning that the pile head is directly pinned to the deck, no horizontal movement occurs (K→∞). In retrospect, as the parameter of the abutment decreases (the back rotation increases), the horizontal pile stiffness increases, restraining more and more the horizontal displacement demand of the deck−abutment−pile system. This is how the performance of South Bridge Road Bridge can be explained: during Darfield earthquake, a certain back rotation was developed, so that the distance H was reduced when Christchurch earthquake occurred. In other words, the pile−foundation responded with greater pile stiffness during the second seismic event compared to the first one.
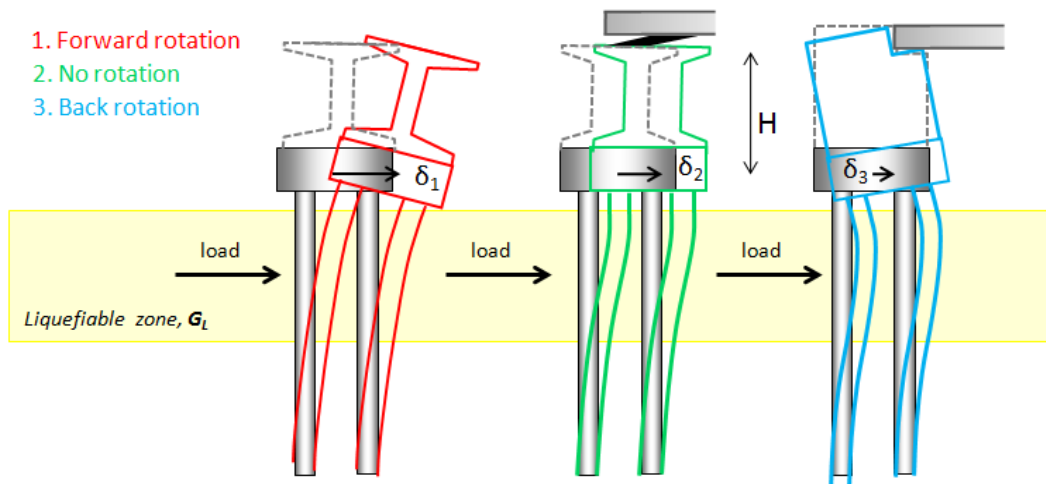

Figure 3.2. Three characteristic cases of pile deformation, depending on the rotation imposed or not by the superstructure.

Moreover, it is evident from Eqs 5.1 to 5.3, that $K_1 \leq K_2 \leq K_3$ always stands true. Therefore, for a given free−field displacement and a given degraded soil shear modulus, G_L, the ratio α obtained from graph in Fig. 3.3.b for each case follows that $\alpha_1 \geq \alpha_2 \geq \alpha_3$, which means that the pile displacement is greater

for Case 1 (cantilever) and less for Case 3 (back rotation), as expected. This is representative of the different response between the old east abutment (Case 3) and the new east abutment (close to Case 1) of Ferrymead Bridge. It should be reminded, though, that increase of pile stiffness due to superstructure constraint does not only induce the beneficial effect of limitation of displacements, but is also accompanied by additional bending moments which can lead to pile failure.
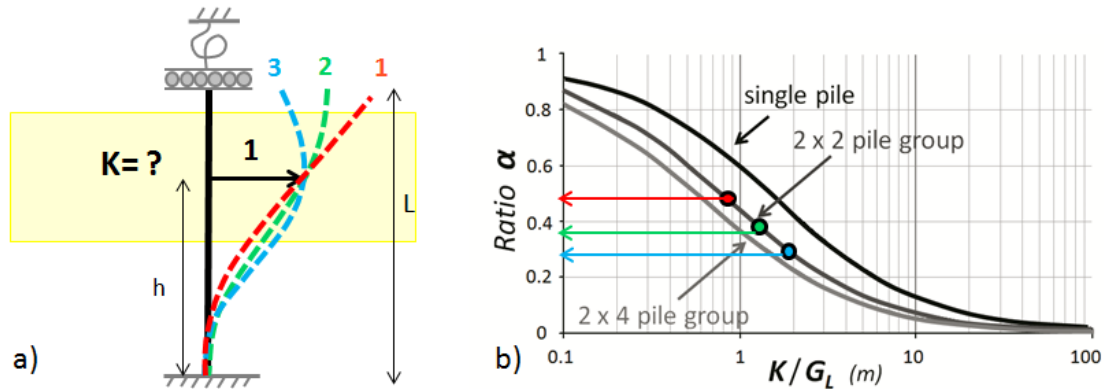

Figure 3.3.a) Determination of pile stiffness, K, as the equivalent concentrated load to cause unit displacement of piles in the middle of the liquefied zone, considering a column beam with appropriate boundaries conditions, b) The ratio α as a function of the relative stiffness between piles (K) and soil (G_L) for three different pile configurations (Tasiopoulou et al., 2012).

4. CONCLUSIONS

This paper sheds light to the bridge deck−abutment−pile interaction due to laterally spreading ground based on lessons obtained by recent New Zealand earthquakes. Liquefaction-induced lateral spreading caused extensive damage to bridges during September 2010 Darfield and the following February 2011 Christchurch earthquake. Typically, most of them are concrete bridges with small to moderate spans, none to two column bents, continuous rigid deck and seat type abutments founded on piles. Three characteristic cases (Ferrymead Bridge, South Bridge Road Bridge and Anzac Bridge) were described with emphasis to the developed deflection mechanism due to superstructure constraint against lateral spreading, which prevented bridge failure. The continuous deck was the only intact structural member after the seismic events, acting as a strut against the symmetric lateral movement of the abutment−pile systems towards the centre of the bridge. The abutments were pinned to the edges of the deck; thus, they back rotated, forcing the piles to develop the same rotation at top due to their rigid connection with the abutment wall. An attempt to quantify the contribution of the superstructure (deck−abutment) to the pile−foundation performance is based on the simplified method proposed by Tasiopoulou et al.(2012).

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