Ground displacement at the North Shore Pier of the Narrows Bridge during the Meckering earthquake

Geoffrey Cocks & Michael Hillman

Coffey Geotechnics Pty Ltd

Abstract

The original Narrows Bridge in Perth, Western Australia was constructed in the 1950s. The Northern shoreline comprised dredged sand fill, placed over a deep sequence of soft and compressible estuarine sediments. During the placement of the fill, the existing soft sediments were deliberately displaced by constructing a sand embankment until a slip occurred. The displacement was only partially successful and a wedge of alluvium of non-uniform thickness was left in place below the sand fill. The retention of this wedge of soft alluvium, and the presence of very loose zones within the sand fill lead to concerns about ongoing lateral creep and horizontal loads on piles. Main Roads Western Australia (the State Road Authority) established a number of survey monitoring points on the North Shore to measure displacement in the X, Y (horizontal) and Z (vertical) directions. These points were monitored regularly until the 1970s and the monitoring data spans the time of the 1968 Meckering Earthquake. When plotted with time on a log scale, the survey displacement data is approximately linear and shows distinct "steps" both vertically and horizontally, corresponding to the time interval in which the Meckering Earthquake occurred. Displacements inferred from the "steps" were in the range of 5mm to 18mm vertically and 10mm to 16mm horizontally. The horizontal movement is consistent with that calculated using the Youd et al (2002).

Introduction

The Narrows Bridge connects Perth to South Perth across a narrow part of the Swan River estuary. During the last Ice Age, the sea level off the coast of Western Australia was much lower and the Swan River flowed in a paleochannel about 20 m to 30m lower than the current elevation. As the sea level rose, the paleochannel was filled with soft marine and estuarine deposits. When it was decided to construct a bridge across the "Narrows" an attempt was made to improve the soil profile. The attempt required the displacement of the soft "mud" at the north shore by rapidly constructing a sand embankment to induce a slope failure. The sand was also required for engineering fill purposes, to raise ground surface elevations well above Swan River flood levels. This work commenced in May 1955 (Marsh 1993). Marsh (1961) provides more information on the reclamation process.

The attempt at displacement was only partly successful and a wedge of soft soil remained in place. There was concern that consolidation of the non-uniform thickness of soft alluvium would result in horizontal movement at the north shore pier of the Narrows Bridge. As a result of this concern, the North Shore pier of the bridge was constructed using a caisson pile system with the load bearing pile located within a larger diameter hollow steel tube driven into stable subsoil conditions some 20m below river level. The outer hollow steel pile was free to move horizontally (with the moving soil) without imposing lateral loads on the inner load bearing piles. The load bearing pile was placed eccentrically inside the outer steel tube, with the large gap (on the north side) to be taken up by movement of the soil and outer tube towards the south. Main Roads established a set of survey monitoring points on the north shore to measure the lateral and vertical movement of the outer steel tube. Survey monitoring spanned the period when the 1968 Meckering Earthquake occurred (Magnitude 6.9).

The Meckering earthquake

The Meckering earthquake occurred on 14 October 1968. The magnitude was approximately 6.9 and the duration was about 40 seconds. The fault line was about 37km long with a maximum vertical displacement of about 2m. The epicentre was approximately 120km east of the Narrows Bridge site.

Observed displacements at the Narrows Bridge North Shore

Vertical (Z) and horizontal (Y) movement of the monitoring point at the north shore of the Narrows Bridge site were plotted by Marsh (1993) from which the following displacements associated with the Meckering earthquake, can be estimated:

Table 1 North Shore Displacements Associated with the Meckering Earthquake

Direction	Location	Displacement (mm)
Vertical	East End	18
Vertical	West End	5
Horizontal	East End	10
Horizontal	West end	16

A sample plot using data scaled from Marsh's (1993) report is presented as Figure 1.

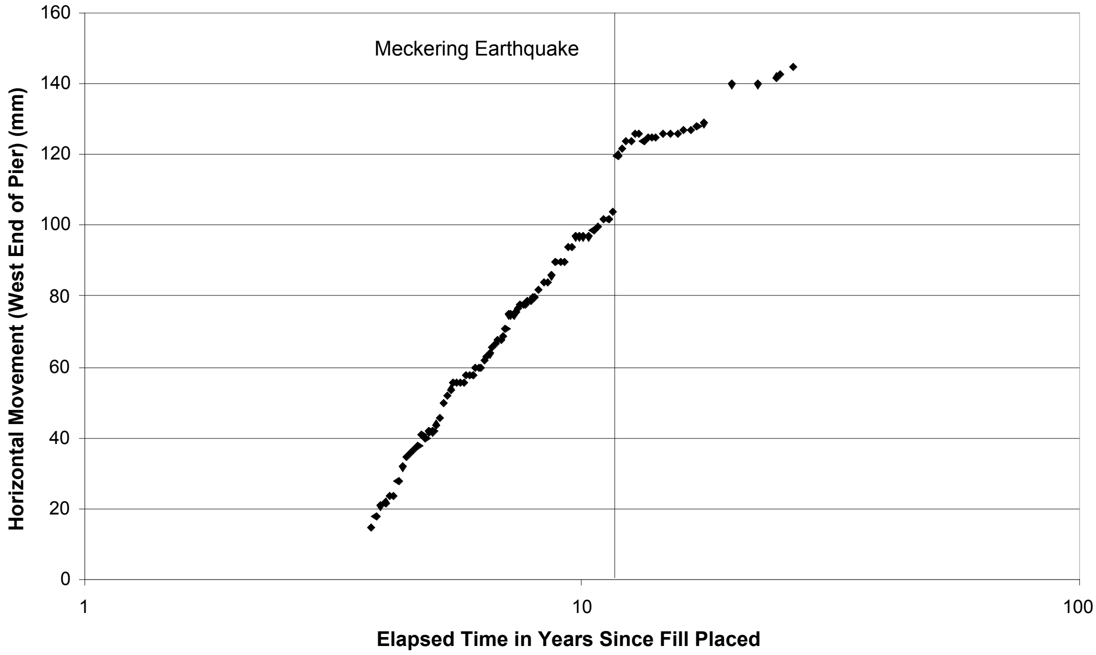

Figure 1 Horizontal Movement at North Shore Narrows Bridge

Marsh's (1993) report only included the displacement in the Y direction (towards the river in the direction of the bridge span).   It is understood that displacement in the X direction has been much smaller than for the Y direction.

Recent investigations

In 1998 Main Roads Western Australia commissioned BHP Engineering to carry out geotechnical borehole drilling and laboratory testing for the proposed duplication of the road bridge over the Swan River at the Narrows. Bore Hole BHPE_03 (NSP) indicated very loose to loose sand with Standard Penetration Test (SPT) blow counts (N) of 4 at 2.5m, 3 at 5.5m and 4 at 8.5m depth. There was a total of about 20m thickness of sand with a SPT of less than 15. The ground water level was not measured but is estimated to have been at about 1m deep based on the ground level and proximity to the Swan River.

In 2003 Coffey undertook geotechnical studies at the Narrows Bridge site as part of the design for a third bridge (to carry the Perth Mandurah Rail) that would be located between the original road bridge and the recently completed duplicate road bridge.

Displacement analysis for the Meckering earthquake

As part of the design of the piled foundations for the new rail bridge, consideration was given to any lateral displacement that may be caused by earthquake liquefaction of the loose sand at the North Shore pier.

Youd et al (2002) proposed an empirical equation for assessing lateral spread adjacent a free face slope, based on multilinear regression:

$$\text{Log } D_H = -16.713 + 1.532M - 1.406\text{Log } R^* - 0.012R + 0.592\text{Log}W + 0.540\text{Log } T_{15} + 3.413\text{Log } (100-F_{15}) - 0.795\text{Log } (D50_{(15)} + 0.1)$$

where

- D_H is lateral ground movement in mm
- M is earthquake magnitude (6.9 for the Meckering earthquake)
- R is the mapped distance to the earthquake (approximately 115km)
- R* is the modified source distance (refer to Youd et al 2002)
- W is the free face ratio (approximately 20% for the Narrows Bridge site)
- T_{15} is the thickness of sand with an SPT of less than 15
- F_{15} is the average fines content (1% for The Narrows Bridge site)
- $D50_{(15)}$ is the average grain size for sand in the zone with SPT <15 (0.45 mm)

Applying these parameters to the North Shore of the Narrows Bridge site, the predicted lateral spread associated with the Meckering earthquake is 10 mm. This is reasonably close to the average measured horizontal movement of 13 mm (refer to Table 1).

Discussion

The method of Youd et al (2002) for estimating lateral spread from liquefaction gave a reasonable fit with the measured displacement at the North Shore of the Narrows Bridge site, corresponding to the time of the Meckering earthquake. It must however be recognised that this does not provide proof that liquefaction occurred. There are other possible explanations of the lateral movement including remobilisation of the original slip.

A number of possible causes of lateral load on the piles were investigated in the design of the rail bridge at the Narrows site. Lateral spread under earthquake shaking was one of the sources of movement included in the design.

Acknowledgements

The approval from Main Roads Western Australia to reproduce the displacement data from the Narrows Bridge site is gratefully acknowledged.

References:

Marsh J G (1961) Reclamation for Narrows Bridge, Perth WA. Jnl IEAust Vol 33 No 7-8

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Youd T L, Hansen C M, & Bartlett S F (2002) Revised Multilinear Regression Equations for Prediction of Lateral Spread Displacement. Jnl of Geotech & GeoEnv, Engng, Vol 128 , No 12 ASCE