Design Considerations of Bridge Abutment Piles Subjected to Embankment Settlement

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Summary Sections of the newly constructed Raleigh Deviation, NSW, Australia traverse flood plains of deep alluvial soils where the road embankments have experienced large settlement during the course of construction. Bridges constructed in these areas are supported on piles. The piles at the abutments are subjected to horizontal and vertical soil movements resulting from ground settlement. As a result, these piles have to be designed for large bending moments, shear and axial forces in addition to their normal loading. Adverse impacts on the deck joint arrangement of the bridge could also arise as a result of soil movements around the piles. Design considerations and options to mitigate the problems of the piles subjected to soil movements are discussed in this paper.

1. INTRODUCTION

Four bridges, as shown below, have been constructed as part of Raleigh Deviation, a new 8 km long highway replacing a section of the existing Pacific Highway at Raleigh, NSW, Australia.

- Bellinger River Bridge
- North Bank Road Bridge
- Valery Road Bridge
- Man Arm Creek Bridge

The bridges are located as shown in Figure 1. Some embankments of the Deviation have been built on flood plains of deep alluvial clays which have undergone significant settlement since commencement of the road construction. Three of the above four bridges are located in the areas with embankments under continuing settlement.

A trial embankment equipped with extensive instrumentation has been constructed to monitor the ground behaviour under the embankment loading. Based on the performance of the trial embankment, the long-term ground movements have been predicted and the impacts to the bridge abutment piles assessed. Further monitoring of each of the bridge abutment sites has been undertaken to confirm the assumptions made in the design.

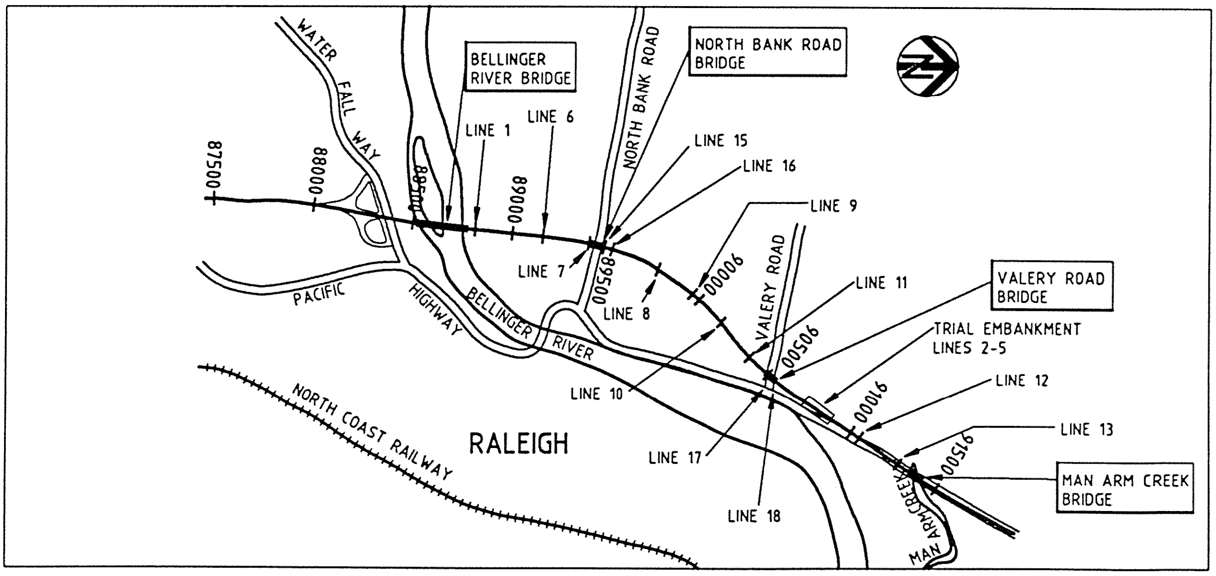

Figure 1. Site plan.

Due to the slow consolidation process of the soil and the time constraints of a tight project schedule, preloading of bridge abutment sites to eliminate long-term settlement was not a practical option, even with the installation of wick drains in the soft clays to speed up the settlement rate.

As a result of the continuing settlement of the soft ground, additional loads on the abutment piles have to be considered in the pile design. These extra loads are:

- downdrag force induced by ground settlement, and
- shear force and bending moment caused by lateral soil movement.

Most of the bridges had been designed and construction of some of these bridges had commenced while the trial embankment loading was being carried out. The structural design of the piles had to be verified and adjusted later based on the results of the trial loading.

To account for the above additional loads on piles, the following considerations have been taken into account in the pile design:

- strength improvement by use of permanent steel casing,
- optimisation of pile orientation,
- additional rock socketing of piles,
- increased pile stiffness and number,
- coating of piles to reduce skin friction,
- restraint of piles by tie-back anchors or strut beams, and
- a system of 'nested' piles to isolate piles from the effects of lateral soil movement.

This paper presents the background information on the project, the geotechnical conditions of the site, the instrumentation arrangement and the monitoring results, the impacts on piles caused by embankment settlement, and the design considerations of the abutment piles.

It is noted that this paper mainly focuses on the field performance at the bridge abutments and the design considerations for the abutment piles subjected to vertical and horizontal soil movements. It is not the authors' intention to present details of the theories and methods adopted for the calculation of soil movements and the induced impacts on piles, which are beyond the scope of this paper.

2. GEOTECHNICAL CONDITIONS

Extensive geotechnical investigations, including boreholes, piezocone probes, test pits and laboratory testing, have been undertaken at and near the trial embankment site, about 100 m north of Valery Road Bridge, as shown in Figure 2.

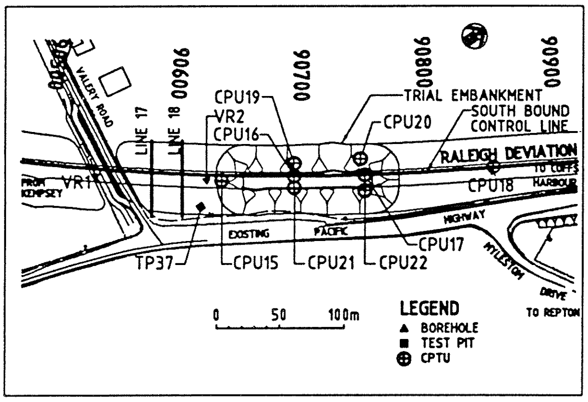

Figure 2. Plan of trial embankment.

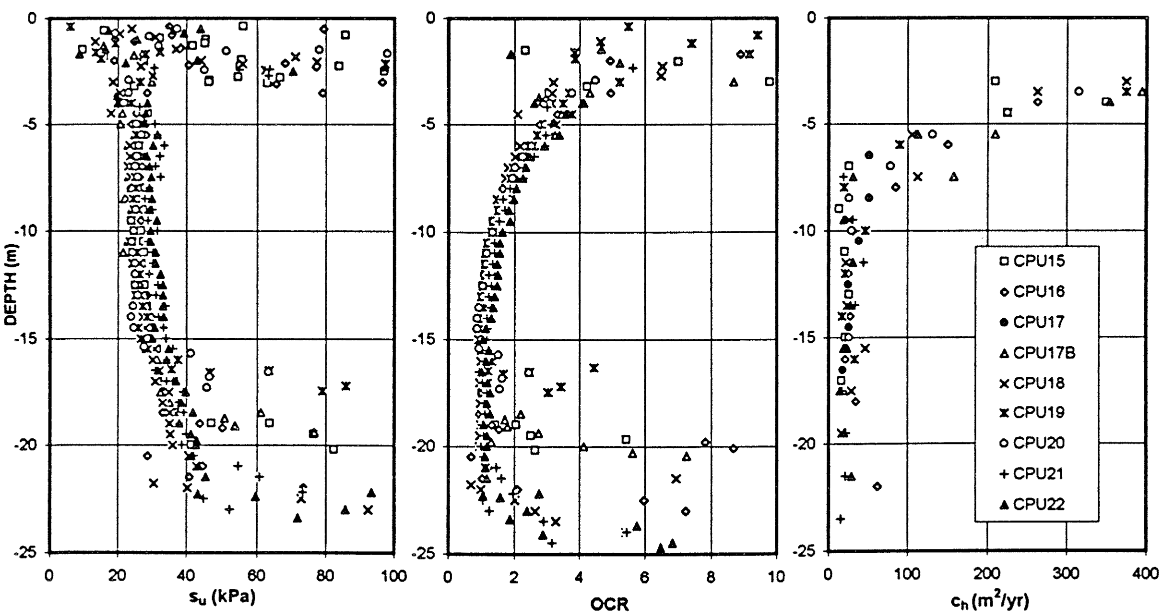

Figure 3. Interpreted results of piezocone testing.

The geotechnical parameters derived from the trial embankment have formed the basis for the assessment of embankment settlement elsewhere. The interpreted data, including undrained shear strength s_u, over consolidation ratio (OCR) and horizontal coefficient of consolidation c_h, from the piezocone testing, are shown in Figure 3. The soil between a depth of 5 m and 15 m has an undrained shear strength as low as 25 kPa and becomes normally consolidated below 14 m. Low coefficient of consolidation below 8 m indicates the nature of slow consolidation of the soil.

The subsurface conditions of the bridge sites based on the drilling are summarised below:

Bellinger River Bridge

0 m – 3 m: clay; clayey silt; firm to stiff.
3 m – 8 m: sand; silty sand; very loose to loose.
8 m – 20 m: clay; clayey silt; very soft to firm.
20 m – 23 m: clay; silty clay; firm to stiff.
23 m – 30 m: clayey gravel; sandy gravel; medium dense to very dense.
> 30 m: phyllite.

North Bank Road Bridge

0 m – 15 m: clay; silty clay; very soft to firm.
15 m – 17 m: sandy silty clay; stiff.
17 m – 23 m: sand; loose.
23 m – 33 m: gravelly sand; sandy gravel; medium dense to very dense.
> 33 m: phyllite.

Valery Road Bridge

0 m – 5 m: silty and sandy clays; firm to stiff.
5 m – 20 m: clay; very soft to firm.
20 m – 27 m: sandy clay; clay; stiff to very stiff.
27 m – 29 m: sandy gravel; gravel; very dense.
> 30 m: phyllite.

Man Arm Creek Bridge

0 m – 2 m: gravelly clay; silty clay; firm to stiff.
2 m – 4 m: silty sand; very loose to loose.
> 4 m: phyllite.

3. INSTRUMENTATION AND MONITORING

Field instrumentation has been installed throughout the project site identified as Line 1 to Line 18, as shown in Figure 1. The instruments used include:

- hydro-static profile gauges (HPG) installed at the base of the embankments to measure the settlement profiles of the natural ground surface across the embankment,
- piezometers installed at various depths in the foundation to measure pore water pressures in response to embankment construction, and
- inclinometers installed at the toe of the embankment to measure lateral soil movements as a result of embankment settlement.

The instrumentation lines relevant to the bridge sites are given below:

- Bellinger River Bridge (BRB): Line 1 (northern abutment).
- North Bank Road Bridge (NBRB): Line 7 (100 m south of southern abutment), Line 15 (northern abutment) and Line 16 (50 m north of northern abutment).
- Valery Road Bridge (VRB): Line 17 (10 m north of northern abutment) and Line 18 (30m north of northern abutment).
- Man Arm Creek Bridge (MACB): Line 13 (20m south of southern abutment).

The numbers of instruments installed on the above monitoring lines are summarised in Table 1.

Table 1. Instrumentation for bridge abutments.

Line	Location	HPG (no.)	Piezometer (no.)	Inclinometer (no.)
1	BRB	1	-	2
7	NBRB	1	6	2
13	MACB	1	6	2
15	NBRB	1	3	4
16	NBRB	1	3	-
17	VRB	1	3	3
18	VRB	1	3	-

4. GROUND MOVEMENT

Significant ground settlement up to 1.5 m has been recorded for the trial embankment and the northern abutment of Valery Road Bridge over a period of about one and a half years. This settlement is considered to be a combination of primary consolidation and creep settlements.

Due to the presence of thick soft clays, wick drains were installed in the areas adjacent to Bellinger River Bridge, North Bank Road Bridge and Valery Road Bridge to accelerate the consolidation process. They were installed at 1.5 m grid within 30 m of the bridge abutment and at 3 m grid between 30 m and 50 m of the abutment.

The measured maximum ground settlements along the instrumentation lines for the bridge abutments are given in Figure 4. Figure 5 shows the recorded maximum lateral deflections of the soil below the toe of the embankment.

The piles installed adjacent to the bridge abutments are expected to be subjected to negative skin friction caused by the ground settlement as well as lateral pressure exerted by the horizontal ground movement. Extensive studies have been undertaken on both subjects, eg. Poulos (1990) and Matyas and Santamarina (1994) on piles subjected to negative skin friction and Poulos (1973), Stewart *et al.* (1992), Chen and Poulos (1997), and Goh *et al.* (1997) on piles subjected to horizontal soil movement.

The measured settlements of the bridge abutments have been well predicted using a coupled numerical method developed by Small *et al.* (1976), Hsi (1992), and Hsi and Small (1992a and 1992b). This method calculates soil deformation in response to the pore pressure dissipation.

Poulos (1972) noted that, due to the non-homogeneous and anisotropic nature of the soil, lateral soil deflections are difficult to predict even though it has been possible to obtain very good predictions of vertical movements and pore pressures. An empirical method suggested by Bourges and Mieussens (1979) has been adopted for the prediction of horizontal soil movements associated with the predicted embankment settlement.

The induced pile deflections and bending moments due to lateral soil movements have been approximated based on the design charts presented by Chen and Poulos (1997). The results have been further modified using a numerical finite element approach.

5. ABUTMENT PILE ARRANGEMENT

Bellinger River Bridge and Valery Road Bridge have abutments formed as pile trestles. These comprise

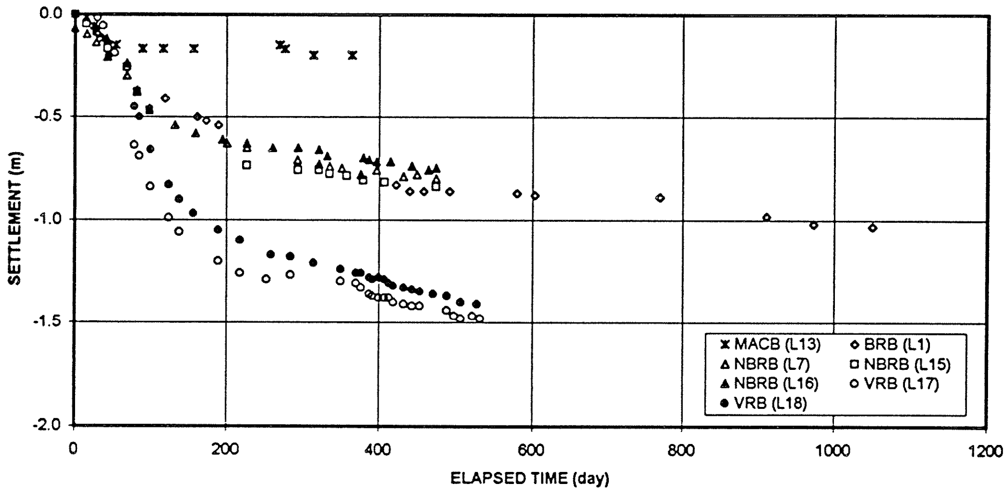

Figure 4. Settlement below centre of embankment.

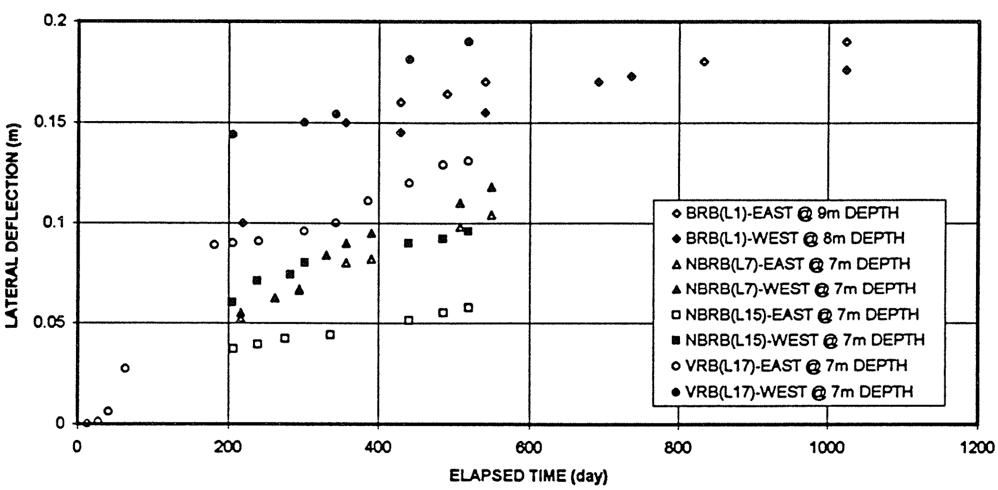

Figure 5. Lateral deflection below toe of embankment.

900 mm diameter cast in situ bored piles with permanent steel casing socketed into rock. Some of the piles in the pile trestle are raked to resist the horizontal forces. The pile arrangement for these two bridges is given in Figures 6 and 7.

North Bank Road Bridge has all the abutment piles aligned vertically and their upper ends united in a pile cap, as shown in Figure 8. The piles for this bridge are 750 mm diameter bored piles with permanent steel casing socketed into high strength siltstone.

At the site of Man Arm Creek Bridge the depth of soft ground is limited and so the expected impact of soil movement on piles is minimal.

6. IMPACT OF GROUND MOVEMENT ON PILES

Movement of piles is often associated with movement of soil around the piles. This pile movement could be vertical and lateral, and its magnitude is not necessarily the same as the soil movement in each direction.

The amount of pile movement will depend on the following factors:

- the stiffness and size of the pile, and
- the stiffness and movement of the soil.

7. PILE DESIGN CONSIDERATIONS

Piles are primarily designed to support the superstructure of the bridge. They carry the dead and live loads. For abutment piles, they also carry the lateral earth pressure from the embankment. An efficient means of resisting the lateral pressure is the use of raked piles.

The forces generated by soil movement represent added and unusual forces, and these forces have been assessed to be high. In the case of the piles for Bellinger River Bridge, the increase in bending moment from this soil movement is almost as much as the normal bridge loading on the piles. These additional forces on the piles are permanent and the stresses generated in the piles have to be added to the permanent bridge loads.

The conventional bored piles used for the bridges are usually very efficient in carrying vertical loads but less efficient in carrying bending moment. The bending moment caused by lateral soil movement is also a concern for durability. The piles must not develop excessive cracking under loading, so that corrosion of the reinforcement does not pose a long-term problem. This imposes a definite limitation on the bending moment capacity of the piles.

The deflection of the piles due to bending also affects the serviceability of the superstructure of the bridge.

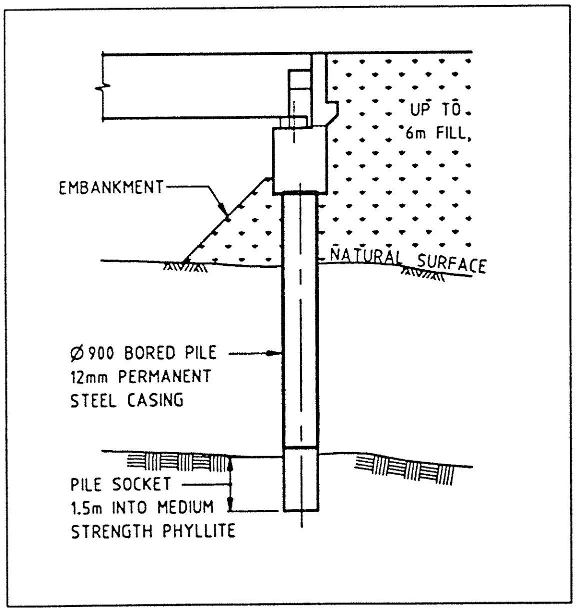

Figure 6. Bellinger River Bridge abutment piles.

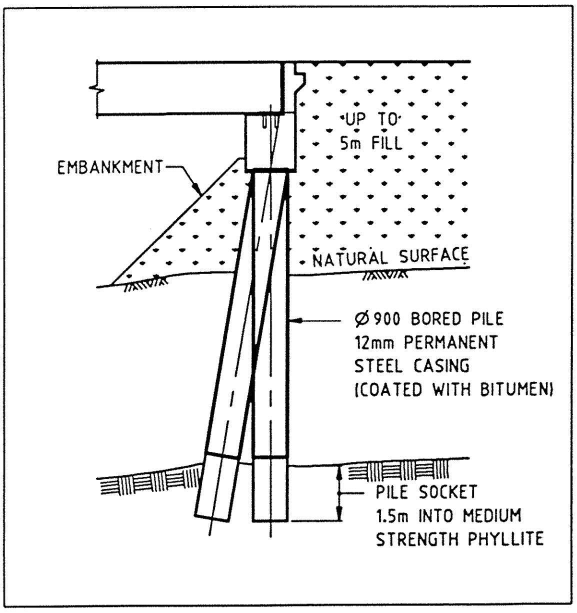

Figure 7. Valery Road Bridge abutment piles.

Vertical movement of soil relative to the pile would produce downdrag force on the pile and lateral movement of the pile would induce bending moment and shear.

Excessive lateral pile movement would lead to closing of expansion joints, preventing their usual movement functions.

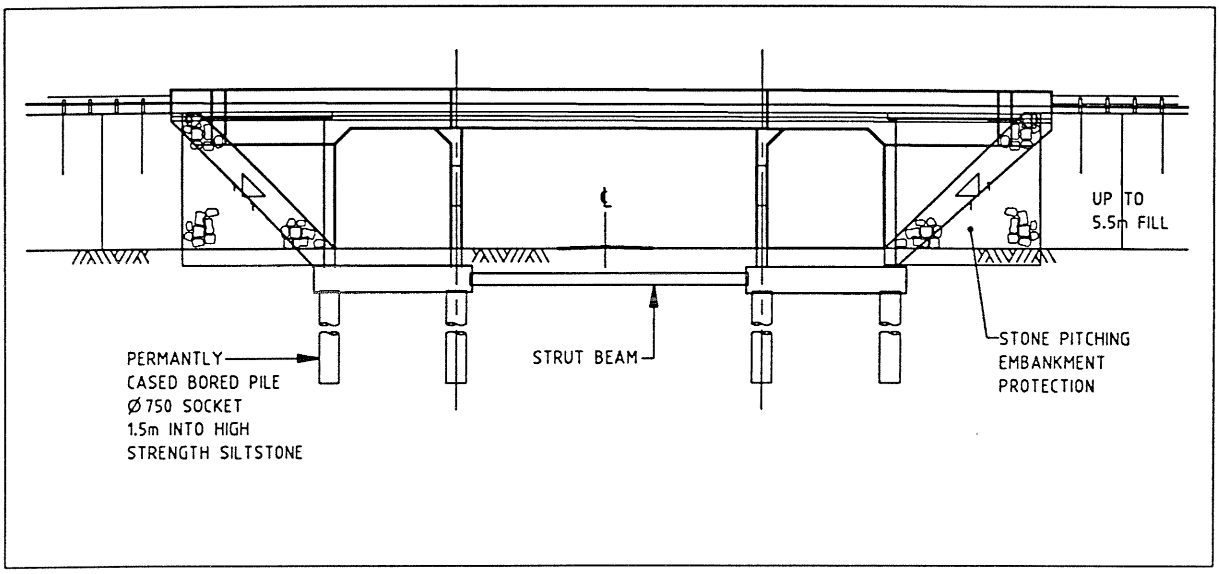

Figure 8. North Bank Road Bridge abutment piles.

8. PILE OPTIONS CONSIDERED

Several options have been considered in the pile design taking into account the extra lateral and vertical forces caused by soil movement.

The option to increase the pile sizes and numbers to increase the load carrying capacity was closely examined for its validity.

The vertical forces caused by the downdrag could be minimised by coating the piles with bitumen to reduce skin friction.

The lateral forces on piles could be minimised by raking some piles. However, this would attract additional bending moment in the pile caused by soil settlement and it was assessed in the design of these piles.

The piles were checked for their rock socket strength to ensure that they have sufficient capacity to carry the increased loads.

The restraint of piles by tying them back with dead-man anchors was investigated. This would help to reduce pile bending moment. However, having a dead-man anchor buried in settling fill was not considered a reliable option and was abandoned.

The specific design considerations of the abutment piles for each of the bridges (excluding Man Arm Creek Bridge) are described below:

North Bank Road Bridge

The original bridge design had been carried out and the piling work had commenced before the full results of the trial loading were known. An additional design check was subsequently undertaken to investigate the full impact of the fill movement on the abutment piles.

The predicted lateral deflection of the piles due to soil movement imparted an added bending moment to the piles. These piles were found to have sufficient capacity with the support of the strut beams at ground level, as shown in Figure 8, to prevent any head movement of the piles.

Valery Road Bridge

The lateral movement of the soil was predicted to cause a deflection of the piles and add a bending moment to the piles. It was then decided that the number of piles should be increased to meet the capacity requirement for bending strength considerations.

The other option considered, but abandoned as being complicated, was a 'nested pile' scheme, which involved driving a secondary pile within an empty casing. The space within the casing would provide a buffer zone against casing deflection caused by the soil movement thus isolating the bored pile from the effect of the lateral soil movement.

Apart from the strength consideration, the movement of the piles would affect the movement of the deck.

Therefore the deck articulation had to be rearranged with the expansion joint moved from the abutment to the mid bridge central pier.

To minimise movement, the piles were alternately raked, and this also helped to provide greater capacity for lateral resistance.

Bellinger River Bridge

Due to soil lateral movement, the projected deflection of the piles would induce additional bending moment to the piles.

Construction of the piles had already begun before the results of the trial loading were obtained. Checks of the as constructed piles were undertaken for their adequacy. It was found that the permanent steel casing had to be fully utilised taking into consideration a deduction for the estimated corrosion over the life of the structure .

9. SUMMARY AND CONCLUSIONS

Some road embankments at Raleigh Deviation, NSW, Australia have undergone large settlement. This settlement together with the associated lateral soil movement has posed significant impacts on the adjacent bridge abutment piles.

Design considerations of the abutment piles subjected to large downdrag and shear forces and bending moment resulted from soil movement have been discussed. These include pile orientation, pile size and number, rock socketing, ground struts, bitumen coating, and permanent steel casing used as a structural member.

10. ACKNOWLEGMENTS

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11. REFERENCES

Bourges, F. and Mieussens, C. (1979). Deplacements lateraux a proximite des remblais sur sols compressibles, Methode de prevision, *Bull Liason Labo. P. et Ch.*, Vol. 101, pp. 73-100.

Chen, L.T. and Poulos, H.G. (1997). Piles Subjected to Lateral Soil Movements, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 9, pp. 802-811.

Goh, A.T.C., Teh, C.I. and Wong, K.S. (1997). Analysis of Piles Subjected to Embankment Induced Lateral Soil Movements, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 9, pp. 792-801.

Hsi, J.P. (1992). *Analysis of Excavation Involving Drawdown of the Water Table*, Ph.D. Thesis, The School of Civil and Mining Engineering, The University of Sydney, 287p.

Hsi, J.P. and Small, J.C. (1992a). Simulation of Excavation in a Poro-Elastic Material, *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 16, pp. 25-43.

Hsi, J.P. and Small, J.C. (1992b). Analysis of Excavation in an Elasto-Plastic Soil Involving Drawdown of the Water Table, *Computers and Geotechnics*, Vol. 13, pp. 1-19.

Matyas, E.L. and Santamarina, J.C. (1994). Negative Skin Friction and the Neutral Plane, *Canadian Geotechnical Journal*, Vol. 31, pp. 591-597.

Poulos, H.G. (1972). Difficulties in Prediction of Horizontal Deformations of Foundations, *Journal of the Soil Mechanics and Foundations Divisions,* ASCE, Vol. 98, No. SM8, pp. 843-848.

Poulos, H.G. (1973). Analysis of Piles in Soil Undergoing Lateral Movement, *Journal of Soil Mechanics and Foundation Engineering Division*, ASCE, Vol. 99, pp. 391-406.

Poulos, H.G. (1990). Design of Piles for Negative Friction, *Piletalk International '90*, Jakarta, Indonesia.

Small, J.C., Booker, J.R. and Davis, E.H. (1976). Elasto-Plastic Consolidation of Soil, *International Journal of Solids Structures*, Vol. 12, pp. 431-448.

Stewart, D.P., Jewell, R.J. and Randolph, M.F. (1992). Piled Bridge Abutments on Soft Clay – Experimental Data and Simple Design Methods, *Research Report No. G1023*, Department of Civil and Environmental Engineering, The University of Western Australia.