Modelling of Test Data from Baandee Lakes Bridge

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Abstract

Many bridges in Western Australia designed in the 1960s and 70s have been deemed structurally deficient in punching shear under the current AustRoads Bridge Design Code (AS5100). However results from destructive testing of the Baandee Lakes Bridge No 1049 has found that current analysis techniques described in the code are conservative and do not represent the actual capacity of the bridge. This paper will discuss how the incorporation of soil-structure interaction along with current analysis techniques can improve the calculation of a bridges structural capacity.

1.0 Introduction

Due to changing traffic conditions and the increasing vehicle loads, techniques used to evaluate the performance of Main Roads Western Australia (MRWA) bridges require constant updating. In fact, the accurate assessment of the load carrying capacity of bridge structures is a key factor in bridge management and fundamental to design strengthening and repair measures.

In 2002, MRWA organised the destructive load testing of Baandee Lakes Bridge, Bridge No. 1049, which is located 250km east of Perth on the Great Eastern Highway. This was part of a research programme aimed at developing a more accurate procedure for assessing the load carrying capacity of similar reinforced concrete flat slab bridges constructed around the late 1960's and early 1970's. Many of these bridges are deemed to be insufficient in punching shear, which, unlike bending actions, can lead to brittle failure mechanisms with little forewarning. The results obtained from both full scale laboratory and on site testing showed that interactions between the soil and the foundations need to be taken into account in order to improve the accuracy of the superstructure analysis. A Dynamic Cone Penetrometer Test performed in 1969 was the only available data to estimate the stiffness of the soil.

This paper describes the incorporation of soil-structure interaction (SSI) into bridge analysis and discusses the SSI effects on the structural capacity and load distribution through different sub-structural members. The main objective of this project is to identify an effective modelling approach for the soil-structure system to match the empirical results and provide more accurate bridge load ratings.

2.0 Derivation of the Load-Deformation curve

The overall load deformation response of an axially loaded pile depends on the axial compressibility of the pile as well as on the shape of the load transfer curves for the soil around the pile. The compression or extension of the pile may be calculated from consideration of the variation of axial load, P, along the length of the pile, for a pile of radius r_o and axial stiffness (EA). Figure 1 shows how shaft resistance, base resistance and compressibility of the pile are represented in the bridge model.

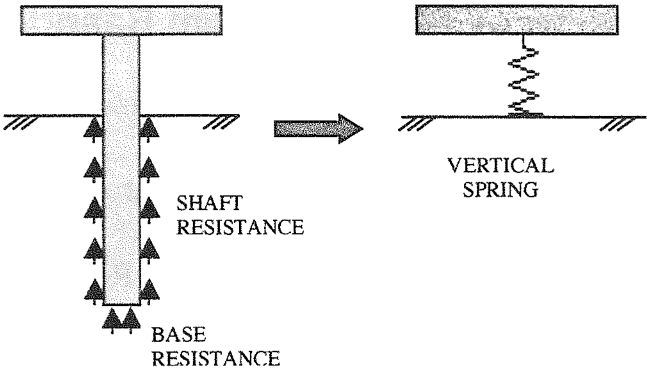

Figure 1 Equivalent Pile representation

The soil data provided by MRWA included a soil profile and the blow count of a Dynamic Cone Penetrometer test (DCPT). In the report by Wenham and Candy (2003) the soil under Bridge No. 1049 consists of a layer of stiff clay over Goldfield Cement. Figure 2 shows the soil profile identified at the site. In clays, the resistance of piles is governed by the shaft resistance rather than bearing resistance, therefore the effective radius of the piles was calculated with respect to the perimeter of the piles. This is shown in the equation below.

$$4b = 2\pi r_o \qquad (1)$$

Where b = width and depth of pile & r_o= effective radius of pile

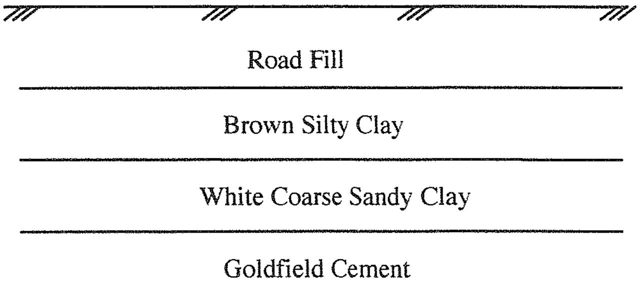

Figure 2 Soil Profile

2.1 Calculation of Soil Parameters.

The DCPT is a test used in the 1960's and 1970's composed of a cone on a shaft that is hit with a 140lb hammer. The blow counts describe the number of blows required to penetrate 300mm of soil similar to the Standard Penetrometer Test (SPT). SPT is different to DCPT as it allows the soil to travel through the centre of the shaft whilst the cone on the DCPT pushes the soil to the side resulting in a larger pressure on the side of the shaft. The similarities between the DCPT and the SPT led to the assumption that these tests can be considered as equivalent tests, on the other hand it has been recognised by Fahey (2006) that the DCPT may overestimate the soil strength.

Based on the report by Kulhawy and Mayne (1990) the SPT data for Baandee Lakes was correlated to the SPT data derived from an existing database of similar soils to obtain the relevant parameters of the varying layers of soil. This information was entered into the software RATZ (version 4-2) written by Randolph (2003) to estimate the piles vertical stiffness. In RATZ, the shear modulus and peak shaft friction for all of the soil layers, the ultimate base pressure, q_b and the pile displacement, w_b, at which the base is mobilised were entered to create a non-linear plot of the pile head load (in kN) vs. Pile head displacement (in metres). RATZ plots the vertical displacement from the top of the pile so the representation of the columns interaction with the soil can be represented by equivalent springs.

2.2 Discussion of the derived Soil Stiffness

The report by Fahey and Jewell (1983) have illustrated the difficulty of correlating SPT to DCPT data, therefore the force-deformation values have been calculated after considering the blow count values within a range of ± 30%. In Figure 3, load-deformation results, as calculated by using RATZ, are reported and compared with the backtracked results in the report by Tse (2002).

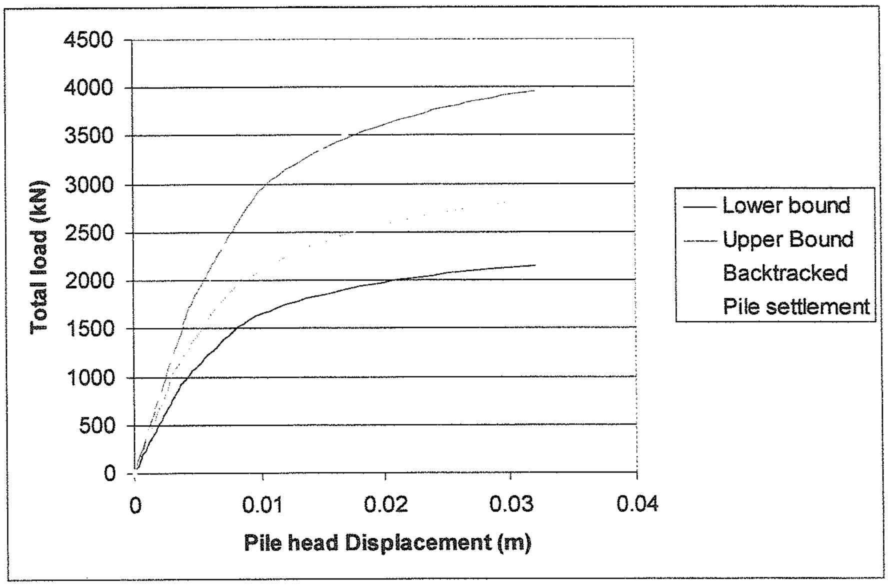

Figure 3 Spring stiffness of Piles

Figure 3 shows that the empirical backtracked results fall into the range calculated by using the RATZ models. As it was confirmed to be accurate and reliable, the information pertaining to spring stiffness of the piles were used to incorporate SSIs in the model of Bridge No. 1049.

3.0 Numerical Analysis of Bridge No. 1049

Once the soil stiffness was calculated and the results validated, an analytical model developed with software ACES Bridge Analysis System (Version 6) was used to investigate the effects that SSIs has on the bridge performance after incorporating springs at the support locations. This was investigated by comparing the resultant reactions for models with the different boundary conditions at the supports.

Three loading conditions were used in the analysis to simulate the effect of soil-structure interactions:

1. Four point loads located symmetrically around the pile. This simulated the four hydraulic jacks discussed in the reports by Wenham and Candy (2002) to obtain punching shear in the destructive test of Bridge No. 1049 and was used to compare the accuracy of the model..
2. To reproduce the effect of vehicle loading on the bridge a single truck (T44 configuration) was simulated to move along one lane of the bridge.
3. Two trucks (T44 configuration), travelling on two lanes (moving in the same direction) were used to determine the effect of saturated load on the piles and presents the worst loading case scenario.

3.1 Finite Element (FE) Models

ACES was used to develop a linear elastic FE model of the flat slab bridge. Concrete properties obtained by Wenham and Candy (2002) from site testing have been assigned to the model. The slab deck was represented as a grillage with structural members defined in both the longitudinal and transverse directions. ACES can only perform elastic analysis and has limited capabilities for FE modelling so the non-linear analysis program SAP2000 (Version 10) will be adopted to model the pile stiffness with a non-linear force-deformation curve. The computer model developed with ACES attempts to integrate the equivalent linear elastic behaviour of the soil to that of the structure. As such the linear stiffness's obtained by the initial gradients of the load deformation plots in Figure 3 were used to model in ACES.

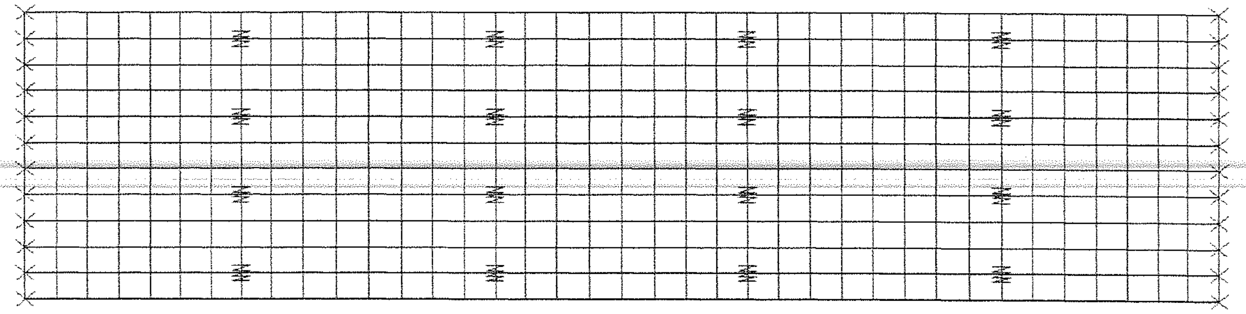

Figure 4 ACES grillage model

4.0 Results and Discussion

The stiffness of the vertical springs representing the columns and the stiffness of the slab strips in the proximity of the loading points were identified to have significant effect on the displacement and reaction force at the column connection. Loading increments of 50kN on each jack were used to simulate the overall response of the bridge. Figure 5 shows how the largest support reaction decreases with the vertical stiffness of the soil. From Figure 5, it can be noted that the applied load is predominantly shared between the directly loaded column and the two adjacent columns in the pier.

The destructive test of Bridge No. 1049 and full scale model showed that, at failure, only 1554kN were transferred to the column out of the total applied force of approximately 3600kN. As shown in Figure 5, the support reactions for an applied force of 3600kN are larger than 1700kN although still significantly lower than that of a fully fixed connection. A non-linear model is being developed to accurately represent the non-linear force-deformation curve which characterises the pile behaviour and interaction with the surrounding soil.

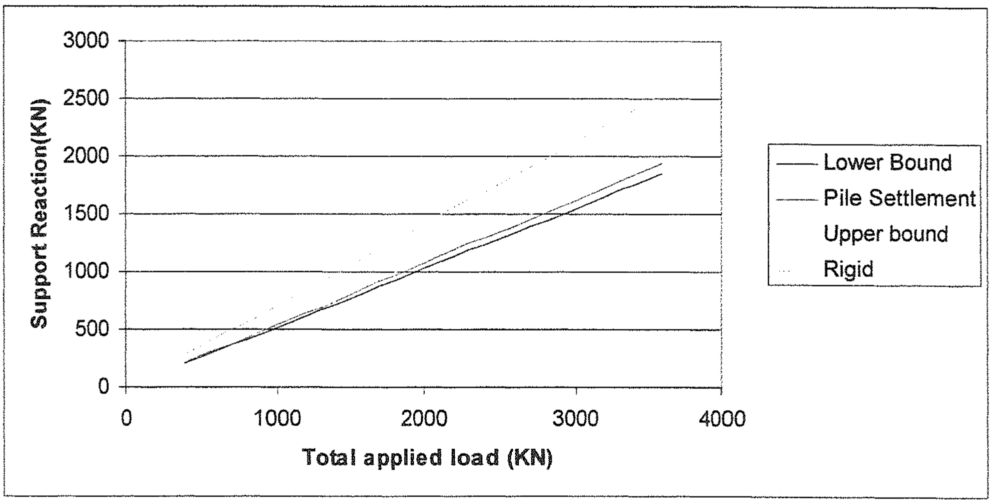

Figure 5 Model results for hydraulic jack load

Given the enhanced accuracy of the linear model, the axial forces in the columns can be used to evaluate the amount of load sharing between the columns in the loaded pier. The inclusion of springs characterize the settling of the piles due to applied loads resulting in enhanced load sharing between piles and a decreased maximum support reaction.

Actual loads on the bridge, such as operational vehicles, were modelled to reproduce actual loads applied to adjacent piles. Having both lanes loaded would represent the worst case scenario. The largest support reactions were recorded for a single T44 truck and two T44 trucks travelling side by side. The results are shown in Table 1.

	Maximum Support Reaction(kN)		Maximum Moments(kN.m)			
	Single T44	TwoT44's	Single T44		Two T44's	
			sag	hog	sag	hog
Lower Bound	315	466	56.6	78.7	85.1	116.6
Medium	329	478	56.4	82.1	84.5	120.3
Upper Bound	337	484	56.3	84	84.1	122.2
Fully Fixed	415	527	55.9	100	82.5	134.8

Table 1 Results for single and dual T44 trucks.

For two T44 trucks travelling side by side, the maximum support reaction in the piles represented by linear springs ranged between 88.4 to 91.8% of the model with fully fixed supports. For the single truck case this ranged between 76 to 81.2% of the model with fully fixed supports. As expected, the load sharing was less evident in the two T44 truck cases but still proved to reduce the maximum support reaction from being 527kN, in the fully fixed case, by approximately 10% to 484kN for the upper bound case. Similarly the Single T44 truck case reduced the maximum support reaction by approximately 20%.

The models were also analysed in bending to investigate the effect of SSI on the bending capacity of the bridge. For the varying models the bending moment diagram for each grillage member was calculated with the recorded maximum sag and hog moments. The moment values are also illustrated in Table 1. SSIs appear to have little effect on sag but improve hogging moments. This means that it might be possible to design the bridge with less steel reinforcement close to the support.

5.0 Conclusion and further works

This paper has shown that the calculation of bridge load rating in shear and, in particular the analysis of punching shear, can be improved by considering load sharing over the whole bridge instead of assuming that the punching shear is concentrated around the column head directly under the applied load. As demonstrated by the single T44 truck test, special heavy vehicles can benefit from the load sharing between piles by ensuring there is no load on the other lane of the bridge. Accurate modelling of soil-structure interactions may lead to significant economic gains as a result of improved load ratings of current bridges and more efficient design process.

The results from numerical models suggest that there is substantial load sharing between adjacent piles, particularly within the same pier. Through the use of RATZ, the DCPT data was able to predict the vertical stiffness of the pile within a ±30% error range. After comparing the models with the experimental results the use of the lower bound linear stiffness was proven to be conservative. The use of non-linear springs is currently under investigation but it is expected to result in lower support reactions and produce more accurate results. The properties of reinforced concrete in cracked conditions may need further consideration since flexural cracks in the concrete slab affect the overall stiffness of the slab. The use of a more accurate soil test would produce more accurate soil parameters to calculate the vertical stiffness of piles, leading to a more refined analytical model to replicate the in-situ behaviour of the bridge.

6.0 Reference

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