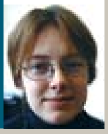

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Prediction of settlement of a re-used foundation

Foundation engineering in general has been developed to estimate foundation capacity. Factors of safety are applied not only to minimise the chance of failure of the foundation, but also to limit settlement of the foundation. Few tools are available to the engineer to predict settlement of a foundation under working load.

This article documents a case history. Two methods of settlement prediction were used for a foundation. A load test was done on the foundation and settlement measured. Results show that the predictions of foundation settlement differed severely, and confidence in the results could only be gained after doing a load test on the foundation

NEW STRUCTURES are built to replace older structures in city centres. Demolition of old foundations is difficult, as they are usually inaccessible. Consequently, the re-use of existing foundations for new structures is becoming increasingly important in South Africa. Settlement calculations for these foundations are complicated partly owing to their complex soil stress history. This article describes such a case history.

An existing road bridge over a railway line in Mpumalanga built in 1969 was to be upgraded. The new design vehicle was the Caterpillar 777 rear dump truck. The GVM of these trucks is in the order of 160 t (60 t front axle and 100 t rear axle).

A new bridge deck was designed to overlay the existing deck. The original deck was built in three spans, simply supported. The new deck was designed to distribute load over the four spread footings built for the original bridge. As a result very little settlement and especially differential settlement could be allowed.

SITE INVESTIGATION

The foundations of the bridge were exposed. A high-quality, undisturbed block sample of the material immediately below the founding depth was taken for laboratory analysis. Test pits were dug close to the foundations to investigate the underlying soil.

The generalised soil profile consisted of a clayey fine and medium sand overlying a well ferruginised layer, described as 'relatively closely packed gravel'. The consistency of the upper material was described as 'medium dense with loose to medium dense patches' and the ferruginised layer

Figure 1 DPL test results of soil profile adjacent to the bridge foundations

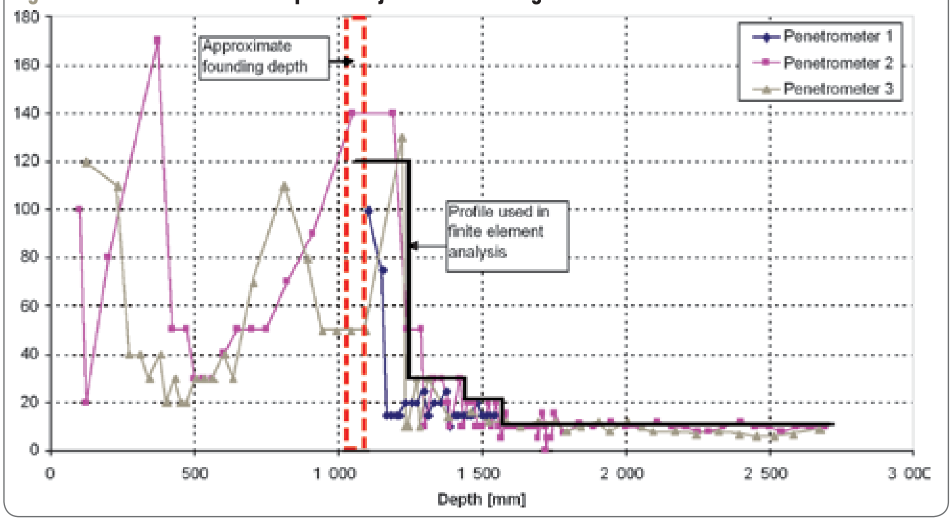
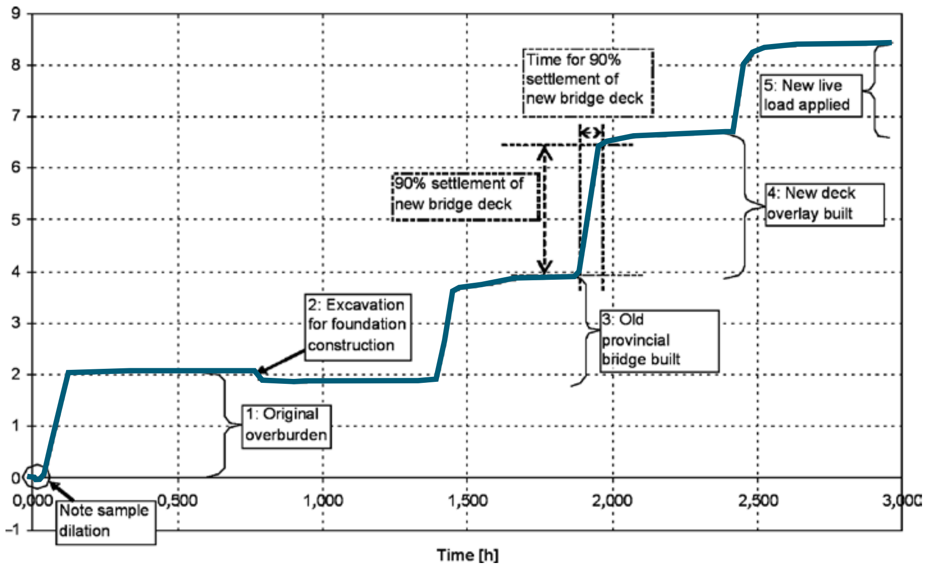


Figure 2 Time for primary consolidation to take place after each stage of the stress path test



was described as dense.

DPL (dynamic penetrometer light) tests were carried out next to the foundations at three locations. The test results are summarised in figure 1. The results confirmed the variable density of the soil profile noted during the test pit profiling. It was of concern that the DPL results consistently showed a loose soil layer extending approximately 250 mm below the founding depth. Penetration per blow in this soil layer was in the order of 120 mm. Visual inspection of the profile indicated that the majority of settlement would take place in the upper 'loose' layer of soil. Owing to concerns about the compressibility of this 'loose' layer a load test was recommended.

SETTLEMENT PREDICTIONS

Foundation settlement was predicted using two independent methods. The first method entailed a simple elastic analysis based on the DPL results. The second method was a settlement calculation based on triaxial stress path results.

Predictions of settlement due to the load test as well as the ultimate working load were made. The applied pressure on the foundation due to the load test was 14 kPa. The total increase in applied load on the foundation consisted of 46 kPa from the bridge deck overlay and a further 39 kPa from the new live load.

Elastic settlement prediction

A simple plane strain finite element linear elastic analysis using the software package Plaxis was carried out. A trend line was hand fitted to the DPL results to distinguish between the various soil layers and to obtain a representative value of penetration for each layer (see figure 1). Soil stiffness (Young's modulus) was derived using the empirical correlation suggested by Packard

Figure 3 **Voids ratio plotted against vertical effective stress**

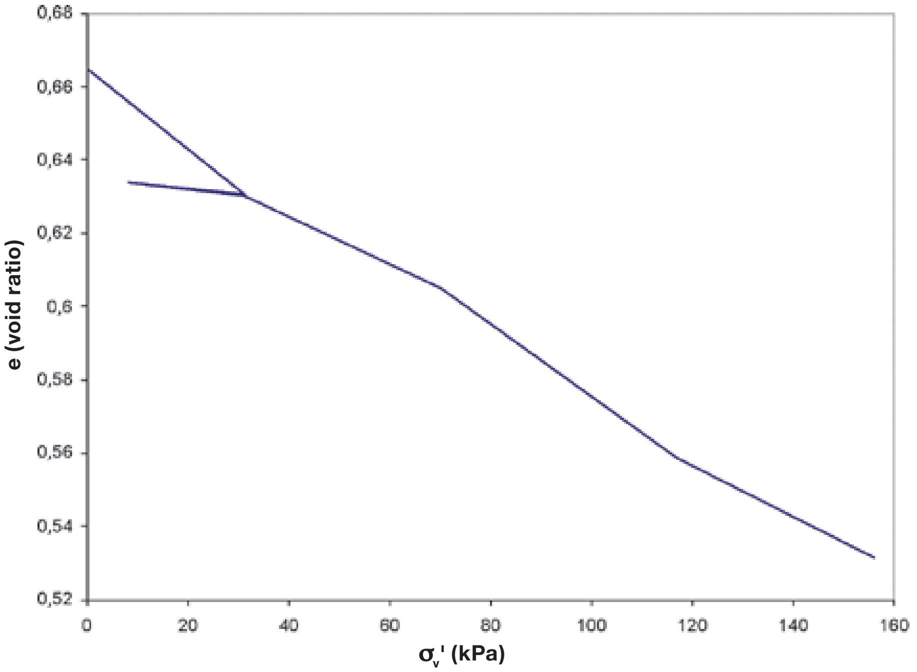


Figure 4 **Full-scale load test in progress**

Figure 5 **The completed bridge in operation**

The relatively short time of consolidation inspired further confidence in the bridge foundations. The new bridge has since been opened and is currently in operation

(1996). These Young's moduli were calculated for the soil profile below the founding level as follows:

- 0 to 0,25 m 2,0 MPa
- 0,25 to 0,4 m 17,7 MPa
- 0,4 to 0,6 m 26,6 MPa
- Below 0,6 m 40,7 MPa

The settlement prediction for the load test was estimated as 2,4 mm. The settlement prediction under full working load was 22,1 mm.

Stress path triaxial test

Stress path testing was carried out on the undisturbed block sample to simulate the stress path of the soil under the foundation. The stress path included stresses to simulate the construction of the original bridge, construction of the new bridge deck overlay and application of the ultimate working load (table 1). The correct stress history was important, as soil behaviour is highly dependent on its stress state.

The test was carried out by Dr Theron in a 38 mm Bishop and Wesley triaxial stress path cell at the University of the Witwatersrand. The cell, back and lower chamber pressures were applied with GDS pressure controllers and measured to 1 kPa using pressure transducers. Volume changes were measured externally by the GDS controllers accurate to 1 ml and internally by high accuracy linear variable differential transformers (LVDTs). One-way drainage was allowed during the consolidation phases.

Table 1 **Effective stresses applied to sample during stress path testing**

Step number	Description	Vertical effective stress (kPa)	Horizontal effective stress (kPa)
1	2 m overburden (assumed)	30	15
2	Excavation of foundations	5	5
3	Construction of old bridge	70	35
4	Construction of new bridge deck overlay	116	58
5	Apply the live load	155	77,5

Consolidation time

Figure 2 shows the consolidation test results in terms of deformation (strain) and time of the various phases. The time required for 90% of consolidation to take place (that is, 90% of excess pore pressures dissipated) after the new bridge deck overlay was constructed could be determined by means of the Taylor method (square-root-of-time method). The time for 90% deformation (consolidation) of the triaxial specimen whilst simulating the new bridge deck overlay was 6,5 minutes.

One-way drainage conditions were assumed under the bridge foundation. The drainage path length of soil below the bridge foundation was 250 mm as the gravel layer was assumed to be free draining. Time for consolidation of 90% of the excess pore pressures under the bridge foundation was calculated to be 1 hour and 17 minutes. This was significant as it meant that most of the foundation settlement would take place before the initial concrete set. Settlement (and differential settlement) after the initial concrete set would thus be reduced greatly.

Settlement calculation

Figure 3 shows the changes in void ratio with applied vertical stress. The coefficient of volume compressibility (m_v) was determined from these results. The coefficient of volume compressibility for the change in stress due to the construction of the new bridge deck overlay was 4,62 x 10^{-5} kPa^{-1}.

The settlement prediction for the load test was predicted as 0,16 mm. The settlement prediction under full working load was 0,98 mm.

Bridge load test

The Caterpillar 777 rear dump truck, modified to be used as a water truck, was used to apply a load to the deck. When completely full, the rear axle load of this truck is 83 t. The rear axle load of the truck used in these tests was approximately 70 t, however, as the water tank was not completely full but 430 mm and 450 mm below the top in the first and second tests respectively. Figure 4 is a photograph of the test in progress.

Table 2 shows the results of the deflection measurements made on the bridge 24 hours after first application of the 70 t load. Note that two separate load tests were conducted on the two abutment foundations. Reference targets measured indicate that the accuracy of the precise levelling results were approximately 0,1 mm. Negative deflection measurements indicate settlement. The average settlement of the bridge foundation in these tests was found to be 0,25 mm.

Conclusions

Two methods were used to predict the settlement of the bridge both during the load test and during construction and operation. Elastic finite element modelling predicted a settlement of 2,4 mm for the load test. Analysis of stress path triaxial test results on an undisturbed sample predicted a settlement of 0,16 mm.

Two load tests were conducted on the bridge. The measured settlement values varied between 0,30 mm and 0,20 mm with an average of 0,25 mm. Elastic modelling of the settlement therefore overestimated settlement by an order of magnitude whereas back analysis of the triaxial test underestimated settlement by 36%.

The triaxial test measured the stiffness of the soil sample after the application of a stress path similar to that of the foundation soil prior to construction of the new bridge deck. The calculated stiffness thus represents the stiffness of the soil under its correct stress state. It has recently been recognised that soil exhibit linear stiffness behaviour at very small strains (0,001%) after which the stiffness decreases with increasing strain. The difference in predicted settlement of the foundation using the two methods followed from the differences in the strain range at which the stiffness measurements were made. The triaxial test measured the soil stiffness in the correct (small) strain range while the DPL, due to the nature of the test, imposed large strains. Consequently, the predicted settlement based on the triaxial test results would be lower than those based on the DPL results. This study has also pointed out that load tests on foundations are of critical importance if accurate settlement predictions are to be made.

An estimate of the rate of consolidation (and hence settlement) could also be made using the triaxial test results. The relatively short time of consolidation inspired further confidence in the bridge foundations. The new bridge has since been opened and is currently in operation (see figure 5). □

Table 2 Deflection measurements of bridge 24 hours after load application

Point	Deflection [mm]
Northern abutment	
1	–0,3
16	–0,3
Southern abutment	
8	–0,2
9	–0,2
Average	**–0,25**

Source:
http://www.saice.org.za/downloads/monthly_publications/2007/CivilEngApril2007web/#/0