PREDICTION STUDY — DRIVEN PILES

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SYNOPSIS

This case study was especially developed for the Conference, and involved the prediction of the load deflection performance of two driven precast piles, both by static analysis and by dynamic methods. After driving the piles to predetermined depths (assessed from the results of prior site investigation) the piles were left for several weeks and then tested to failure under static load. After a further four weeks, they were "restruck" for the purpose of determining dynamic information for assessment by the CAPWAPC method.

Sixteen participants submitted predictions based on static analyses. Dynamic analysis was undertaken by four participants, and presented as a group result for comparison with the static load performance.

1. INTRODUCTION

This prediction problem was initiated by John Wagstaff Constructions Pty. Ltd. who proposed that test piles be installed and dynamic measurements taken to allow comparison of predictions of pile capacity by the CAPWAPC method with those determined by static load testing. This idea was developed to the stage where detailed site investigation data was obtained and circulated, to allow participants also to predict pile performance based on engineering soil properties.

Two piles were installed on a site in Hemmant, Qld., one being founded in clays and the other in deeper sands. Participants were asked to predict the load deflection curve, estimating the load to cause settlements of 2, 5, 10, 20 and 50 mm for each pile.

2. SITE INVESTIGATION DATA

Site investigation comprised:

. A borehole to 30·m with undisturbed samples in clays and standard penetration tests in sands at 1.5 - 2.0 m depth intervals.
. An electric friction cone penetrometer test to a depth of 32 m.
. Marchetti dilatometer tests at 0.5 m intervals from 1.5 to 28.5 m depth.
. Laboratory testing for confined compression strength of selected clay samples in the depth range 1.5 - 24 m.

The results of the borehole are given in Fig. 1, and a summary of the cone test and dilatometer test result is given in Table 1.

Assessment of the shear strength of the clays can be made from:

. the cone penetrometer test - here determined as $c_u = (q_c - 6')/13.5$
. the dilatometer tests - calculated in accordance with procedures recommended by Marchetti.
. the laboratory confined compression tests - taken as half the unconfined compression strength.

These results are summarised in Fig. 1, which indicates very close agreement between the alternative methods of strength assessment.

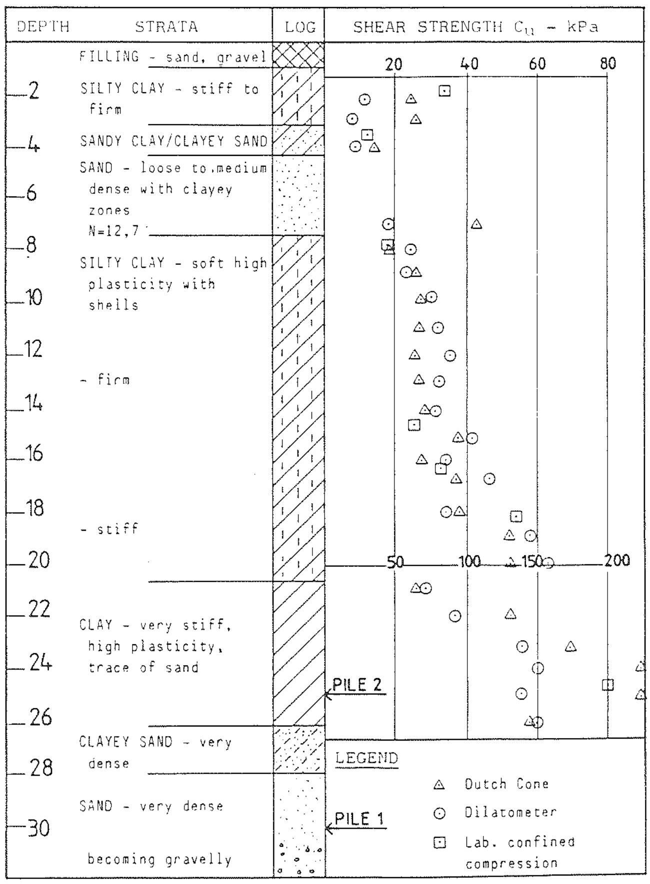

Figure 1. Soil Profile

TABLE 1 -TYPICAL IN-SITU TEST RESULTS

Depth (m)	Cone Penetrometer Test Cone (MPa)	Sleeve (kPa)	Friction Ratio (%)	Marchetti Dilatometer Test Material Index	Constrained Modulus (MPa)	Shear Strength (kPa)	Earth Pressure Coefficient	Laboratory Confined Compression (kPa)
3	0.4	5	4	0.45	0.8	8	0.5	23
5	4.5	40	1	9.70	30.8	-	0.6	
8	0.3	6	5	0.14	1.1	24	0.7	37
12	0.4	8	4.5	0.22	2.5	35	0.7	
16	0.5	14	4	0.21	2.0	34	0.6	65
20	0.8	20	4	0.26	5.6	62	0.8	109
22	1.8	120	7	0.63	23.7	94	0.9	
24	3.0	170	6	0.43	28.9	150	1.2	395
26	2.0	70	4	0.65	35.9	130	1.0	
28	8.6	70	1	0.61	3.8	37	0.4	
30	14.1	120	1					
32	48.0	400	1					

3. PILING DATA

From the site investigation results, it was decided that it would be appropriate to install piles to depths of 25.0 and 30.5 m. This would give one pile founded in the clays and one in the sands, with a potential ultimate capacity in the range 1000 to 2500 kN, within the likely range of shaft ultimate capacity and available testing equipment. The piles were "Balken" piles, of high strength precast concrete, 275 mm square, cast in lengths of up to 12.2 m, with mechanical jointing during driving.

The piles were driven using a Banut 600 piling rig with a 5 tonne hydraulic hammer. Measurements were made of driving resistance and final set and these are given in Table 2. The piles were "restruck" some 4 to 5 weeks after testing and these measurements are also included in Table 3.

Each of the piles was fitted with force and velocity transducers so that measurements could be taken for assessment of pile capacity by the "dynamic" method. These measurements were recorded both during the initial driving and the restrike.

Table 2 - Pile Driving Details

Depth (mm)	Hammer Drop (mm)	Blows/metre Pile 1	Pile 2
2 - 3	100	9	15
4 - 5	100	21	25
7 - 8	100	4	7
11 - 12	100	11	7
15 - 16	100	11	12
19 - 20	100	31	29
21 - 22	200	37	28
23 - 24	200	99	72
25 - 26	400	68	
27 - 28	400	112	
29 - 30	500	105	

4. TIMING

The piles were driven on 26th February, 1988 and were static load tested 6 to 7 weeks later during 8th to 13th April. The restrike was originally planned for about two weeks after testing (to allow for possible regain in strength following relatively high pile deflections during testing), but was delayed until 11th to 25th May due to unavailability of equipment.

Table 3 - Driving Sets (at Final Level)

	Drop (mm)	Set mm/blow	Temporary Compression (mm)
Pile 1			
1st Drive	500	9.6	11.0
Restrike	800	1.8	16.0
Pile 2			
1st Drive	500	21.0	8.0
Restrike	800	2.8	14.0

5. PILE TESTING

Both the piles were tested to failure by static load testing procedures in accordance with Section 5 of AS 1289. Kentledge was used to provide the test load reaction, comprising a stack of precast pile sections (drawn from stock). The loads were applied by a hydraulic jack and deflections were measured by dial gauges mounted on a transverse reference beam.

In each case, piles were loaded in increments up to a nominal "working load" which was held for 6 hours. They were then unloaded and reloaded, with continuance of loading then until failure occurred.

The load deflection curves are given in Figs. 2 and 3. On each of these, a dotted line is shown, which is the result of a subsequent retest discussed in Section 11.

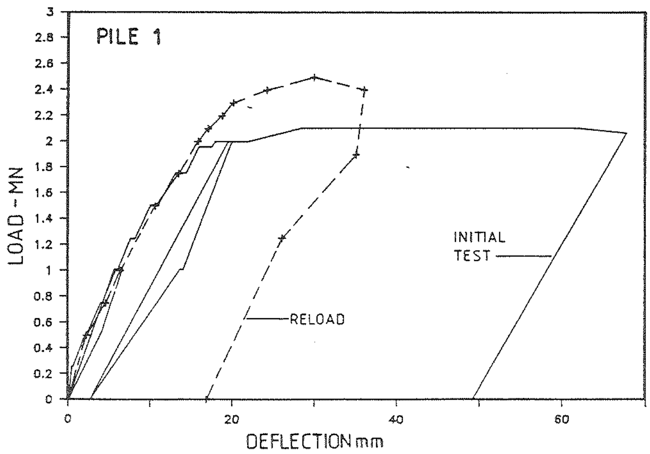

Figure 2. Test Load Results Pile 1

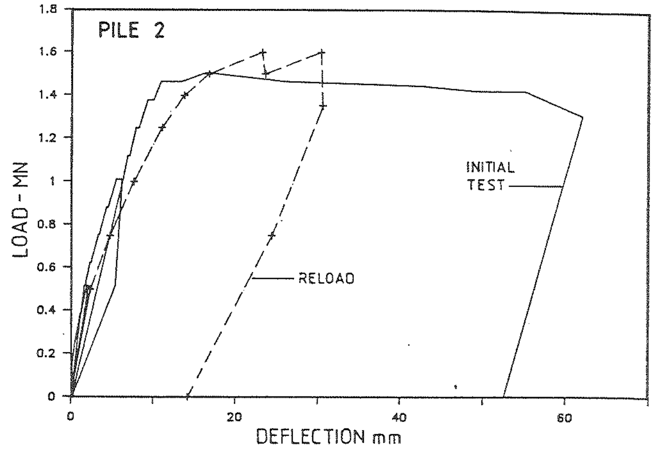

Figure 3. Test Load Results Pile 2

6. CAPWAPC ANALYSIS

Details of the dynamic analysis using the CAPWAPC (Case Pile Wave Analysis Programme - Continuous Model) were presented by Julian Seidel of Piletest Pty. Ltd. (a subsidiary of John Wagstaff Constructions Pty. Ltd.). Dynamic measurements were made during pile driving by Piletest and the data from the testing was digitised and sent to four other organisations for analysis.

- Pile Dynamics Inc. - Cleveland, USA
- Balken Piling - Sweden
- Road Construction Authority of Victoria
- Maunsell & Partners - Melbourne

Each organisation was sent a data set from the final driving blow of each pile and data sets for the first three blows and the fourteenth blow delivered to each pile on restrike. The organisations were free to analyse whichever data set they thought most appropriate.

In the CAPWAPC process (Goble G.G., Rausche F, Likins G.E., 1980) the user defines a model of the pile and the soil. The pile is divided into 1 metre elements and soil models are applied at every element. The elastic pile modulus and wave

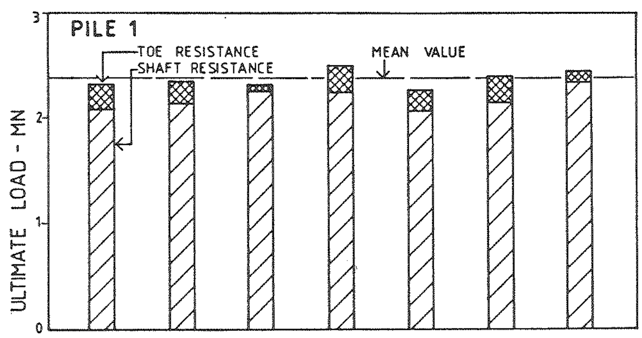

Figure 4. Variation of CAPWAPC Estimates Pile 1

speed are defined and an assumed resistance distribution, soil quake values and dynamic resistance parameters are entered. The measured velocity curve is applied to the top of the model and a force response is predicted and compared with the measured response. Changes to the assumed parameters are made in an iterative manner until the best match between predicted and computed responses is achieved. The total capacity and its distribution are then fully defined.

Comparisons of the analyses of the first restrike blows from all five organisations are shown in Figures 4 & 5. The mean resistances determined by all participants were 2371 kN and 1572 kN for test piles 1 and 2, respectively. The standard deviations represent only 3.5% of the mean value in both cases.

Piletest was the only organisation to analyse all stages of driving and restrike for both piles and typical CAPWAPC results are tabulated in Table 4.

Table 4 - CAPWAPC Results

Resistance Distribution	Driving Final Blow (kN)	Redrive Blow 3 (kN)	Redrive Blow 14 (kN)
Pile 1			
Shaft	716	2158	1806
Toe	406	244	385
TOTAL	1121	2402	2191
Pile 2			
Shaft	111	1187	907
Toe	394	364	564
TOTAL	505	1551	1471

It is recognised that the CAPWAPC method determines an ultimate pile capacity which is the pile capacity mobilised by the available driving

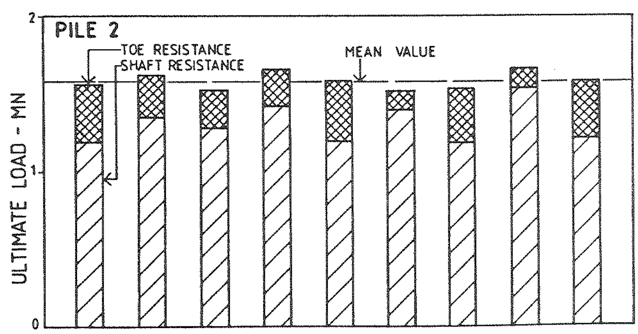

Figure 5. Variation of CAPWAPC Estimates Pile 2

energy. If the driving produces only low sets (less than 3 mm for most circumstances) the mobilised resistance is probably less than the ultimate pile capacity. In the restrike, pile sets were only 2 - 3 mm per blow.

Estimates of ultimate load based on the CAPWAPC measurements were:

Pile 1 - 2270 kN
Pile 2 - 1570 kN

Since the goal of the prediction exercise was to predict the capacity at 50 mm pile head movement, a means of extrapolating the CAPWAPC results was necessary (although not normal practice for such work). A procedure was devised to allow estimation of upper and lower bound values, the mean of which was taken as the ultimate load.

The predictions of ultimate capacity thus obtained were:

Pile 1 - 2620 kN
Pile 2 - 1750 kN

Comparisons between actual load deflection curves and those predicted from the CAPWAPC analysis are given in Figs. 6, 7, 8 and 9.

7. STATIC PILE LOAD PREDICTIONS

Sixteen participants made predictions of pile performance based on static analysis, with predictions of the pile load at deflections of 2, 5, 10, 20 and 50 mm. The predictions were compared with actual static load performance on the bases of:

- initial slope - calculated from the secant for deflection of 3.5 mm.
- ultimate load (i.e. load at 50 mm).
- overall best fit - determined from the sum of the deviations from the measured load for each of the target values.

Predictors reported a variety of methods of analysis. For the shorter pile, founded in clay, reliance was based mainly on shear strength. For the longer pile, reliance was based on the cone test and in some case, on intuition and judgement, particularly in the estimation of load-settlement performance.

Analyses were made by the writer using the methods of the Australian Piling Code. This used the recommended "alpha" factors for adhesion in the clay and the medium dense sand parameters for estimating end bearing resistance in the sands. Initial deflection slopes were estimated from modulus values and the deflection formulae given in the code. The wide range of soil strengths resulted in uncertainty regarding a single appropriate modulus value. Values of 70 MPa and 35 MPa were used for the base modulus for Piles 1 and 2, respectively.

Calculations were also made for ultimate load by the Hiley formula, using the final sets as measured during the restrike. Predictions are compared with measured results in Figures 6, 7, 8 and 9.

8. ULTIMATE LOAD PREDICTIONS

For Pile 1, the individual predictions of ultimate load are compared with the measured ultimate load in Figure 6. Figure 9 shows the "best" overall prediction and the range of predictions as compared with actual performance. The bar chart in Figure 6 uses the 50 mm deflection for determination of ultimate load, whereas the maximum load value was slightly ...

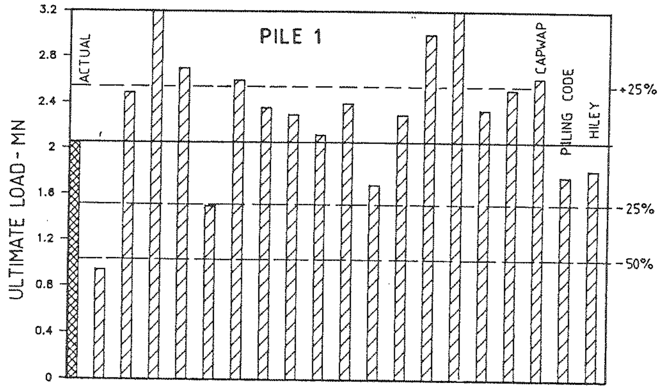

Figure 6. Comparison of Ultimate Load Predictions Pile 1

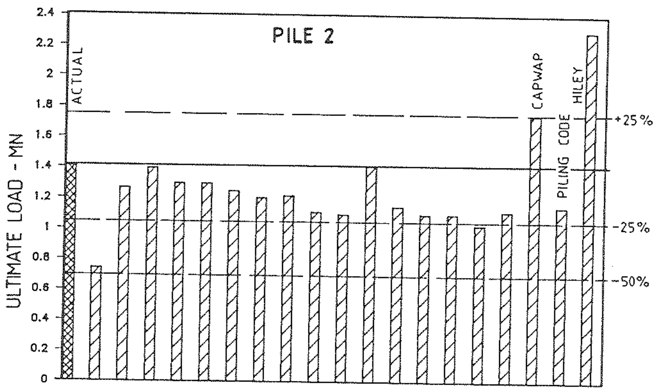

Figure 7. Comparison of Ultimate Load Predictions Pile 2

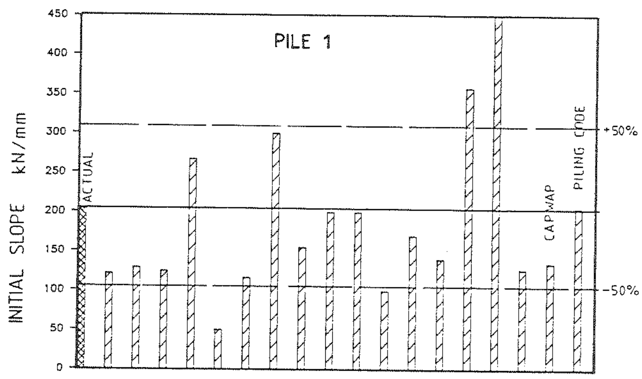

Figure 8. Comparison of Slope Predictions Pile 1

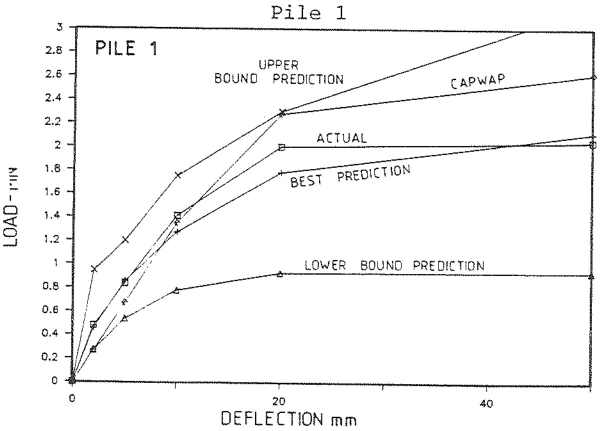

Figure 9. Comparison of Load Deflection Curves Pile 1

Of the 16 predictions, 5 were within about 10% and 12 were within about 25% of the actual value. Most predictors slightly overestimated ultimate pile capacity and both the Piling Code and the Hiley formula underestimated pile capacity by about 12%.

For Pile 2, only the CAPWAPC analysis overpredicted (by about 10%) the ultimate load, and all the static analyses underpredicted the load, with all but 2 predictions being within 25% of the actual value. Once again, the Piling Code indicated a value which was about 20% below the actual value.

9. SLOPE PREDICTIONS

There was a greater variability in predictions of the slope of the load deflection curve then for ultimate load. Most (but not quite all) participants correctly predicted almost identical initial slopes for the 2 piles. Of the 16 predictions for Pile 1:

- 1 was within 10% of actual - as also was the calculation based on the Piling Code.
- 12 were within 50%.
- 12 underpredicted the slope (i.e. estimated the pile to move more than it did).

The CAPWAPC analysis underestimated pile stiffness by about 15% - less than the average of the static predictions.

The comparison of predictions is given only for Pile 1, and a generally similar range of results was given for Pile 2.

10. BEST PREDICTIONS

The organisers arranged a sweepstake on the best predictions of the load at 50 mm deflection. No-one predicted the post-peak reduction in load which occurred after 20 mm deflection and as a result, the closest estimate of the 50 mm load was therefore not the best overall prediction.

Sweepstake winners were:
Pile 1 - Jim Millar, Frankipile Australia
Pile 2 - A. Scotnicki, S.E.C. Victoria

Awards were presented by John Wagstaff Constructions to participants with the best overall prediction based on deviations from the actual curve:
Pile 1 - Jim Millar, Frankipile Australia
Pile 2 - P. MacDonald, R.C.A., Victoria.
Best overall predictor for both piles:
Ivan Hanstorfer - R.C.A., Victoria.

11. FURTHER PILE TESTING

Following the completion of predictions and comparison with the static load test values, Piletest (J. Siedel) undertook re-testing of the piles by static loading. Because of the relatively long delay between the static load testing and the restrike (about 5 to 6 weeks) it was thought that there may have been further "set-up" of the clays which increased the ultimate capacity.

Static load testing was carried out in August, 1988 (3 months after the restrike) using incremental load testing in one cycle to failure with a load being applied in increments which were held in each case for five minutes. By comparison with the initial testing, this should have resulted in a slightly steeper load deflection curve.

The test results are shown as dotted lines in Figures 2 & 3, with increases in the ultimate load being recorded for both piles. Comparitive results are also included in Figures 6 to 9. A comparison of the results is given in Table 4.

Table 4 - CAPWAPC Results Summary

Pile	Founded In	Ultimate Load* Test 1+ (kN)	Ultimate Load* Test 2+ (kN)	CAPWAPC Prediction (kN)	CAPWAPC (kN)**
1	Sands	2210	2500	2620	2370
2	Clays	1500	1600	1750	1570

* by static load test - maximum value
\+ Test 1, April 1988 Test 2, August, 1988
** initial analysis (limited deflection)

12. CONCLUSIONS

The following conclusions are drawn from the pile prediction results.

1. There was keen interest and generally good ability in predicting pile performance. Most participants predicted ultimate loads within 25% of actual measured values.

2. Average results underpredicted the capacity of the pile founded in clay and overpredicted that of the pile in sand.

3. The CAPWAPC results agreed well with the static load tests, with slight overprediction of ultimate load and underprediction of stiffness in both cases. Due to pile "set-up" and the delay between static testing and the restrike, the CAPWAPC analysis would have been carried out on a slightly "stronger" pile than indicated by the static load test. Agreement with the 2nd series of static load test results is excellent.

4. Back analysis for the case of the pile founded in clay indicates that the ultimate load can be approximated very closely by the following:
   - shaft adhesion in soft clays - $\alpha = 1$
   - shaft adhesion in stiff clays - $\alpha = 0.9$
   - end bearing capacity in stiff clays - $9\ c_u$ ($c_u = 160$ kPa)

   For the case of the pile founded in sands, the ultimate pile capacity was closely approximated by shaft adhesion values given above for the clays, and in the sands by a shaft adhesion averaging 80 kPa and an end bearing capacity of 4000 kPa.

13. ACKNOWLEDGEMENTS

Grateful thanks are due to the following organisations who contributed to the testing and installation:

- John Wagstaff Constructions Pty. Ltd. - pile installation and dynamic testing.
- D.J. Douglas & Partners Pty. Ltd. - Dutch cone and Marchetti dilatometer testing, static load testing.
- Coffey & Partners Pty. Ltd. - borehole logging and laboratory testing.
- Daly Bros. Pty. Ltd. - borehole drilling.