Application of Stress-Wave Theory to Piles, Niyama & Beim (eds) © 2000 Balkema, Rotterdam, ISBN 90 5809 150 3

The application of high strain dynamic pile testing to screwed steel piles

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ABSTRACT: Screwed steel piles have been in commercial use in Australia for about 3 years and are becoming a popular foundation support for small to medium commercial structures. Although new to Australia this type of pile is described in the old British Foundations code CP4 –1954. In Australia they would previously have been described as micro-piles as they were used for small loadings only but they are now becoming used for more regular pile applications, with serviceability loads increasing to well over 1000kN. They comprise a relatively small diameter steel tube with one or more relatively large diameter screw flights near the toe and sometimes at intervals along the shaft. The structural and geotechnical design of these piles is still evolving.

This paper will describe several projects where dynamic pile testing has been successfully used to demonstrate the capacity of these piles with a range of sizes, lengths and ground conditions. In one case a static load test was conducted after the dynamic test and provided a close correlation with the dynamic test result in a Grade A prediction. The general methodology used to conduct the successful tests with the PDA/CAPWAP system will be described

1 SCREW PILES

These piles comprise a steel tube of 325 or 350MPa grade steel with one or more auger screw flights near the toe or at intervals along the shaft. Originally the screw flights were quite "steep" much like a "cfa" auger piling rig, but more recent designs have used a much "flatter" screw and it is much wider than would be used for an auger rig intended for removing soil. Piles for some projects are galvanized for corrosion protection. The piles observed by the Author include a pointed vertical plate at the toe, which prevents any substantial amount of soil entering the steel tube, hence internal friction does not need to be considered.

Piles have been excavated after installation to inspect disturbance of soils along the shaft. Anecdotal reports from independent geotechnical engineers after inspecting excavated anchors in sandy clay suggest that the auger flight does not significantly disturb the surrounding ground mass. This is also suggested by high shaft friction shown in dynamic test results as presented in this paper.

The piles are screwed into the ground using a hydraulic torque motor attached to earthmoving machinery, normally being an excavator. No specialised purpose-built pile installation machinery is required and, as commonly available equipment is used, reliability and ease of repair would appear to the Author to be good.

Although the equipment that is used is commonly available these piles still appear to be installed by specialised screw piling contractors. We are aware of at least 3 companies that specialise in manufacture and installation of screw piles in Australia. As this pile type is presently used at the low capacity end of the piling "market," price competition appears to be vigorous. A photo of a typical installation is shown in Figure 1.

Piles currently range in size from 76mm outside diameter x 3.8mm wall thickness with a screw flight diameter of 350mm and serviceability loads of 50-100kN to 273mmODx9.3mm wt with a screw flight diameter of 1m for serviceability loads of up to a claimed 1800kN.

Connections for the pile to the hydraulic motor and splices to other sections of pile currently comprise a bolted external flange butt joint. This has advantages for dynamic pile testing as the horizontal flange stiffens the tube against buckling at the top during the impact of a drop weight. However it is the Author's view that this has a disadvantage for the behaviour of the pile in that if this flange penetrates below ground level then an open annulus is

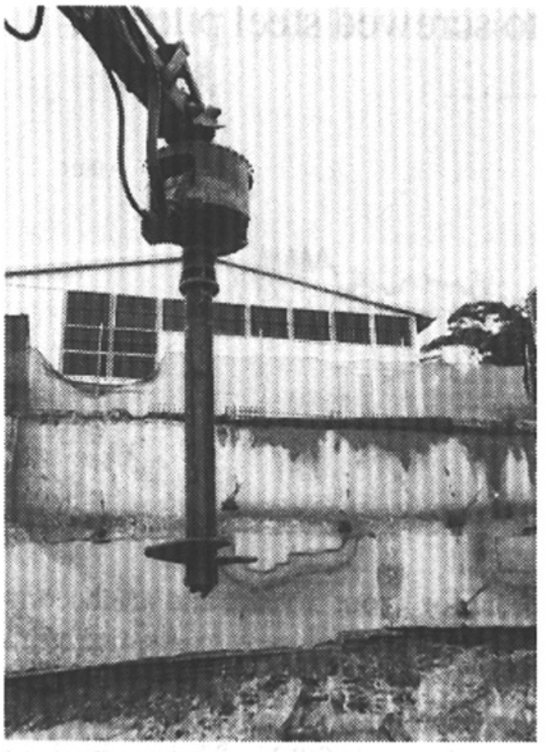

Figure 1 - Installation of screw pile

created around the pile that reduces lateral support. However, in very soft soils it may be an advantage in reducing negative skin friction. It is understood that at least one company is developing a new pressed fitting, which does not extend beyond the outside diameter of the steel tube. The Author has not dynamically tested a pile with the new joint.

Concerns have been raised by some clients that, based on design calculations, the connection between the screw flight and the pile tube is a weak point in the system as almost all pile resistance to vertical load is supposed to be provided by the screw flight. Concerns include the stiffness of the auger flight and the strength of the welded connection to the steel tube. Although these concerns are well founded the Author's experience is that CAPWAP analyses suggest the shaft does supply considerable resistance through shear friction with the soil. The Author has also not observed any failure of the screw flight connection during testing, which is generally to loads of 2 to 2.5 times the serviceability load plus dynamic effects. Nevertheless, it is understood that this concern is also being addressed with development of what has been termed an "inter-brace" connection to increase stiffness of the joint and the length of weld at the joint. This should also increase the stiffness of the piling system.

The screw pile contractors all attempt to relate installation torque to the load resistance of the pile and adopt torque as the pile acceptance criteria. The Author is not fully convinced that the installation torque can provide a quantitative measure of vertical load resistance, which is mostly provided by end bearing. It is accepted that the torque provides a qualitative measure of resistance but the overburden pressure, plasticity and moisture content of the soil and the relative proportion of clay in the soil, particularly at the level of the screw flight, would appear to also affect torque resistance and thus only when these conditions are also considered can the installation torque provide a quantifiable measure of vertical load resistance. With the present "state-of-the-art" it is considered that the resistance should be assessed using geotechnical calculations, with appropriate uncertainty factors, termed "geotechnical reduction factors" in the current Australian Piling Code (Reference 2). If higher geotechnical reduction factors are to be used (ie lower "factors of safety") then the Code requires a proportion of piles at each site to be tested in order to verify load resistance. The Author agrees with this requirement. At least one of the contractors has chosen to use dynamic testing by an independent consultant to provide this resistance verification.

2 DYNAMIC PILE TESTING

The Author uses the PAK Pile Driving Analyzer from Pile Dynamics Inc. together with the associated CAPWAP signal matching software. The method and current "state-of-the-art" has been described in Goble et al (1996).

A special cable drop hammer and frame was made up by one of the Contractors specifically for dynamic testing of his screw piles. See Figure 2. The drop weights comprise 2tonne and 4tonne solid circular billets of steel of about 350mm diameter and 2.6m and 5m long respectively. The guide frame allows for a maximum hammer stroke of about 2m. The frame is also supported laterally by 4 guy wires

Figure 2 - Test Rig

that are generally tied to adjacent screw piles, being either production piles or temporary anchors specifically for the test.

The large weight of the rams compared to the pile weights provides for a long-acting input pulse. This can be seen in the test results presented below, where the resistance also acts for a long time compared to conventional dynamic tests on piles with larger shafts.

Testing has so far been conducted on the steel tubes only prior to any concrete infill, where used. Owing to the relatively small shaft diameter compared to the pile capacity it has been generally found that testing is limited by shaft stresses rather than geotechnical capacity of the piles. However this is not always the case.

3 CASE STUDIES

3.1 *Sydney International Airport*

This was the first project where the Author had encountered screw piles and the design appeared to be under early development. Several configurations were tested, being 89x5.5mm tubes with single 350mm screw flights near the toe (working load 100kN) and 168x7mm tubes with either two 700mm screw flights (working load 500kN) or with 5 flights (working load 600kN). All piles penetrated the ground about 8m. Ground conditions were moderately dense to dense medium sands.

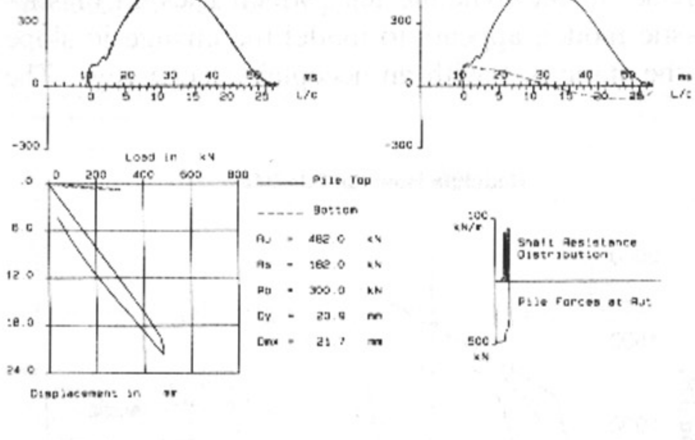

Figure 3 -Plots for SP9

CAPWAP modelling of the piles should not include the screw flight as taking part in the travel of stress waves along the pile ie a significant increase in shaft impedance over a very short distance, of only a few millimetres, at the screw flight is not required. As the flights are only a plate attached to the side of the pile the Author does not accept that it truly is involved in the travel of the stress wave and we almost never model the flights as anything other than supplying a point resistance with low stiffness.

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Sydney International Airport, Project: 97037
Pile: SP9 Blow: 1 Data: ABA Foundations
Collected: 03-Apr-97 Operator: Jon Cannon CAPWAP(R) Ver. 1996-2

CAPWAP FINAL RESULTS

Total CAPWAP Capacity: 482.0; along Shaft 182.0; at Toe 300.0 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile at Ru kN	Sum of Ru kN	Unit Resist. w. Respect to Depth kN/m	Unit Resist. w. Respect to Area kPa	Smith Damping Factor s/m	Quake mm
				482.0					
1	1.1	.6	.1	481.9	.1	.13	.47	.292	8.000
2	2.1	1.6	.1	481.8	.2	.08	.30	.292	8.000
3	3.2	2.7	.2	481.6	.5	.22	.78	.292	8.000
4	4.3	3.8	.9	480.7	1.3	.81	2.91	.292	8.000
5	5.3	4.8	5.9	474.8	7.2	5.56	19.86	.292	8.000
6	6.4	5.9	81.1	393.7	88.3	76.30	272.49	.292	8.000
7	7.4	6.9	4.5	389.2	92.8	4.24	15.14	.292	8.000
8	8.5	8.0	89.2	300.0	182.0	83.99	299.97	.292	8.000
Average Skin Values			22.8			22.76	76.49	.292	8.000
	Toe		300.0				2439.02	.079	7.000

Soil Model Parameters/Extensions	Skin	Toe
Case Damping Factor	.900	.400-Smith Type
Unloading Quake (% of loading quake)	50	100
Unloading Level (% of Ru)	10	
Resistance Gap (included in Toe Quake) (mm)		.500
Soil Plug Weight (kN)		.15

Figure 4 -Summary table for SP9

Owing to the small shaft diameter conventional (2F+2V) gauges were placed individually at 90° intervals around the piles. Gauges were bolted to the pile using drilled and tapped holes as with conventional testing of larger steel tube piles. Testing was started with small blows and then larger and larger blows were used until shaft stresses reached or approached the rated yield stress of the steel. As the piles are small diameter and therefore relatively elastic it was found that a cushion was unnecessary between the drop weight and the piles. If the piles had been cut off then an external connection flange was re-attached prior to testing in order to stiffen the top of the pile shaft.

The purpose of the testing was proof testing of working piles rather than as pure research tests. In all cases the testing demonstrated more than 2 times the working load. During the testing the piles were "set" as with testing of conventional piles. The fact that a sizeable permanent "set" could be achieved suggested that the testing was mobilising a reasonably high proportion of the available geotechnical resistance. However, the testing was generally stopped owing to high dynamic stresses in the shaft rather than reaching the ultimate geotechnical resistance of the piles with very high "sets."

The piles with 5 flights could not be "set" at all and they were probably significantly over-designed. The Author has not seen this design used again.

We CAPWAPed data from all piles. During CAPWAP analysis we used high "quakes" for both shaft and toe resistance as the shaft resistance was really provided by high level "toes." The CAPWAP models show resistance concentrated at the flight locations, which seems reasonable. The CAPWAP second toe option was not used to keep compatibility with the multi-flight analyses although this might be just as valid. The CAPWAP analysis was in other respects normal and we would expect similar accuracy to conventional analyses. The results show considerable resistance and owing to the high hammer/pile weight ratio and the elasticity of the system the resistance "stays on" for a long time. This is shown in the data plots and results table for piles SP9 and SP23 in Figures 3, and 4.

3.2 *Redcliff Hospital, Brisbane*

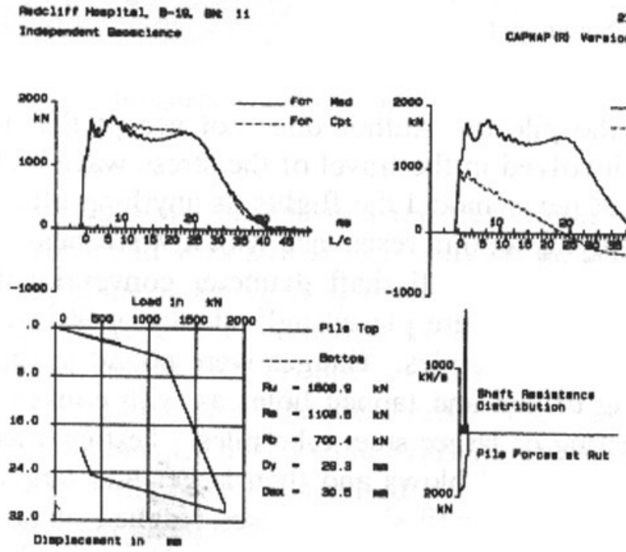

Figure 5 - Plots for B19

Ground conditions comprised completely weathered sandstone, which was essentially very stiff-hard clayey sand or sandy clay with reported undrained shear strength of up to 600-700kPa. This project was much more recent and the piles were much larger and more heavily loaded than previous tests. Piles were 219ODx8mm wt with 2 flights near the toe. The flights were nominally 0.85m diameter but were actually made from square plates 0.76m across with rounded corners and thus the area would be slightly less than a 0.85m circle. Note that the flight diameters were about 4 times the shaft diameter and it is questionable that they were stiff enough to truly be working at the outer edge. The pile design/constructor is aware of this possibility and is developing a stiffer flight as described earlier. Required working loads were 850 to 1000kN and it was necessary to demonstrate 2 times the working load.

The CAPWAP plots and summary table for pile B19 are shown in Figures 5 and 6. Resistance was again modelled with concentrations at the flights,

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Redcliff Hospital, Project: 98057
Pile: B-19 Blow: 11 Data: Steel Foundations
Collected: 27-May-98 Operator: Jon Cannon CAPWAP(R) Ver. 1996-2

CAPWAP FINAL RESULTS

Total CAPWAP Capacity: 1808.9; along Shaft 1108.5; at Toe 700.4 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile at Ru kN	Sum of Ru kN	Unit Resist. w. Respect to Depth kN/m	Unit Resist. w. Respect to Area kPa	Smith Damping Factor s/m	Quake mm
				1808.9					
1	.9	.6	49.6	1759.3	49.6	105.20	152.91	.146	2.616
2	1.4	1.1	49.6	1709.7	99.2	105.20	152.91	.146	2.616
3	1.9	1.6	49.6	1660.1	148.8	105.20	152.91	.146	2.616
4	2.4	2.1	900.6	759.6	1049.3	1910.27	2776.55	.146	2.616
5	2.8	2.5	59.2	700.4	1108.5	125.49	182.40	.146	2.616
6	3.3	3.0	.0	700.4	1108.5	.00	.00	.146	2.616
Average Skin Values			184.8			369.50	569.61	.146	2.616
Toe			700.4				1297.10	.007	25.000

Soil Model Parameters/Extensions		Skin	Toe
Case Damping Factor		.740	.022-Smith Type
Unloading Level	(% of Ru)	20	
Soil Plug Weight	(kN)		.25

Figure 6 - Summary table for B19

which is considered reasonable. The friction predicted along the shaft away from the flights is also high at about 150kPa, which suggests a Meyerhof α=0.25, which is also considered reasonable. The piles were very short for dynamic testing and it was necessary to use special start-up procedures in order to by-pass CAPWAP default minimum length limits. However, other than the abnormal initialisation a standard CAPWAP modelling procedure was followed. We again CAPWAPed data from all piles.

A static load test was conducted on this pile after the dynamic test. The results of the static test were obtained some months after the dynamic testing was reported so the dynamic test was a "Grade A" prediction. Both the static and the dynamic test passed the initial elastic behaviour of the pile and the "break" in the dynamic test, which uses an elastic-plastic model, appears to model the change in slope of the static test with an acceptable accuracy. The

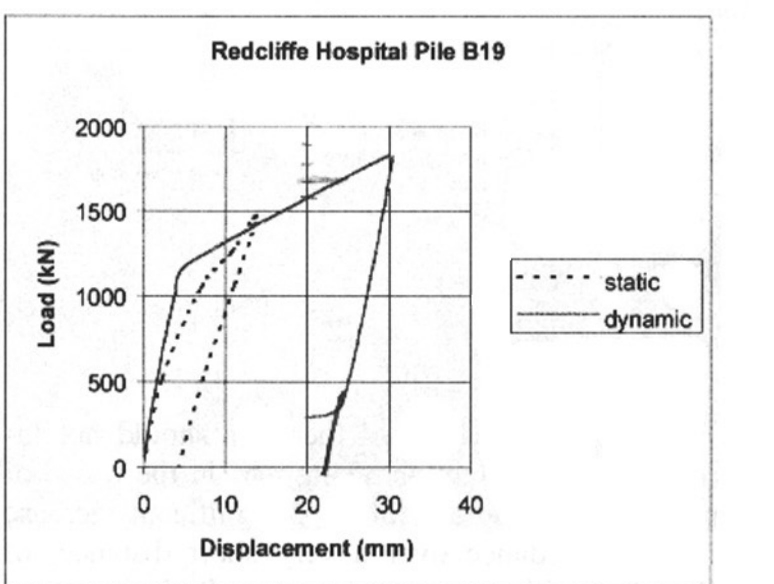

Figure 7 Static/dynamic correlation for B19

correlation is shown in Figure 7. The static load test was conducted in accordance with the Australian Piling Code AS2159-1995 to 1.5 times serviceability load with measurement of deflection vs time at various loads. These time dependent measurements have been removed from the static results presented here. The dynamic test mobilised considerably more resistance and the test was again limited only by stresses in the pile shaft.

3.3 *Redlands Mater Hospital, Brisbane*

This was a recent project and testing had become reasonably procedural. Two pile sizes were tested. The smaller piles were 89x5.5mm with a single auger flight that was basically a 350mm square with chamfered corners. Larger piles 114x6mm were also tested. These were also fitted with a single flight that comprised a chamfered square but the chamfers were larger such that the flight was essentially a 450mm diameter circle. Pile penetrations varied from 2.2 to 5m. Ground conditions comprised stiff clays over stiff to hard gravely clays. The project engineer required testing to demonstrate at least 2.5 times the "working" or serviceability load. This demonstrated load varied between 250 and 625kN. We tested 8 piles, which comprised 15% of the total piles. It is the Author's opinion that with this proportion of testing the required "factor of safety" of 2.5 is unnecessarily high. In accordance with the Australian Piling Code, which is a "partial factor" Code, it would be possible to adopt a geotechnical reduction factor of 0.8. For a typical pile this would suggest an overall "factor of safety" over serviceability of about 1.8.

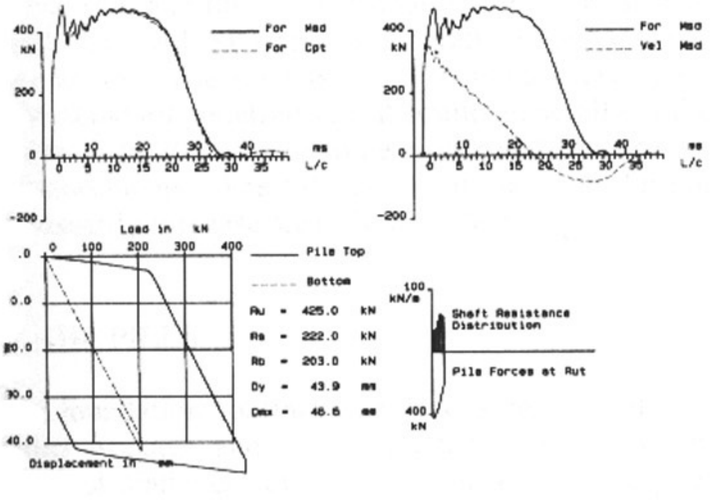

Figure 8 - Plots for 109 extension

Independent Geoscience 06-Oct-99

Redlands Mater Hospital, Project: 200011
Pile: 109 extension Blow: 1 Data: Steel Foundations 2t
Collected: 05-Oct-99 Operator: Jon Cannon CAPWAP(R) Ver. 1996-2

CAPWAP FINAL RESULTS

Total CAPWAP Capacity: 425.0; along Shaft 222.0; at Toe 203.0 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile at Ru kN	Sum of Ru kN	Unit Resist. w. Respect to Depth kN/m	Unit Resist. w. Respect to Area kPa	Smith Damping Factor s/m	Quake mm
				425.0					
1	1.9	1.6	32.5	392.5	32.5	34.85	97.35	.185	1.200
2	2.8	2.5	34.6	357.9	67.1	37.04	103.47	.185	1.200
3	3.7	3.4	46.0	311.9	113.1	49.32	137.76	.185	1.200
4	4.7	4.4	55.6	256.2	168.8	59.61	166.51	.185	1.200
5	5.6	5.3	53.2	203.0	222.0	57.04	159.32	.185	1.200
Average Skin Values			44.4			41.89	132.88	.185	1.200
Toe			203.0				1276.73	.104	39.000

Soil Model Parameters/Extensions		Skin	Toe
Case Damping Factor		.500	.258-Smith Type
Unloading Level	(% of Ru)	60	
Soil Plug Weight	(kN)		.10

Figure 9 - Summary Table for 109 extension

In this case we did not conduct CAPWAP analysis of data from every test. CAPWAPs were initially conducted on data from those piles with a mobilised resistance close to the requirement, this being for about half of the tests. A very close correlation was found between the Case method field estimates and the CAPWAP results, and because the other tests had proved 120 to 170% of the required ultimate resistance using the field "Case Method" further analysis was considered unnecessary, especially with regard for the already high "factor of safety."

One of the most highly loaded test piles was tested at 2 different penetrations with the pile being extended by 1.5m between tests. The torque resistance of this pile was quite high during installation at both levels but during testing the measured set was very high (32 and 37mm/bl) and the mobilised resistance was also correspondingly low at both penetrations. This is an example of why installation torque does not give a good indication of pile capacity. Eventually this pile was augmented with additional piles. CAPWAP results for this pile are shown in figures 8 and 9.

4 CONCLUSIONS

Dynamic testing can be conducted quickly and accurately on this unusual new pile type. Testing can be conducted using similar procedures to dynamic testing of more common pile types with small modifications to allow for the shorter pile length, if necessary. Resistance concentrated at the flight locations provides a realistic model of the pile.

The use of testing to verify pile performance should be conducted on every project, as the installation torque does not give a reliable quantitative estimate of pile resistance. Testing on each project is already common practice for driven piles where measurement of pile set appears to give a better quantitative indication of pile resistance than the installation torque applied to screw piles.

A Grade A dynamic prediction has demonstrated an excellent correlation of the dynamic test results with conventional static load test results.

REFERENCES

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