On the Subject of Piles in Tension

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ABSTRACT Some of the difficulties which may be encountered with traditional full-scale static load pull out tests both in terms of practicalities of setting up the test and interpretation of the results are presented. A simple model is described that appears to match the behaviour of the reinforced concrete under tension and that of characterising the skin friction behaviour with a single hyperbolic function, such as that suggested by Kondner (1963), Chin (1970, 1972) and employed in the Cemsolve® method of pile behaviour analysis, Fleming (1992).

An alternative to a traditional pullout test is now finding wide acceptance with the introduction of bi-directional load testing. The innovative solutions provided by casting a loading jack within a test pile itself are described in detail; and offer two approaches, in one, an additional reaction pile is located below the test pile – installed at the same time but to a greater depth, and the second is a method of analysis of the test results from a conventional bi-directional test which is used to estimate the upward behaviour derived from the geotechnical behaviour of the components measured.

1. INTRODUCTION

It is often thought that performing a full scale load test by applying tension will mobilise the skin friction directly and that the results would be very clear and easy to interpret as only skin friction should dominate the pile's load displacement behaviour. While this can be true in some circumstances, this paper describes some of the possible difficulties which may be encountered with a traditional pull out test, both in terms of practicalities of setting up a tension test and the interpretation of the results, and suggests a different approach which can be safer and more cost effective.

The author has been involved in the back-analysis of numerous tension test results which depart from the expected load displacement behaviour governed by skin friction and linear elastic elongation alone. A simple model is described that appears to match the behaviour of the reinforced concrete under tension and that of characterising the skin friction behaviour with a single hyperbolic function, such as that suggested by Kondner (1963), Chin (1970; 1972) and Fleming (1992) and employed in the Cemsolve® method of pile behaviour analysis. Cemsolve® is part of a propriety software package, which is used for the back analysis of static pile load test results to determine unique pile behaviour, soil parameters and assess pile installation techniques, based on the design method, Cemset®, Fleming (1992).

An alternative to the traditional pullout test is now finding wide acceptance with the introduction of bi-directional load testing. The innovative solutions provided by casting a loading jack within a test pile itself are described in detail; and offer two approaches: in the first, an additional reaction pile is located below the test pile, installed at the same time as the test pile but to a greater depth, and the second is a method of analysis of the test results from a conventional bi-directional loading test carried out on the test pile, revealing the upward behaviour derived from the geotechnical behaviour of the components measured.

The issue of whether the skin friction upwards or downwards are considered to be different is discussed and also whether there are perceivable differences in the behaviour of a pile which has been pulled out instead of being pushed out.

2. CONVENTIONAL PULL OUT LOAD TEST

Perhaps one of the most marked departures from the linear fractional (hyperbolic) characteristic representing pull-out test data can be attributed to some permanent change to the pile material behaviour. It is for this reason that it is widely accepted that extrapolation of tension test results need to be done with great caution.

Where tension loads are applied to concrete piles, it can be expected that at some stress the concrete or grout may crack and separate completely, even when reinforcing steel exists. The tension stress cracks may start to appear at loads corresponding to between 5% and 10% of the compressive strength.

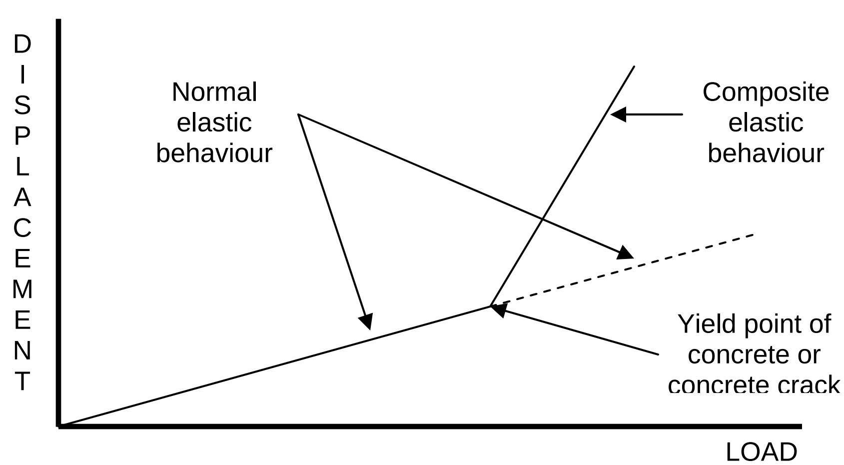

Fig. 1 Change of elastic modulus with tension load in reinforced concrete

If reinforcing steel exists in the pile, the reinforcement may be capable of sustaining the tension force after cracking of the concrete/grout. Consequently the resulting elastic behaviour of the pile head would show a compound effect which includes the elastic component from the reinforcement. This is shown diagrammatically in Figure 1.

Ho (1998), reports similar findings in the analysis of the behaviour of a 1.2 m diameter tension pile. In practice, there is no reason to suppose that the transition at the yield point should be so marked, as characterised with this bilinear model. A gradual transition between elastic elongation of the solid pile structure and that of the cracked or bobbined structure is more likely. Such a model for a gradual transition has been developed specifically for anchors by Degil and Fleming (1997).

2.1 Examples

The following examples represent a first approximation that may be carried out in the back analysis of the test results. By characterising the elastic behaviour up to the yield point of the reinforced concrete, and subsequently by considering the composite elastic behaviour. The Cemsolve® model for the elastic component may be made to take into account the yield point and subsequent stiffness modulus and is shown in each of the analyses. The overall Cemsolve® analysis simply adds this composite elastic behaviour to the skin friction which is modelled using a single hyperbolic function whose asymptote represents the ultimate capacity. This is a fundamental premise of the analysis method which does not require the distribution of friction to be assessed.

In each of the following figures, the test data points interpreted for each representative load step applied are shown together with the pile head behaviour modelled and the estimated composite elastic tension behaviour. The model for the elastic behaviour has been derived initially from the modulus of the concrete (Ec), derived stiffness of the pile cross section (EA), the length and the distribution of friction. The yield point has been assumed to correspond to the interpreted point of inflection and subsequent elastic stiffness optimised to match the test data.

The smaller diameter pile/anchor examples included here have been selected as the proportion of steel in the cross section is small in caparison with the cross section of the grout/concrete. These therefore illustrate better the change in elastic behaviour as the load applied exceeds the yield point. As the steel content increases and approaches 5% of the total cross section, sometimes a necessity for the higher test loads in larger diameter pull-out tests, the stiffness of the steel and concrete/grout become comparable and the yield point showing the change of elastic performance is less noticeable.

2.1.1 Example 1

A grouted anchor of 140 mm nominal diameter installed in a clay filled embankment, with a 20 mm diameter Dywidag bar full length. A 5.3 m length was tested in tension. The volume of grout used was 0.12 m^3, cube strength was 65 MPa at 28 days.

The interpreted test results and analysis are shown in Figure 2; illustrating both the pile head load-displacement and the behaviour with the assumed composite elastic component. Grout cracking can be interpreted as occurring at an applied load of just over 60 kN, i.e. a stress of 3.9 MPa. This high value is perhaps because of the significant steel content in the anchor.

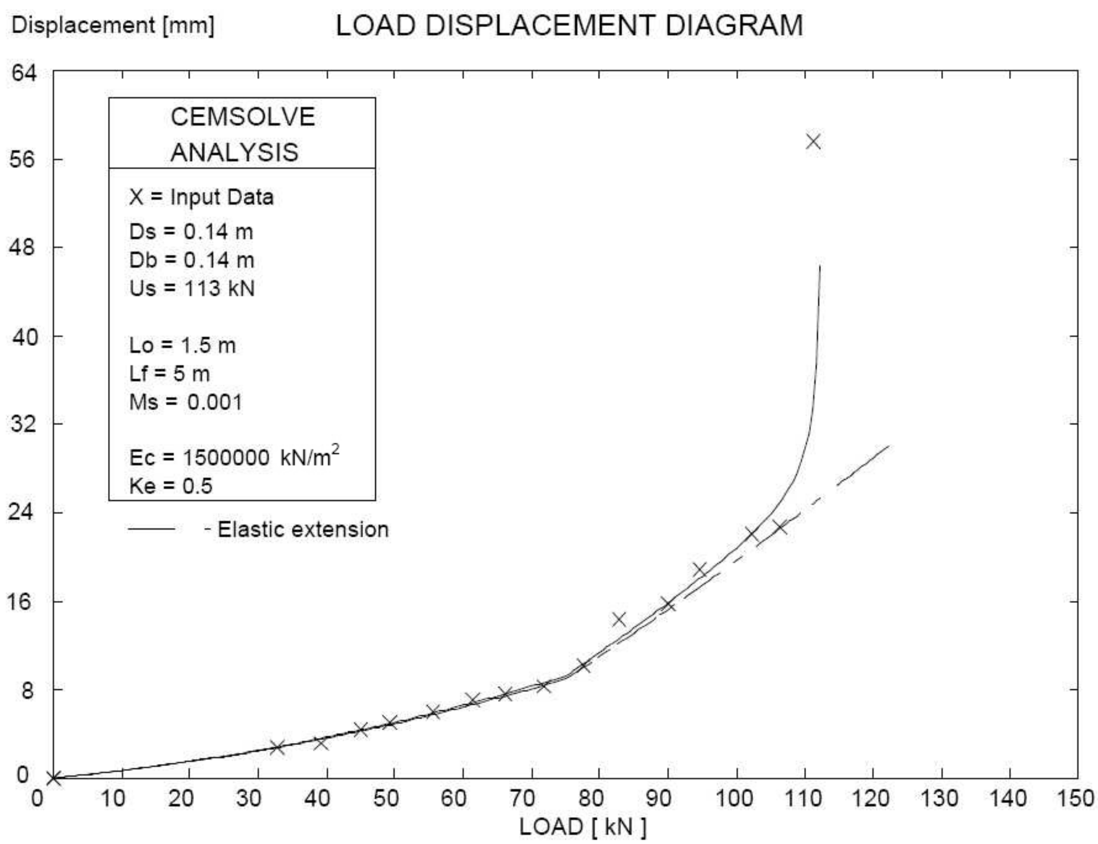

Fig. 2 Anchor tension test results and Cemsolve Analysis

2.1.2 Example 2

A precast pile of 270 mm square cross section was driven through Thanet sand backfill onto chalk. The soil profile consisted of 0–13 m loose silty fine silt with SPT values generally reported to be 5 to 10 blows per 300 mm, underlain by 13–15 m chalk of increasing hardness to considerable depth. The water level was reported to be about 12 m below ground level. The results from the tension test and the analysis are illustrated in Figure 3.

Cracking of the concrete can be interpreted as occurring at an applied load of 135 kN (i.e. a stress of 1.8 MPa). At subsequent loads, a compounded elastic modulus of $E_c = 3$ MPa may be assumed to model the composite elastic behaviour.

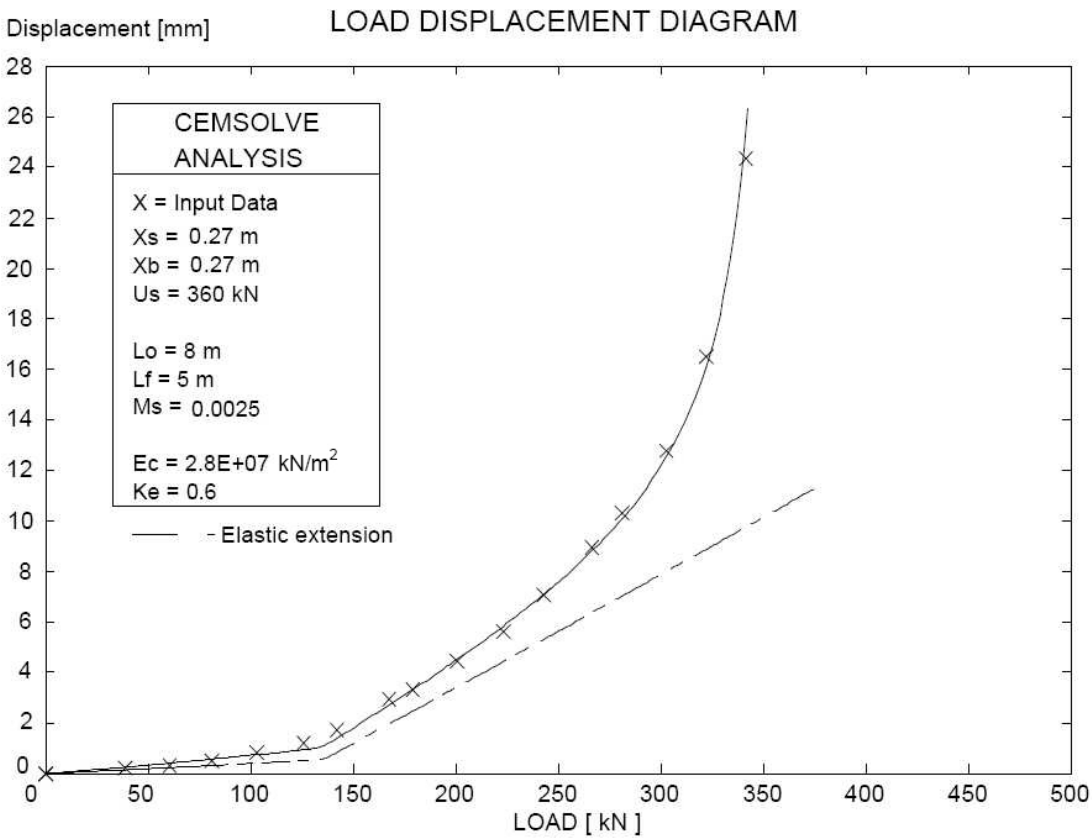

Fig. 3 Precast 270 mm square -Tension test and Cemsolve Analysis.

2.1.3 Example 3

A tension test was performed on a 0.37 m diameter, driven cast in-situ pile in Avonmouth, UK. The pile was installed to a length of 14 m, approximately 3 m into Marl.

The steel reinforcement cage was reported to consist of three T 25 mm diameter bars. The data interpreted from the tension test is shown in Figure 4. The deduced cracking level upon analysis is at 330 kN, equivalent to 3.5 MPa. The composite elastic behaviour has been modelled using a modulus E_c = 4.4 MPa.

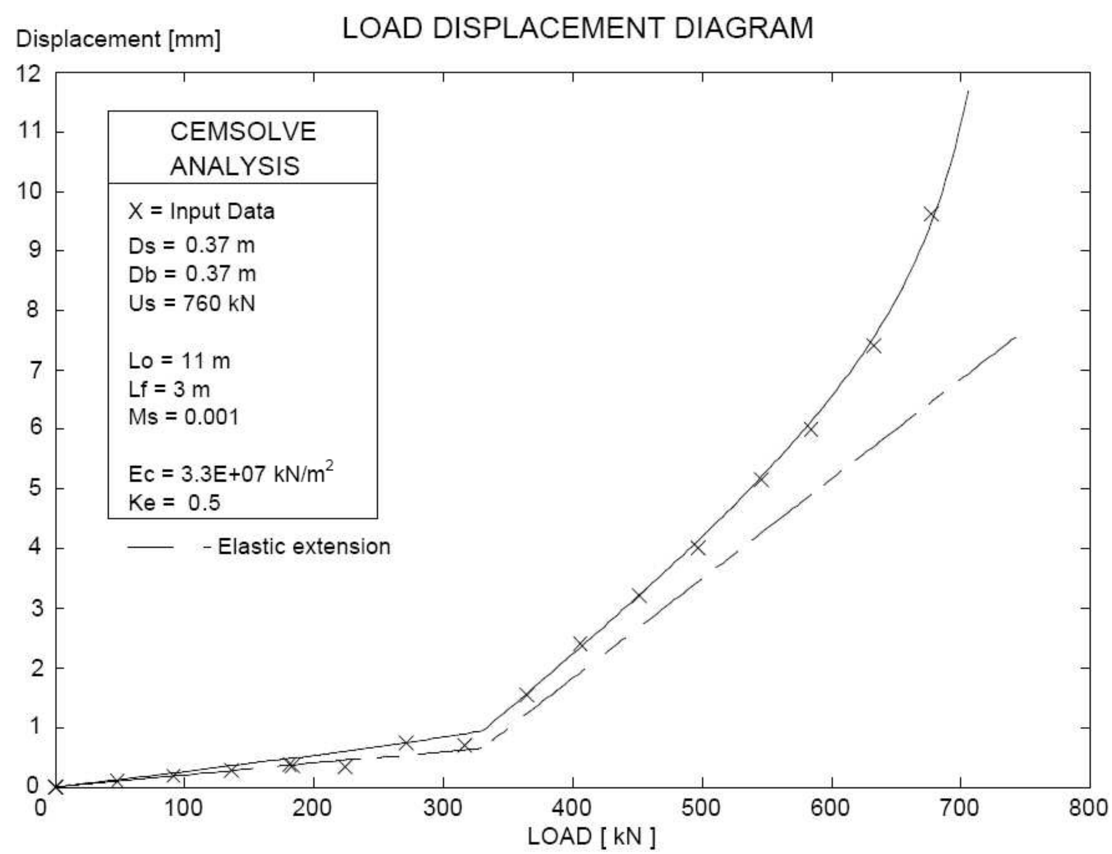

Fig. 4 Driven pile tension test and Cemsolve Analysis

2.1.4 Example 4

A tension test on a 600 mm rotary pile installed to a depth of 11.2 m. The reinforcing steel employed was five T 32 mm diameter bars. The soil profile consisted of 0–3.4 m of back-fill, 3.4-6.8 m brown clay, 6.8-10.5 m boulder clay underlain by sandstone.

As illustrated in Figure 5, cracking can be assumed to be occurring at 520 kN (i.e. a stress of 1.8 MPa).

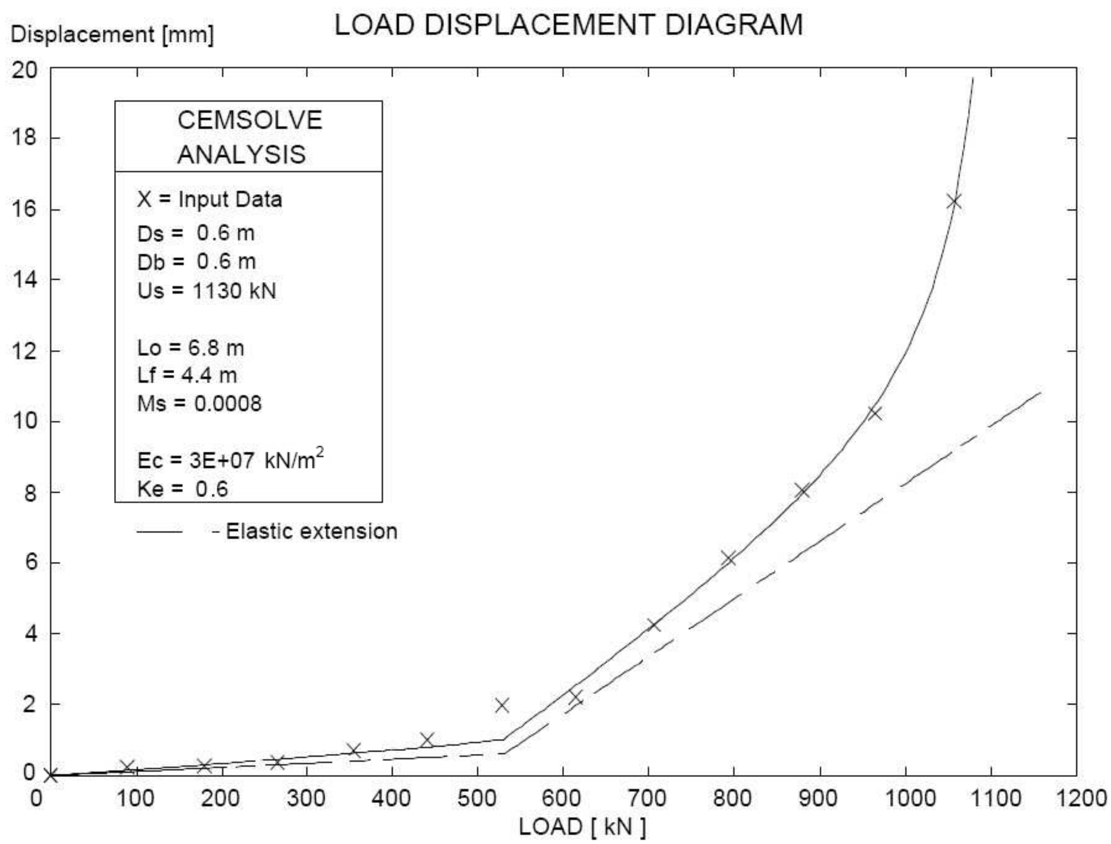

Fig. 5 Rotary bored pile 600 mm diameter — Tension test and Cemsolve Analysis

2.1.5 Tension Behaviour under Traditional loading - conclusion

Analyses that have been made from pull-out tension test results of piles of various diameters and installed in a variety of soil profiles, suggest that, at a generally predictable stress on the cross section, an additional mechanism comes into play and needs to be taken into consideration when trying to interpret the test results. It has been found that the structural behaviour of a pile pulled in tension can depart from the predicted linear single elastic response but can be modelled by an additional linear elastic component whose origin starts at predictable stress values. Once this additional component is incorporated into the modelled elastic response, a single hyperbolic function can be used to model to overall load-displacement measured.

2.2 Pull-out Test Arrangements

When test loads are high, the logistics of setting up a loading system for tension tests on concrete bored piles can be quite difficult as the quantity of steel needed to transfer the load down into the test pile has to be sufficient for the test loads applied, necessitating multiple steel bars. Further, all of the bars need to be tied into the reaction beam in a manner which uniformly distributes the load to each and all of the steel bars.

Two typical approaches are described for high loads on substantial test piles:

Figure 6 shows the steel bars coming up from the test pile through a series of spreader plates and capped with a bolt. The spreader plates need to be of sufficient size to allow additional steel bars to take the tension load around the sides of the reaction beam to a further plate mounted above the loading jack placed on the top of the reaction beam (not shown).

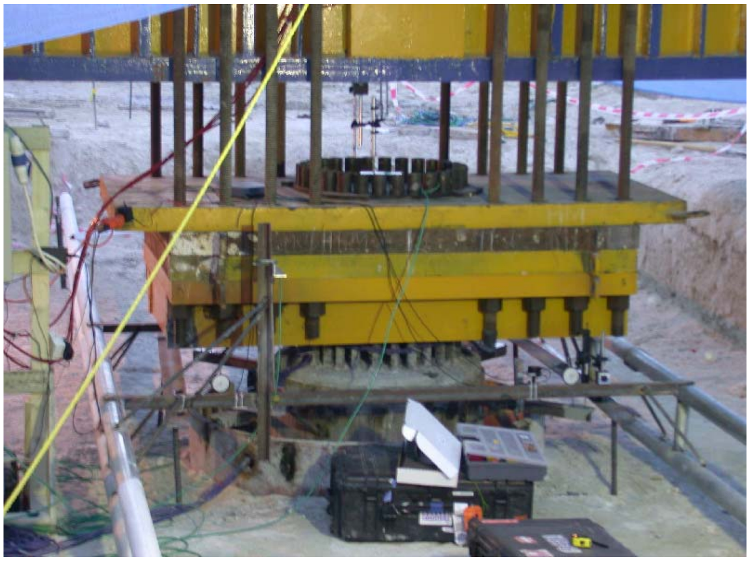

Fig. 6 Pile head requirements on a 10 MN pull out test

In Figure 7, a slightly different approach is to tie the tension bars from the test pile to the reaction beam directly, and then load the reaction beam upwards by using two jacks at either end of the reaction beam seated on reaction piles.

Fig. 7 Pile head requirements on a 18 MN pull out test

A difficulty with both of these approaches is that as the maximum test load required is increased, the congestion of the tension bars, coupling bars, etc., make the steel content at the top of the pile considerable to the point of potentially interfering with the normal concreting operation. Further, the safety aspects of the design and assembly of such reaction systems at ground level require meticulous attention to ensure the construction and testing can be done in a safe manner.

3. BI-DIRECTIONAL TESTING TO DETERMINE TENSION BEHAVIOUR

The challenges of setting up reaction beams and anchor piles at ground level to enable a pull-out tension test, become more difficult the larger the test load required. As a consequence, not only do the reaction beams become a significant size, but the required cross section of steel coupling the reaction beam to the pile also becomes close to unmanageable.

The difficulties with the steel connecting the test pile to the reaction beam are further complicated when the required final cut-off level of the pile is below the test platform, as complex friction reducing sleeves may be required. If the top of the concrete of the test pile is left below the test platform level, it is even more difficult to ensure that the tension test arrangement applies a perfectly axial tension load. Consequently, additional resistance may be induced in the test pile and lateral forces on the reaction system may compromise its safety and stability.

In contrast, using a bi-directional test, the loading element is cast within the test pile itself. No reaction beams are required at ground level, reducing significantly the footprint of the test and the safety hazards associated with heavy reaction beams.

3.1 Push-Out Test

The concept of the push out test is to install the test pile exactly as desired, but rather than pulling the pile from a reaction system above the pile head, an O-cell is arranged at the bottom of the pile so that the pile is tested in compression upwards, pushing the pile out.

The test pile can be constructed to meet the design test length and the O-cell loading arrangement can be located directly under the test pile length so that when pressurised, load is applied upwards, directly into the pile under test.

In cases where the predicted end bearing capacity is larger than the skin friction, the O-cell arrangement can be placed at the bottom of the test pile and the upward movement of the test pile will reveal the skin friction governing its behaviour. Where the end bearing reaction is not sufficient on its own to overcome the friction of the test pile, an additional length of pile can be formed, below the required test pile to provide additional reaction and installed at the same time. This additional section of pile below the O-cell, with sufficient total capacity derived from the additional skin friction and end bearing (if desired), acts as the reaction to load the test pile upwards, as illustrated in Figure 8. In this manner, the full test pile is loaded in compression in an upward direction. It is to be noted that the top of the pile does not need to be installed up to ground level and the top of concrete can be arranged at any desired elevation.

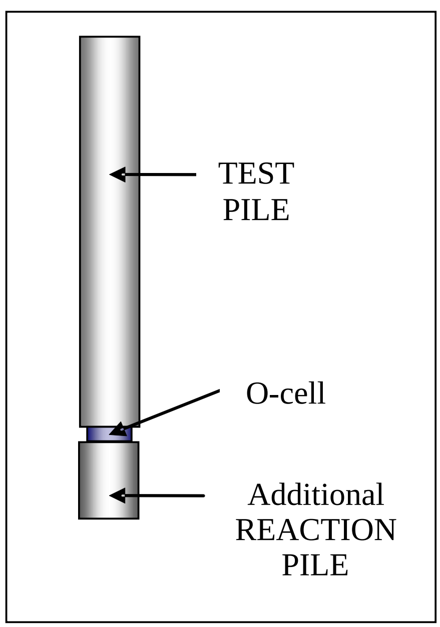

Fig. 8 Illustration of O cell arrangement for a push-out test

3.2 Derived Pile Head Behaviour

Various methods of analysis of bi-directional results to compute the pile head compressive behaviour were put forward by M. England (2008). In summary, the presented analytical methods require the measurement and assessment of the individual elements and then, either the measured behaviour is combined, or the modelled behaviour is combined, to derive the pile head load displacement behaviour under compressive load.

In a similar manner, the combined behaviour of the test pile may also be determined for the upward tension characteristic, making allowance for the elastic extension of the pile and for the composite elastic behaviour, should the equivalent tension stresses be sufficient to induce cracking of the concrete.

If the response of the pile is to be computed directly from a bi-directional test, the full frictional behaviour may be computed from the upward movement from the O-cell level, which directly reveals the skin friction of the upper section. In addition, the frictional behaviour of the section below the O-cell may be back analysed, using either Cemsolve (Fleming 1992) or by using the results obtained from strain gauges, allowing the magnitude of friction and end bearing of the element mobilised downwards to be assessed. A total friction behaviour downwards from the O-cell level can then be resolved and combined with the friction measured upwards in order to determine the ultimate skin friction behaviour that will govern the upward pile movement. Figure 9 illustrates the top of a test pile being loaded bi-directionally for the purpose of deducing the pile head behaviour under tension.

Fig. 9 Typical pile head arrangement for a bi-directional test
(The steel beam across the top of the test pile is a reference beam)

3.3 Magnitude of Skin Friction According to Direction of Loading

One of the main issues which may contribute to perceived differences between skin friction (side shear) upwards or downwards can be associated with the definition of ultimate capacity. If the definition is based on the load mobilised at a given displacement, this would be less than the asymptotic definition and is dependent on the magnitude of the displacement used in the definition. If the friction mobilises more displacement upwards than the same friction downwards it could be perceived that the ultimate capacity is less just because a larger displacement may have been mobilised upwards.

Chin and Vail (1973) report a lower pullout friction exhibited on a series of driven precast piles than exhibited in downward compression from previous loading. On closer examination of the procedure followed, two aspects of the testing procedure, which appear not to be accounted for in the original interpretation, are believed to be the cause of the conclusions offered. If these issues are addressed in the light of today's perceived understanding of pile testing and subsequent behaviour, a different interpretation, consistent with the friction being equal in both directions may be more appropriate.

Where the same pile is tested first in compression and then in tension, suitable allowance needs to be made for the locked in stresses resulting from the first compression test, and then, in addition to the tension forces externally applied as part of the test, upward forces from the base (once it has been unloaded) can be expected. Using methods such as Cemsolve, the magnitude of the locked in stresses can be estimated and the resulting reduced skin friction behaviour in a subsequent tension test may be predicted. Such a method is presented by England (2000).

Figure 10 attempts to illustrate diagrammatically the locked in forces, which must be balanced upwards and downwards, and consequently the starting point for the upward behaviour that would result if previously loaded in compression.

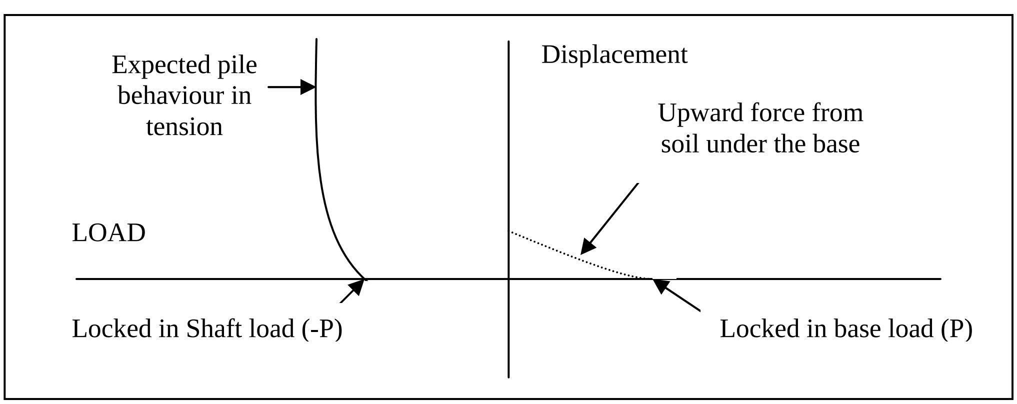

Fig. 10 Locked in forces after loading and resulting upward friction available

A second issue associated with the original interpretation by Chin of his test results, was that constant rate of penetration tests were used for both the compressive and tension loadings applying relative rapid loading. The rate of loading may have resulted in increased apparent short term friction which could have exaggerated the differences due to loading direction.

The above issues may offer an explanation as to why the initial interpretation made by Chin might have indicated a difference in friction upwards to downwards.

In the author's experience of compression and tension tests, using reaction systems with tension pile anchorages in a range of different soils, the ultimate skin friction mobilised under compression of a pile is indistinguishable from that exhibited under tension. It is accepted that the movements to mobilise the same reaction in friction might be slightly different according to the different boundary conditions as described in England (2005).

A secondary issue is Poisson's ratio, which can be summarised as the change in cross section of the pile as a result of compression or tension; since the stiffness of concrete (and steel reinforced concrete) is relative high, the effect of change of section as a result of axial compression or tension is negligible.

4. CONCLUDING DISCUSSION

Analysis of pull out behaviour of a wide range of sized anchors and piles, installed with concrete or grout (some examples of which are illustrated), each exhibit the yield point at tension stresses within a predictable and narrow range which can be attributable to the pile material.

It is therefore important that the elastic shortening model assumed for the elongation of the pile material is extended to account for the composite behaviour resulting from the cracking of the concrete/grout at loads higher than the yield point.

If the elastic extension is modelled in this way, a single hyperbolic function can be added to the elastic behaviour to model pile performance in tension using the Cemsolve analysis method.

Care needs to be taken with the definitions of ultimate skin friction capacity when assessing results for friction mobilised upwards and downwards. The asymptotic definition, as described by Chin (1970), is suggested as the most appropriate.

Numerous tension tests have been performed from ground level as "pull-out tests" and more recently, by "pushing-out" the test pile using the bi-directional method of loading. As the test loads become significant (>2MN) the option of installing an O-cell as the loading device to perform a full scale push-out test has many advantages in terms of speed, ease of assembly, safety and the subsequent interpretation.

If a more efficient and cost effective solution is sought, the Osterberg method of bi-directional loading may used to test the pile, and, using well established analytical methods for combining the resultant behaviour, the load-displacement that would result from a pull out test can be deduced.

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