A Conservative Method of Analysis of test results from bi-directional static load tests.
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Abstract
As the use of bi-directional load testing of foundation elements becomes more widespread, a consistently conservative method of interpretation of the test results is presented which ensures that, although the mechanics of the test are slightly different to top-down loading, the ultimate capacity that may be interpreted is not overestimated.

Introduction
Bi-directional loading tests using Osterberg cells (O-cells®) are now becoming common practice around the world, particularly where the loads to be applied are high (above 5MN) or where it is not convenient to perform top-down loading tests. The advantages of using this type of loading system are numerous, Schmertmann et al (1997) and England (2003).

The O-cell is a hydraulically driven, high capacity, sacrificial jack-like device installed within the foundation unit. When pressurised, it applies load in two directions: upward against skin friction and downward against either end bearing alone or end bearing plus some skin friction. The results automatically separate the resistance of each component which then require suitable combination and analysis to reconstruct the equivalent top load characteristic of the pile.

The TIMESET® analysis method, which allows back analysis of displacement-time to determine final settlement at each applied load and CEMSOLVE®, which permits interpretation of friction and end bearing from load-settlement results have, until recently, had only been applied to measurements of load-displacement-time recordings of the pile head during top-down static load tests. The appropriateness of these methods is considered for the modelling of the behaviour of each element resulting from a bi-directional test; that is to model both the upper “normal friction” elements and “friction and end bearing” of the pile elements below a single level O-cell. In so doing, a method of interpretation of bi-directional test results is postulated which ensures a conservative equivalent top-load response is interpreted.

Displacement-time-load analysis
Initial application of the TIMESET analysis, England (1992 and 1993), shows that the method can be sensibly applied to each set of displacement time recordings at each load and a projected settlement independent of the duration of load application, can be calculated and used for load settlement analysis.

The principle of the method is well proven for modelling the relative displacement-time behaviour for pile head loading. It employs two hyperbolic functions to model the
measured displacement-time behaviour under each applied constant load.

Relative settlement
\[ \Delta_r = \frac{W_s}{T_s} + \frac{W_b}{T_b} + t \] 

where \( t \) is the elapsed time since the assumed application of constant load, \( W_s \) and \( W_b \) are respectively asymptotic values for each of the individual functions and \( T_s \) and \( T_b \) are the times taken for the modelled components to get from the origin of the scales to half of their asymptotic value. (This \( T_{50} \) point has been chosen arbitrarily as a convenient means of defining the curve).

The match of the mathematical model to the measured data may be optimised numerically with ease.

The following two figures show a series of displacement data recorded for both the element above the O-cell and below, where these have been plotted on the same relative time scales from the moment of application of each constant load to allow closer examination of the relative displacement-time characteristic.

A limitation of the matching process may exist when the duration of the data to be matched using this model is insufficient to determine a unique solution during optimisation. In practice, for top-down static load tests, a duration of load application of 3 hours has been proven to be adequate. In the case of bi-directional testing, the load application period appears to be closer to 60 minutes; an assumed reasoning for this is that the bi-directional test applies the loads
directly into the governing founding strata and therefore additional time for redistribution of load along the pile shaft is not required. This aspect also allows the testing specification to be optimised without compromising the quality of interpretation which may be carried out.

Figure 3 Load displacement diagram with projected settlement points to $t = \infty$.

The projected settlements illustrated in Figure 3 can correctly be associated together to determine the load-settlement behaviour of each component (upwards and downwards) in a manner which is unaffected by the length of load hold employed to collect the data.

**Friction or side shear**

1.1 *What happens above the O-cell*

If the friction of the element mobilised above the O-cell is modelled by a single hyperbolic function alone, as postulated in the Cemset/Cemsolve pile behaviour model, described by Fleming (1992), then the measured data can often be projected to an ultimate asymptotic friction value, even if not fully mobilised.

If the measured response of the upper element contains components similar to end bearing behaviour, and manifest as an additional low stiffness behaviour once the friction is fully mobilised, upon interpretation, the additional capacity due to a low stiffness component could easily be recognised and ignored in the interpretation. A reason why some additional component other than just friction may be found, could be due to minor protrusions or eccentricity of applied load. The protrusion beyond the nominal envelope could assist with enhancing the capacity but the effect is generally expected to be negligible. Eccentricity of loading could in effect, mobilise some lateral resistance which would not necessarily be present in a top down loading test on the same pile.

The stiffness that governs how the friction is mobilised with load applied (defined as $M_s$, the “flexibility factor”, Fleming 1992) appears to be different on compression tests when loading upwards or downwards.

$$\Delta_s = \frac{M_s D_s P_s}{U_s - P_s} \text{......... (2)}$$

where $\Delta$ and $P$ - settlement and load applied respectively

$M_s$ - shaft flexibility factor [dimensionless]

$U_s$ - ultimate shaft capacity

$D_s$ - effective shaft diameter

The top-down behaviour is characterised in the majority of cases by a value that for all practical cases appears to be constant at around 0.001. A limited evaluation on some bi-directional tests selected at
random is showing a significantly
different flexibility factor (equivalent
to being less stiff) and a range of
values. This means that the
measured upward displacement, in
general, is of greater magnitude due
to friction, than would be observed in
top down loading (ignoring elastic
shortening effects).

This effect is illustrated in Figures 4
and 5 below, where the friction
behaviour has been plotted against a
normalised scale of percentage of
mobilised to ultimate resistance:

![Figure 4: Typical top-down Ms of 0.001](image)

![Figure 5: Typical shaft above the O-cell; Ms of 0.005](image)

While both of these graphs illustrate
a single hyperbolic function, the
difference can readily be seen when
the displacement at say 50% of the
ultimate is reviewed. The typical
frictional movement above the O-cell
is up to 5 times more than might be
expected in a top loaded element.

1.2 On the subject of friction
upwards and friction
downwards

Good published data that could help
to resolve the issue of variation of
friction according to vertical
direction of movement is very
limited.

An early reference, Chin et al
(1973), concludes that a 20% reduction in pull out resistance was
experienced in soft alluvium. Careful
study of their test methods reveal
that they employed constant rate of
penetration tests in compression and
then subsequently applied the same
rate of extraction in tension. Two
interpretation difficulties can be
attributed to this:

1) It is well known now that
constant rate of penetration tests
can show significantly enhanced
frictional and end bearing
behaviour, as reported by
England (1994), so any
conclusions based on CRP tests
should be treated with caution.

2) A result of compression tests is
that, due to the different
behaviour characteristics of skin
friction and end bearing, forces
get locked in between the pile
base and the shaft once the load
at the top of the pile is removed.
A method of analysis of these
locked in stresses can be
calculated when modelling the
pile behaviour using
CEMSOLVE. Knowing the
locked in stress can allow an
estimate to be made of the effect
this has on the subsequent pullout
resistance. An example of this is
There is also added conservatism applied to tension piles, as the consequences of failure in tension may be significant and typically greater than the consequences of exceeding friction in compression loading. This added conservatism leads to additional factors-of-safety which have often been misinterpreted as reduced friction in tension.

In summary, the question can be reduced to several potential mechanisms that might be considered to cause a difference:

- At a microscopic scale, there is little evidence to suggest that the soil responds differently to movements downwards or upwards.
  - Provided the movements are small, the soil does not know nor care which direction the pile moves with respect to the soil.
- The fact that there is no overburden pressure at the surface could affect the overall friction response.
  - In terms of ultimate friction, there is no fundamental mechanism which should cause a difference for the small movements induced during testing. A change of stiffness behaviour has been alluded to earlier.

In conclusion, there is insufficient published data to determine from experimental evidence reviewed to date whether there is a difference between frictional capacities upward to downwards.

**Pile section below the O-Cell**

The load-settlement behaviour of the element of the pile below the O-cell can be considered to be identical to a top down load-settlement behaviour, and the methods of analysis such as Cemsolve can be used without modification. There is, however, a school of thought that suggests that when the O-cell is close to the pile base, some disruption of the end bearing behaviour could result, as a consequence of relaxation of the overburden pressures and can even be detrimental to the behaviour with a test using the O-cell when compared to top-down tests.

If one assumes that the discontinuity resulting from movement of the O-cell affects the base behaviour, it should be appreciated that the in-situ stresses may be reduced and one might assume that the end bearing capacity and stiffness could be affected. Several studies are underway to find a means of evaluating this effect. A step towards reducing this is by having the void produced around the O-cell filled with water at a constant hydrostatic pressure, by maintaining a constant level at the surface. A practice routinely observed but difficult to maintain in soil of high permeability.

When considering the long-term behaviour of the frictional element below the O-cell, this may also be reduced as a result localised reduction of overburden pressures, again resulting in conservative results.
Elastic shortening

The elastic behaviour of any column is clearly additional to any settlement in the soil. In general, the elastic shortening depends on the development of load transfer between the pile and the soil along its length, as well as on any free length or nearly friction free length at the pile head, and on the load being transferred at the pile base.

Elastic shortening is not (as postulated) in general, a linear function for materials like concrete, but it may be assumed to follow an elastic function within the usual range of testing piles. A simplified method can be used, such as that proposed by Fleming (1992).

The method for modelling the shortening of a continuous length of foundation element requires the parameters indicated in Figure 6, with shortening being considered in three stages:

1. A low friction length extending to a distance $L_0$ from the top of pile.
2. A length $L_f$ over which friction is transferred.
3. The whole pile shortening as a column as a function of load after the ultimate shaft friction has been reached due to the reaction from the pile base.

Figure 6 Diagram of parameters contributing to $c/s$

The first of these elements is easily considered and the shortening $\Delta_1$, is given by

$$\Delta_1 = \frac{4}{\pi} \frac{L_o P}{D_e^2 E_c} \ldots \ldots \ldots \ldots \ldots \ldots (3)$$

where $E_c$ is Young’s modulus for the pile material in compression, $D_e$ is the equivalent diameter, $L_o$ the friction free length and $P$ the load applied.

The second stage represents the elastic shortening which takes place during load increase up to the stage when ultimate shaft friction has been mobilised. If friction is uniform, then the elastic shortening will be equivalent to that of a column of length $0.5L_f$.

The introduction of an equivalent length, $K_e L_f$, allows for the effect of a varied distribution of friction on the elastic shortening. The coefficient applied to the effective friction length is designated $K_e$, and would have values between 0.5 and 1.0, depending on the ground.
conditions. The shortening can be expressed as
\[ \Delta_2 = \frac{4}{\pi} K_e L_f P \] ............(4)

Since friction is generally mobilised at small displacements and end bearing at large displacements in most soils other than rocks, the assumption and simplification that the effect from end bearing is negligible until the friction is fully mobilised is made. When the applied load \( P \) exceeds the ultimate shaft load \( U_s \), then additional load causes shortening of the length \( L_f \) so that it may be treated simply as a column carrying the excess load, and the shortening of \( L_f \) becomes
\[ \Delta_3 = \frac{4}{\pi} \frac{(P - U_s) L_f}{D_i^2 E_e} \] ............(5)

Since total elastic shortening \( \Delta_e \) is the sum of the elemental shortenings being brought into play, then for loads \( P \) up to the ultimate shaft load \( U_s \),
\[ \Delta_e = \frac{4}{\pi} \frac{P(L_o + K_e L_f)}{D_i^2 E_e} \] ......(6)

and for loads which are greater
\[ \Delta_e = \frac{4}{\pi} \frac{1}{D_i^2 E_e} [P(L_o + L_f) - L_f U_s(1 - K_e)] \] ......(7)

By combining equations (6) or (7) as appropriate, the total elastic shortening of a circular pile for any load up to the ultimate may be estimated.

To model the elastic compression of the upper section of the pile \( \Delta_0 \) above the point of application of load, the following considerations are needed.

1. The position of the O-Cell with respect to the start of the friction zone can be defined as \( O_c L_f \) as illustrated in Figure 7.

2. The introduction of a second equivalent length, \( K_e \), allows for the effect of varied distribution of friction on the upper element above the O-cell.

The coefficient applied to \( O_c L_f \), the effective friction length, \( K_e \), is defined as the effective location of the centroid of friction transfer from the top of the friction zone. Its effect, needs to be inverted when the load is being applied from below and would have values, depending on the ground conditions, close to 1.0 and is illustrated in Figure 7 below. The shortening can be expressed as
\[ \Delta_{02} = \frac{4}{\pi} \frac{(1 - K_e) O_c L_f P}{D_i^2 E_e} \] ......(8)

Which can provide a reasonable estimate for loads up to the maximum skin friction \( U_{s2} \) at which the elastic compression reaches its maximum value.
1.3 Equivalent top loading

The behaviour of the element below the cell will behave according to the measured response and no adjustment should be needed.

The elastic compression of the top section that would have occurred during top loading, needs to be taken into account. To estimate the top down elastic behaviour, it is possible to subtract from the total for the section, as in equation 6, the elastic compression integrated already in the measured upward response. Alternatively, it can be recomputed, but now the friction is effective from the top.

\[
\Delta \sigma_2 = \frac{4 (K_c)}{\pi} \frac{O_c L_f P}{D_s^2 E_c} \quad \text{(9)}
\]

It remains to add in the elastic behaviour of the friction free zone, which can be calculated from equation (3) and depends on where the top of the pile is assumed to be.

**Installation method.**

To date, it is the experience of LOADTEST, that the O-cell installation method has not had an influence on the resulting pile behaviour, provided that the area surrounding the O-cell arrangement is completely filled with concrete or grout and the bearing plates do not scrape material from the bore walls during installation, this debris can result in an initial soft base response.

Concreting of bored piles under fluid might be thought of as a potential hazard to ensure the O-cells are successfully enveloped in concrete. To date, no evidence has been found where debris around the O-cell could have been deduced.

Installation of the reinforcing cage fitted with the O-cell arrangement, is unlikely to be significantly different to any normal pile installation as the O-cell arrangement is invariably contained within the diameter of the steel cage. In only a few cases, the concreting below the O-cell arrangement needs special attention and modification to standard concreting practice.

**CONCLUSIONS**

The effect of duration of load needs to be taken into consideration. In most materials the creep effect can be significant and is particularly so for large movements.

Bi-directional tests and computed equivalent top down behaviour gives conservative results for the following reasons:

i) There is no conclusive evidence for the magnitude of friction
upwards to be different to that experienced downwards. Some engineers consider using only 80% of the upward measured friction for sands, and in general it is more typical to use 95-100% for the downward friction. This approach is conservative in its own right

ii) Measured frictional behaviour upwards generally shows more displacement than might be typically expected of frictional behaviour of top-down load tests.

iii) End bearing, if affected by the method of loading, would reveal diminished capacity and stiffness.

As a result, the application of bi-directional tests and their interpretation, do not reveal capacities greater than those that would be derived from top-down load testing and measured displacements can generally be considered as more conservative.

References: