

A Conservative Method of Analysis of test results from bi-directional static load tests.

M. England BSc MSc PhD DIC

LOADTEST, 14 Scotts Avenue, Sunbury on Thames, Middlesex TW16 7HZ, UK

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.

$$\text{Relative settlement } \Delta r = \frac{W_s t}{T_s + t} + \frac{W_b t}{T_b + t} \quad (1)$$

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.

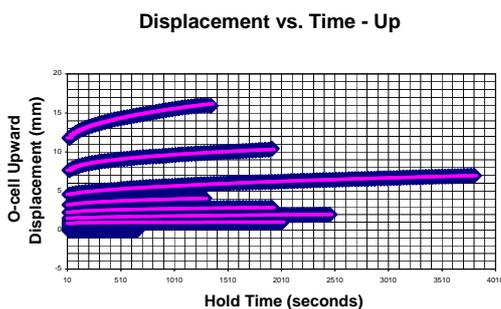


Figure 1 Measured & matched displacement of upward element for each load on relative time scales

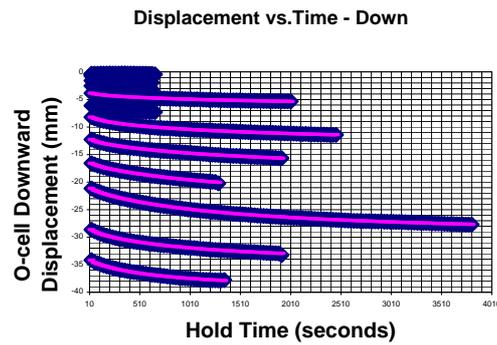


Figure 2 Measured & matched displacement of element below O-cell for each load on relative time scales

Figures 1 & 2 show both the measured data and the modelled characteristic and they illustrate how the model can be made to match the measured data with remarkable accuracy even when the relative displacement is small. The modelled behaviour is practically indistinguishable from the measured displacement. The purpose of this analysis is to allow extrapolation from the period in which the data was measured to determine the final settlement that would occur if the loads were held indefinitely. Figure 3 shows the data for each load as vertical lines on a load-displacement diagram, with the projected settlements points (at $t = \infty$) marked.

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.

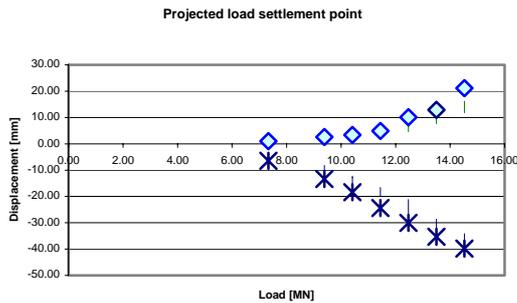


Figure 3 Load displacement diagram with projected settlement points to $t = \infty$.

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.

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

- where Δ 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:

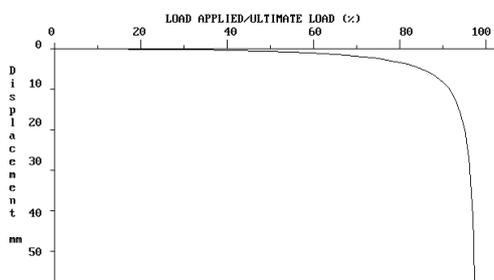


Figure 4: Typical top-down M_s of 0.001

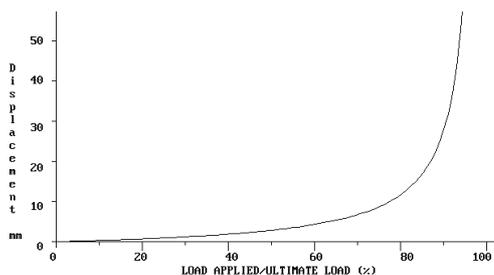


Figure 5: Typical shaft above the O-cell; M_s of 0.005

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 presented in England (1999).

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 under way 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 of 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_o 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

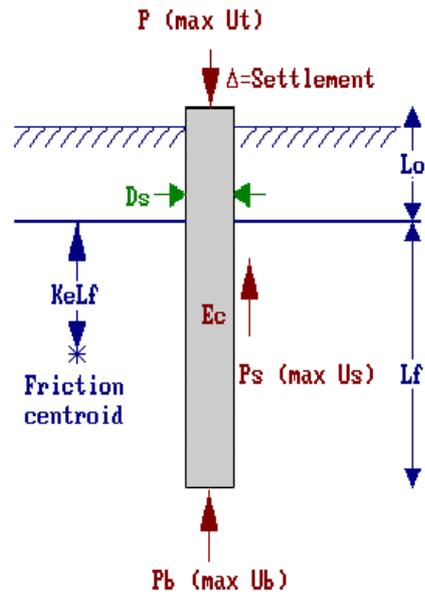


Figure 6 Diagram of parameters contributing to e/s

The first of these elements is easily considered and the shortening Δ_1 , is given by

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

where E_c is Young's modulus for the pile material in compression, D_s 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 $0.5 L_f$.

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

$$\Delta_2 = \frac{4}{\pi} \frac{K_e L_f P}{D_s^2 E_c} \dots\dots\dots (4)$$

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

$$\Delta_3 = \frac{4}{\pi} \frac{(P - U_s) L_f}{D_s^2 E_c} \dots\dots\dots (5)$$

Since total elastic shortening Δ_E is the sum of the elemental shortenings being brought into play, then for loads P up to the ultimate shaft load U_s ,

$$\Delta_E = \frac{4}{\pi} \frac{P(L_o + K_e L_f)}{D_s^2 E_c} \dots\dots\dots (6)$$

and for loads which are greater

$$\Delta_E = \frac{4}{\pi} \frac{1}{D_s^2 E_c} [P(L_o + L_f) - L_f U_s (1 - K_e)] \dots\dots\dots (7)$$

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 behaviour of the section below the O-Cell, this can be estimated with the equations (6) and (7), with L_o set at zero.

To model the elastic compression of the upper section of the pile Δ_{O2} 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_{e2} , 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_{e2} , 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

$$\Delta_{O2} = \frac{4}{\pi} \frac{(1 - K_{e2}) O_c L_f P}{D_s^2 E_c} \dots\dots\dots (8)$$

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.

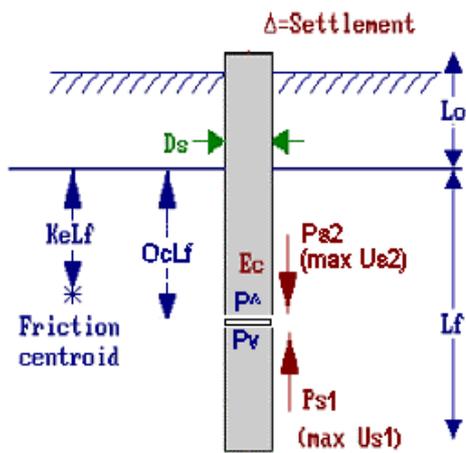


Figure 7 Parameters for modelling the elastic shortening of the upper section

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.

$$\Delta_{O2} = \frac{4 (K_{e2}) O_c L_f P}{\pi D_s^2 E_c} \dots\dots\dots (9)$$

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:

- Chin, F. K. and Vail, A. L. (1973) "Behaviour of piles in Alluvium", Moscow ICSMFE Vol 2.1 pp47 – 52
- England, M (1992), "*Pile settlement behaviour: An Accurate Model*", Application of Stress Wave Theory of Piles, The Hague, A.A.Balkema, 91-97.
- England, M (1993), "A Method of analysis of stress induced displacement in soils with respect to time". International seminar, Deep foundations on Bored and Auger Piles, BAPII Ghent, A.A.Balkema June, p241-246.
- England M & Fleming W.G.K (1994), "Review of foundation testing methods and procedures", Geotechnical Eng. Proc. Instn Civ. Engrs. Geotech. Engng, 107, July, 132-142.
- England, M. G. (1999) "A pile behaviour model", PhD Thesis, Imperial College, London.
- England, M (2003) "Bi-directional static load testing – State of the art" International seminar, Deep foundations on Bored and Auger Piles, BAPIV Ghent, Millpress, June pp309-313
- Fleming, W.G.K (1992) "A new method of single pile settlement prediction and analysis", Geotechnique, Vol XLII, No3, Sept.
- Fleming, Weltman, Randolph & Elson, (1992), "Piling Engineering", 2nd Edition published by Spon p100
- Schmertmann, J. H. & Hayes, J. A., 1997, "The Osterberg Cell and Bored Pile Testing - A Symbiosis," Proceedings: 3rd International Geotechnical, Engineering Conference, Cairo University, Cairo, Egypt. Pp 139-166.