Deep Foundations on Bored and Auger Piles – Van Impe & Van Impe (eds)

Review of methods of analysis of test results from bi-directional static load tests

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ABSTRACT: Results from bi-directional tests are not the same as those obtained from top loading tests and although bi-directional test data often contain more geotechnical information, it is the characteristic behaviour of the head of the pile which is of interest. In order to provide an equivalent top loading characteristic, methods have been developed to enable the addition of the individual components measured.

Bi-directional loading test 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.

This paper aims to describe and review the merits of some of the direct methods currently employed and some of the analysis methods which can be used as well as the application of finite element analyses using measured behaviour.

Keywords: Loadtest, Osterberg cell, O-Cell, static load tests, bi-directional load test.

1 INTRODUCTION

Application of the method of bi-directional testing results in the foundation element under test being separated in more than one element and each is static load tested separately or in combination. For example, with a single level loading arrangement, as illustrated in the diagram of Figure 1, effectively two independent static load tests are performed simultaneously and produce two completely separate sets of results, England (2003).

Bi-directional loading tests using Osterberg cells (O-cells®) are now becoming common practice (with over 300 tests performed per year) around the world, England et al (2006), particularly where the loads to be applied are high >10MN or where it is not convenient to perform traditional top-down loading tests.

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.

While the geotechnical information obtained directly for each of the elements tested might be sufficient, in some situations, it is found important to determine how the head of the foundation element would behave under load. This paper describes some of the methods for assessing the behaviour of the combined elements.

Multilevel tests are now performed frequently and triple level bi-directional tests have been employed on a few occasions; these cases provide an even greater challenge to recombining the behaviour of each of the components into a representative load-settlement characteristic.

The challenge is to understand the merits of the differing methods which may be used to recombine the behaviour characteristics used in assessing how the top of the foundation element would perform.

The TIMESET® analysis method, which allows back analysis of displacement-time to determine final settlement at each applied load and CEMSOLVE®, permits interpretation of friction and end bearing from load-settlement results have, until recently, 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.

It is worth appreciating that with bi-directional testing the top of the pile/barrette need not be constructed up to ground level or even expected cut-off level for the testing, so estimates may be required regarding the elastic shortening of the column above the test element up to the desired level.

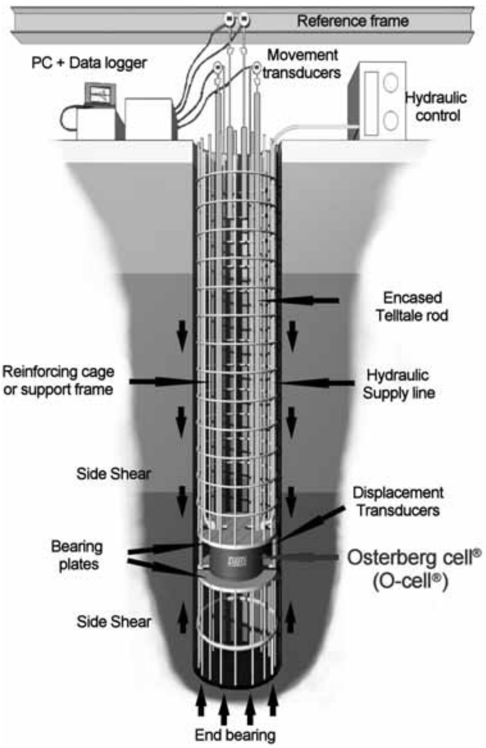

Figure 1. Single level: concept diagram.

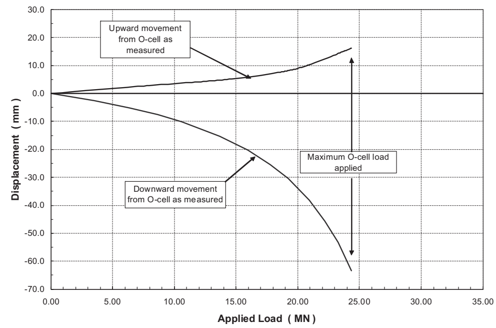

Figure 2. Typical bi-directional load test results.

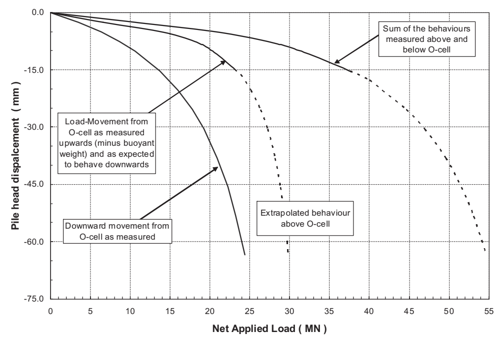

Figure 3. Sum of measured responses.

As discussed in England (2005), the compressive ultimate capacity of the behaviour of the element upwards will be assumed to be of the same ultimate skin friction as if the load were downwards, and the buoyant weight of the element will be subtracted.

2 ANALYTICAL METHOD

The data recorded during a bi-directional load test (OLT) include the elastic compressions that are part of the movement data obtained. For the purposes of illustrating the approach used, the descriptions will be limited to results from a single level O-cell assembly in which, it is expected that the upward behaviour measured is governed by skin friction and the behaviour downwards by skin friction and end bearing.

The data illustrated in Figure 2 shows a typical recording of the upward and downward displacement behaviour with respect to applied load in a single level bi-directional test up to the maximum test load applied.

To recombine the geotechnical behaviour measured (plus embedded elastic compression), the two measured components may readily be combined by adding the resultant loads for common displacements, having subtracted the buoyant weight of the element above the O-cell from the upward movement. Figure 3 illustrates the two measured behaviours to be combined along the load axes. This addition using common displacements has a slight drawback in as much as if the displacements upwards and downwards are not the same, the direct summation of the two can only be up to the smaller of the two displacements and then reliance is placed on extrapolation to project the element with the lesser movement in order to give a resulting behaviour up to a nominal load or the applied net load.

Where the upward movement is projected, this can be done with high reliability as the behaviour is normally dominated by skin friction only and a single hyperbolic curve can be made to match the recorded data.

Generally, in the design of a single level bi-directional test, the downward movement is normally expected to be larger than the movement upward; and therefore the end bearing component may be mobilized if sufficient load is applied. However, should the behaviour of the pile elements not follow expectations, or the load be insufficient to mobilize the available skin friction downwards, projection of the downward movement is required, this can either be done using a single hyperbolic matched to the data pertinent to the end bearing behaviour (assuming the friction element is fully mobilised), using the method developed by Chin (1970), or can be done with a pair of hyperbolic functions as per Fleming (1992).

It then remains to estimate the elastic behaviour which was not present in each element during the test (referred to as the "measured behaviour curve") and then this elastic behaviour can be added to the result along the vertical axis, as illustrated below in Figure 4.

It may be noted that the elastic compression in the equivalent top load test always exceeds that mobilised in a bi-directional O-cell test.

The formulation of a simplified approximate solution in which a centroid of friction transfer is assumed to model the effect of distributed friction mobilised during the test is straightforward, Fleming (1992). The elastic component in the upward total movement measured can therefore be assessed, estimated and compared to the actual measured compression. This location of the centroid of friction transfer can also be used to assess the effect of skin friction distribution if the element were downwardly loaded, and if the element is not fully mobilised during the test, the centroid may be re-assessed for the equivalent elastic compression which would occur if the loading was at the top of the test pile if appropriate.

The elastic behaviour of the element below the O-cell is already contained within the test data so no additional influence needs to be considered.

3 MODELLING METHOD

The main difference from the method described above, where the measured behaviour is added together with respect to common displacements and the additional elastic shortening not expected to be in the test data is added to the result, is found by using Cemsolve®, Fleming (1992) in which the elastic component (measured) is also modelled leaving the geotechnical behaviour (actual friction and end bearing) to be determined; this represents the rigid element behaviour.

Once the modelled rigid behaviour of each element is obtained; these, and the elastic behaviour expected for the entire foundation element can be added together.

Figure 5 below shows a typical Cemsolve® analysis of the bottom portion of the test pile, although in this case the element of the pile below the O-cell is short and therefore the elastic component does not contribute much to the total settlement. In the analysis, it is estimated that the frictional component down is Us = 1100 kN and the ultimate end bearing Ub = 4200 kN with a base stiffness typical of clay, Eb = 48000 kN/m^2:

At the same time as the downward behaviour displayed above was recorded, the upward movement in this 1200mm diameter reinforced concrete pile was also logged and is presented in Figure 6 below.

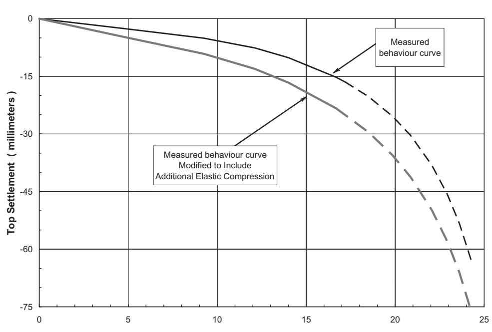

Figure 4. Additional elastic shortening.

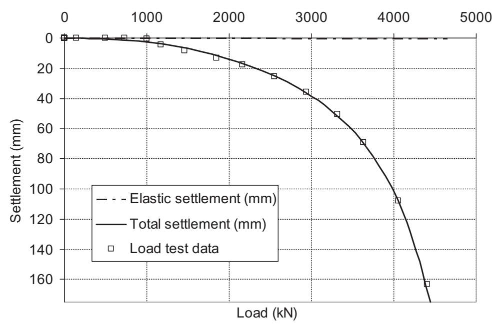

Figure 5. Cemsolve of downward movement.

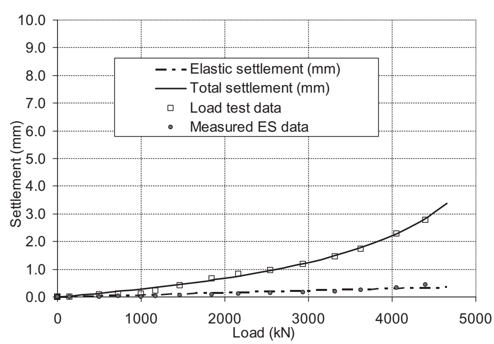

Figure 6. Cemsolve of upward movement.

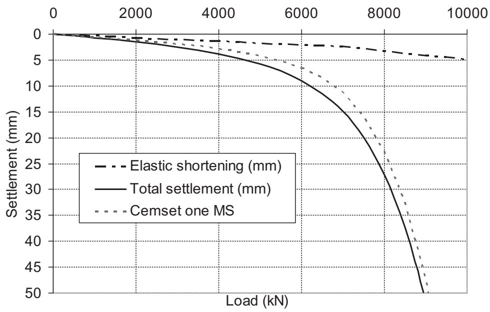

Figure 7. Cemset model with extra component.

The data points correspond to the measured upward displacement and the measured elastic shortening, the solid curve represents the modelled behaviour.

The elastic behaviour can be modelled directly from the measured data, and the remaining geotechnical behaviour can be matched using one hyperbolic function defined by Ms (flexibility factor) and Us (ultimate capacity). Buoyant weight of the upper section can be subtracted from the modelled ultimate capacity.

As pointed out in England (2005), the stiffness (flexibility factor Ms) can exhibit different values for the upward compressive behaviour in comparison to the expected downward behaviour; this can be attributed to the different boundary conditions, and therefore one may add together the modelled geotechnical behaviour measured for each element or one may choose to adopt a more typical flexibility factor expected for traditional top-down loading behaviour of foundation elements.

To illustrate the difference which may exist, the data presented in Figure 7 has also been plotted assuming a flexibility factor Ms upwards of 0.002. In this illustration, the dotted curve represents the traditional top-down loading behaviour expected and the solid line represents the summation of the modelled behaviour upwards and downwards. In essence, this approach allows for the addition of two separate hyperbolic functions for the skin friction of different ultimate capacities and one modelling the end bearing component giving a more conservative prediction of pile head behaviour.

4 FINITE ELEMENT METHOD

There are several approaches to modelling each of the elements and several different programmes which may be perfectly appropriate to model the data recorded either as just load-displacement or to include also any results from strain gauge measurements and then recombine these into predicted structural performance.

Fellenius et al. (1999) describes the use of The Advanced Geotechnical Analysis Code (AGAC) with which they have made several finite element analysis studies with this program which models the soil as an elastoplastic material and uses the bounding surface plasticity model to characterise the stress-strain-strength response of the soil. In this particular paper, the FE analysis of a 28 m deep barrette in the Guadalupe Tuff formation of the Makiti area is described. The parameters of the model were adjusted to obtain agreement with the bi-directional test results and from this model the expected top-down prediction was obtained.

Russo et al (2003) reports on their early findings of FEM analysis reporting a higher pile stiffness response from bi-directional tests when compared to top-loading; this is to be expected as the elastic shortening in a top-down loaded pile is more than that

LOADTEST employ the FB-MultiPier analysis program which is a nonlinear finite element analysis program capable of analyzing multiple interconnecting bridge pier structures. This analysis program couples nonlinear structural finite element analysis with nonlinear static soil models for axial soil behaviour to provide a robust system of analysis for coupled bridge pier structures and foundation systems. FB-MultiPier performs the generation of the finite element model internally for the geometric definition of the structure and foundation system as input graphically by the designer. Given the characteristics of the structure of the foundation element and the measured stress-strain at the pertinent levels, in a simple manner, the expected load-settlement behaviour at any elevation can be assessed with ease.

The use of Finite element or Finite difference computations to assessing the behaviour is no longer such a rare occurrence. The application finds its way into practice more regularly when the bi-directional testing methodology is applied at more than one level: In multilevel tests, the loading is necessarily done in stages, pressurising each level according to a predefined sequence relevant to the results required, and it is therefore essential to ensure the influence of previous loading stages are taken into account adequately.

5 EXPECTED ACCURACY

Direct comparisons of predicted pile head behaviour from a bi-directional test and actual is difficult to obtain reliably as separate test piles need to be installed and tested by each static loading method. In addition, the testing regime and the method of interpretation also need to be carefully chosen.

Further, because the loads applied with bi-directional tests are often far larger than those even available for top-down loading, comparisons can be a little difficult to obtain.

In principle, because bi-directional tests are full scale static loading, the results can be expected to correspond. Issues regarding softening of the ground around the bi-directional loading device only lead to conservative interpretation of the response of the soil and foundation element.

It is therefore for the engineer to assess the results obtained and how conservative these may be relative to the specification for the structure.

6 CONCLUDING REMARKS

The analysis of each separate measured response from a bi-directional test may be sufficient for many applications, but where the load-settlement response of the head of the foundation element is required, two direct methods are shown by way of example.

Where the elements of the test foundation have not been fully mobilised, the addition of the measured behaviour is perfectly suited to describing the combined behaviour of two elements.

Once one or both of the elements of a single level bi-directional test are moved sufficiently and can be modelled, the combination of the modelled elements can give a complete behaviour characteristic of the entire foundation element up to ultimate capacity.

When multilevel loading assemblies are employed within a single foundation element, it sometimes becomes imperative to find more sophisticated methods, such as Finite Element Analysis techniques to model the induced stresses in the different phases of loading.

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