Bi-directional Static Load Testing – State of the Art

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Keywords: Loadtest, Osterberg cell, O-Cell, static load tests

ABSTRACT: The use of static load testing in optimising design and providing verification of suitability and constructability continues to be unsurpassed in the foundation industry. The utilisation of top load reaction testing appears to be that with which most European engineers are familiar, but a variation on this, which has become just as conventional in some parts of the world, is the use of bi-directional testing allowing tests to near ultimate capacity to be performed more conveniently, economically and safer.

A purpose build jack, (such as an Osterberg Cell) is cast within the pile at a chosen location typically half way down the "capacity length" of the pile in a manner in which the upper and lower portions of the pile are tested against each other. Techniques for computer controlled loading and remote control by GSM links can readily be applied and the quality of data recorded and reliability is excellent. The numerous applications and methods of analysis are described.

Where the confidence in prediction of capacity is not high, a technique using O-cells™ arranged at two different levels maximises the information that can be retrieved from a single test pile by sequentially loading from one level and subsequently loading at the other.

A review of the advantages and disadvantages is presented and how some of the perceived shortcomings have been overcome together with an appraisal of current usage around the world.

1 INTRODUCTION

There are several reasons why engineers specify full scale loading tests; the most interesting, from a geotechnical point of view, is the optimization of the foundation design. Of similar importance but of structural significance is the correct performance of the element under load. From a foundation engineering or contractor's perspective it is often achieving adequate or the maximum capacity from the surrounding ground with the approved design.

Design considerations alone often lead towards a necessity for performance verification.

The merit of each testing system that may be prescribed comes with limitations and advantages. Sometimes it is difficult to appraise these fully when deciding which testing method might be most appropriate. This paper attempts to highlight some of the differences between top down and bi-directional testing.

2 TOP DOWN STATIC LOAD TESTING

The most sophisticated arrangement the author has witnessed is a system developed and patented by Cementation in the UK., where the entire testing process has been completely automated and remote access to the data and the pertinent parameters controlling the test are accessible by remote GSM data link as described in England (1999).

Similarly, the assembly of reaction systems can also be optimized. The most cost effective arrangement for providing a reaction system at ground level is with the use of anchor piles. Ready assembled systems have been designed and constructed to allow for rapid connection to anchor piles. Fig 1, illustrates a 2MN assembly which takes less than 1 hour to erect and connect to the 2, 4 or 6 anchor bars. These types of reaction systems are also safer as their scope for collapse and fall is minimized.

Fig 1 Ready assembled reaction system

Similar arrangements have been designed for loads up to 5.5MN. Transportation of the steel required for greater loads necessitates that the reaction system be made up of several components and consequently assembly time becomes considerable.

3 BI-DIRECTIONAL PILE TESTING

A sacrificial jacking system is cast within the pile body. Upon application of load, the pile is separated into two elements and load is applied to both elements simultaneously. Instrumentation of the elements reacting against each other is critical to the success of the test.

The use of bi-directional testing has become prevalent in the last decade with the use of the purpose built systems such as those pioneered by Osterberg (1989) and carried out routinely around the world. For a full description see Osterberg et al (2001).

4 COMPARISONS

4.1 *High Loads*

The practical problems which are experienced when trying to assemble a top down load test, when loads need to be in excess of around 10-20MN, start to be significant. Although multiple jacks can readily be deployed, the design and assembly of a suitable reaction system becomes an engineering challenge.

Two main features of bi-directional testing, which can make it preferable over top down static load testing, are:

1. the saving in terms of cost, transport, installation and erection of kentledge, anchors or anchor piles as well as the associated reaction system required above ground level.
2. a significant improvement in terms of safety; assembly of a loading system at the head of the pile is not required and the loads applied are buried.

The installation of an O-Cell on an existing steel reinforcement cage can typically be performed within one day. In contrast, a reaction system for loads up to 15MN may take over a day to assemble.

The use of multiple jacks/cells can be used to advantage in a bi-directional test, it can even be an aid as the geometry of a multiple cell arrangement allows for concrete feed down the centre of the pile if required.

Fig 2 Assembly of multiple O-cells

Loads with bi-directional tests have continued to break world records, with the current highest equivalent test load being 151MN. On a 2.4 m diameter pile, 41 m long, in Arizona.

4.2 *Mobilized load*

The maximum load which may be applied in any loading test is controlled by the extension of the jack.

In top down tests, jack ram extensions of 150-300 mm are typical; O-Cells are manufactured with potential expansion of 150 and 225 mm.

In the case of a single level bi-directional test arrangement, the two elements controlling the extension of the jack are: 1) The upper element, controlled predominantly by skin friction, which once fully mobilized, will allow the jack to reach a maximum extension without application of further additional load. 2) The lower element, whose behaviour will be governed predominantly by end bearing and according to the cell location more or less skin friction.

This limitation can be reduced with the use of multilevel load application. Either by combining a bi-directional cell with load application from the top or by the use of cells arranged at more than one level within the pile body.

A procedure often employed for a test using multilevel cells would first apply load to the lower cell, and subsequently, while allowing the first cell to re-compress, apply load at a higher level. The middle element would move down allowing its frictional resistance to be determined directly until re-engaging the resistance from the lowest element.

A further test now often applied, is full compression of the middle section to determine the elastic modulus directly.

The use of multilevel cells within the test pile accounts for approximately 20% of the O-Cell tests performed to date.

4.3 *Rock Sockets*

A difficulty with evaluating skin friction in rock sockets is ensuring the load applied reaches the area of interest. In the case of top down tests, it is found that the frictional behaviour is often indistinguishable from the stiff end bearing and additional sensors within the pile body are needed to evaluate the friction distribution.

Bi-directional tests can be arranged to apply the load directly into the rock sockets (or other zone of interest) and thereby the resultant behaviour is more readily interpreted.

Several applications of bi-directional tests in rock sockets have revealed in all but a few cases that the frictional behaviour has been significantly under-estimated.

4.4 *Use of test pile*

A misconception often applied in the UK is that any pile tested to over 1.5 times its working/service load is not suitable for integration into the structure.

What should be considered the correct approach is whether the pile has suffered any structural damage during testing and, is the subsequent behaviour of the test pile suitable and meets any differential settlement requirements. The reload behaviour is, to a first approximation, predictable using methods such as that described by England (2000), and can be assessed.

In the case of a top down test, locked in stresses at the base will reduce the pile settlement upon reload, leaving the total capacity nominally unchanged. Similarly, bi-directional tests, generally release the locked in stress applied and the subsequent pile head behaviour, after fully grouting in and around the cell, is with an increased base stiffness behaviour usually up to loads greater than the service load and thereafter reverting to the original stiffness.

4.5 *Stresses applied*

Only half the stresses are applied to the concrete in a bi-directional test when compared to the equivalent loading from ground level. This allows tests to be performed sooner than might be necessary in top down tests.

Consideration needs to be given to the reduced applied stresses structurally and further, it should be apparent that in a bidirectional test the structural performance of the top of the pile remains untested.

4.6 *Selection of pile to test*

When it comes to expendable preliminary pile tests, it is obvious that these need to be preselected. For proof tests, it can be perceived a disadvantage to have to select the pile to be tested using the bi-directional approach. In practice, preselection is also common place when choosing a pile for proof loading in top down tests as practical reasons, such as space restrictions, often impede the installation of anchors or erection of reaction systems.

Of particular advantage with bi-directional tests, is that the working area around the pile required for the test is minimal and significantly less than that needed for a top-down test.

A perceived reservation with casting an O-Cell in a pile is the effect this may have on the concreting and subsequent behaviour, from all the tests performed to date no evidence of zones where poor cover of concrete could have been concluded. In addition, particular attention is paid to the insertion of the reinforcing cage to ensure no additional debris is produced.

4.7 *Testing*

The most up to date testing systems for top down loading are now fully computerized and the entire testing schedule is programmed and can be supervised by remote GSM connection to the controlling computer system on site. It is intrinsically safe and well proven.

In bi-directional testing, the loading equipment is similar, but the degree of instrumentation tends to be higher as in effect two simultaneous load tests are being carried out and monitored. An advantage when the load is applied within the pile is that the duration of load can be less. In top down tests, additional time needs to be allowed for load transfer along the length of the pile.

Both top down and bi-directional tests can be carried out using maintained loads in a manner in which the creep effects are manifest in the measured data, and can be modelled using methods such as England (1993) to calculate projected long-term settlements.

4.8 *Interpretation of results*

In all loading test, varying degrees of interpretation are needed to establish a definitive long-term behaviour characteristic.

If the pile is not moved sufficiently, little can be said about the behaviour. In the case of top loading, methods of interpretation such as Fleming (1992) are poor if the measured behaviour is controlled predominantly by elastic shortening. For the same load in a bi-directional test, the separate behaviour of skin friction and end bearing mobilized are more informative.

In the case of multi-level bi-directional tests, the summation of the performance of each of the contributing elements is required.

One of the advantages with O-cell testing, assessment of the impact of construction technique is generally easier, Schmertmann et al (1998).

4.9 *Top load movement curve must be calculated*

Some engineers find it useful to see the results of a bi-directional load test in the form of a curve showing the load versus settlement of the pile if it were top-loaded. The test results can be combined by adding the loads mobilized at equal displacements. The additional elastic shortening may then be included as added settlement.

A limited number of comparisons have been made between the equivalent pile head movement and top loading test results.

Peng et al (1999), reports the results of an Osterberg cell test on a 1.2 m diameter, 37.2 m long bored pile in Singapore, compared to an adjacent pile with the same dimensions actually top-loaded by kentledge. The results are shown in Fig 3, the data from the bi-directional test shows slightly lower displacement, due probably to the loads being held for 4 minutes as opposed to 1 – 24 hours in the top down load test.

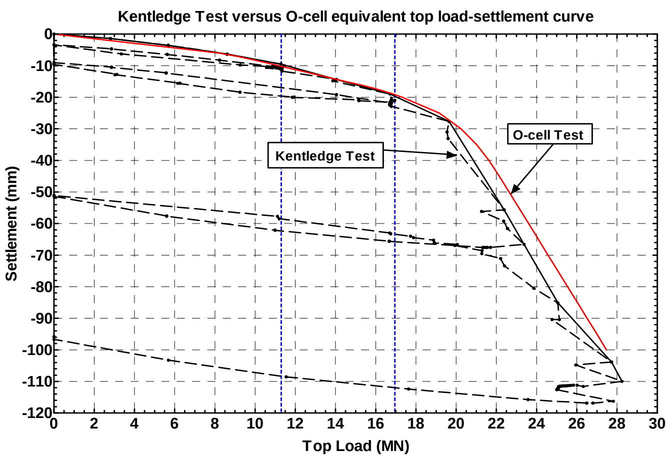


Fig 3 Comparison between top down and bi-directional

4.10 *Applications*

While in several countries up to 1% of the piles installed are static load tested, it still appears more routine to apply loads top-down from the pile head.

However, many circumstances impede the full scale testing using top-down testing systems and bi-directional testing is becoming conventional.

To date over 600 tests using Osterberg Cells have been performed and the interest in using the method systems and the number of different applications continues to grow.

O-Cells™ have been installed in precast piles, CFA piles, barrettes, several of the tests have been carried out over water. O-Cells™ have been used to measure the rock modulus in lateral tests.

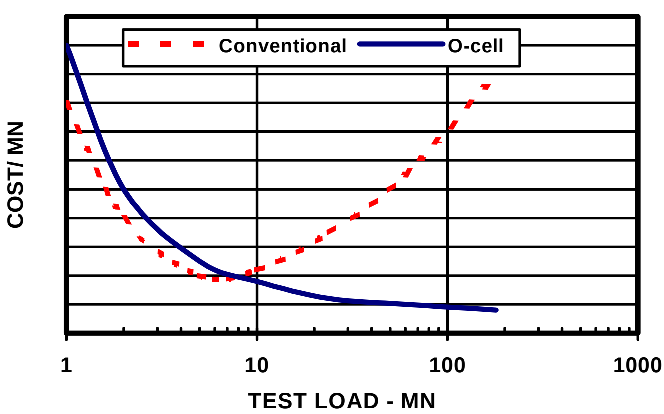
A notable majority of piles tested in this manner are working piles; the value of being able to integrate a test pile into the structure being a significant driving factor.

Also notable is the application of bi-directional testing to bridge foundations, driven principally by cost and practical aspects.

5 COST

The current comparison between cost of top down and bi-directional load tests in the USA is illustrated in Fig. 4. The costs per MN are similar at loads up to 5MN. At higher loads, bi-directional tests become increasingly more cost effective.

Fig 4 COMPARISON OF LOAD TESTING COSTS CONVENTIONAL VS. O-CELL



As the number of bi-directional tests increases, the costs of transportation and mobilization of personnel are appreciably reduced.

6 CONCLUSIONS

Although the execution of top-down load tests have been optimized and made as cost effective as possible, there is scope for yet a further development in the practice of full-scale foundation testing using bi-directional tests.

The Osterberg Cell is being used routinely in many parts of the world and provides:

- Very high loading capability, unmatched by top-down testing.
- Considerable costs savings at loads above approximately 5MN
- Significant advantages in terms of space and safety
- No additional reaction system needed with its concomitant transportation and erection.
- Automatic skin friction and end bearing separation.

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