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Optimum loading specifications for O-cell bi-directional static load testing

Caractéristiques optimum pour essai de charge statique bidirectionnel utilisant la cellule d'Osterberg

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ABSTRACT

The O-cell bi-directional load testing technique is, in effect, two static load tests performed simultaneously. One test is performed upwards against skin friction and the other concurrent in the downwards direction against combined lower section skin friction and end-bearing. Many hundred of tests of this type are now being carried out each year around the world, often on the most prestigious and signature structures. Similarities between traditional top down load testing and the bi-directional testing method are many, both being full scale static load testing techniques. However, due to the unique nature of the bi-directional testing method, the standard testing procedures and specifications generally prescribed for traditional top down static load testing can be improved to take into consideration the positioning of the loading jacks and the unique nature of the testing technique. The authors have been involved in the preparation of some of the specifications for traditional top-down static loading tests and also in the formulation of project specific testing programmes to maximise the geotechnical information which can be retrieved from O-cell bi-directional tests. Some of the well accepted specifications such as ICE SPERW 2007, ASTM D1143D 2007 and the European pile testing specification and guidelines may be applied directly to bi-directional loading tests. Their appropriateness is reviewed in relation to O-cell bi-directional static load testing to indicate how the maximum geotechnical information may be obtained by minor modification/improvement to the specifications and how they can be optimised with respect to hard soils and weak rocks. Loading increments, creep measurements and load cycling are discussed and recommendations for adaption of the conventional standards and specifications are made.

RÉSUMÉ

Le technique d'essai de charge bidirectionnel utilisant la cellule d'O-cell est, en effet, deux essais de charge statique effectués simultanément. Un test est effectué vers le haut contre la résistance de frottement latéral et la concurrente dans la direction vers le bas contre la résistance de frottement et de pointe. Plusieurs centaines d'essais de charge de ce type sont actuellement effectués chaque année dans le monde, souvent sur les structures les plus prestigieuses. Ressemblances entre l'essai de charge traditionnel du haut vers le bas et la méthode d'essai bidirectionnelle sont nombreuses, les deux étant des techniques statiques d'essai de charge. Toutefois, en raison de la nature unique de la méthode d'essai bidirectionnelle, les procédures d'essai et les spécifications généralement prescrit pour l'essai de charge statique traditionnel du haut vers le bas peut être amélioré pour prendre en compte le positionnement des vérins de chargement et de la nature unique de la technique d'essai. Les auteurs ont été impliqués dans la préparation de certaines des spécifications pour les essais de chargement statique traditionnel et aussi dans la formulation des programmes de projet plus spécifiques afin d'optimiser l'information géotechnique qui peut être récupéré à partir d'essais de charge bidirectionnelle utilisant la cellule d'Osterberg. Certaines des spécifications bien acceptées comme ICE SPERW 2007, ASTM D1143D 2007 et les spécifications européennes d'essais de chargement dans les puits forés et les lignes directrices peuvent être appliquées directement à des essais de chargement bidirectionnel. Leur pertinence est examinée en relation avec la cellule de charge bidirectionnelle d'essais statiques d'indiquer comment le maximum d'informations géotechniques peuvent être obtenus par modification mineure ou amélioration des spécifications et la façon dont ils peuvent être optimisés en ce qui concerne les sols durs et des roches faibles. Les incréments de chargement, les mesures de fluage et de cycles de charge sont discutés et des recommandations pour l'adaptation des normes conventionnelles et les spécifications sont faites.

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Keywords: Bi-directional, static load testing, loading schedules, Cemset®, CEMSOLVE®, TIMESET®, O-CELL®

1 COMPARISON OF LOADING TECHNIQUES

The principal difference in the methodology of O-cell bi-directional testing and the traditional static load testing is the positioning of the point of load application. The load application for traditional static load testing is at the top of the foundation element, hence the use of the common terminology ‘Top Down’ testing or Top-down load testing.

By the use of a hydraulically driven, calibrated, sacrificial jacking device, (the O-cell®) installed within the shaft of a pile, barrette or similar load bearing foundation, a bi-directional static load test can be performed where the resistance data is automatically separated into component parts. In effect, two static load tests are performed simultaneously, working in two directions, upwards, against skin friction and downwards, against skin friction and end-bearing. The results of these compression tests are then combined to give an equivalent top down foundation behaviour under a static loading test.

The load can be applied within the foundation, providing sufficient reaction is available from the soil above and below the loading devices. The loading arrangement may be placed near the base of the foundation element or at a calculated balanced position within the shaft (Figure 1). It is recommended that when the O-cells are required at or near the base, the O-cells are placed at least twice the diameter above the base of the foundation shaft to allow for concreting below the O-cell assembly. This also allows for the concreting process to scour and clean the base.

For driven piles where the tube is closed at the end, the O-cell can be placed so that the loading is directly located at the end plate or shoe. The shoe is fixed in place during driving but is allowed to move freely downwards when the O-cell arrangement is loaded.

For rock sockets in hard intact rock, the O-cells can also be placed at the toe of the pile to load the end bearing directly using the friction of the rock socket shaft as reaction; several techniques exist for ensuring successful direct connection to the end bearing.

ICE [1], ASTM [2] and other static load testing specifications have considered generally the top down loading position in the drawing up of the testing specifications. However, with such a differing technique, certain modifications to the specifications should be considered when specifying the O-cell testing method.

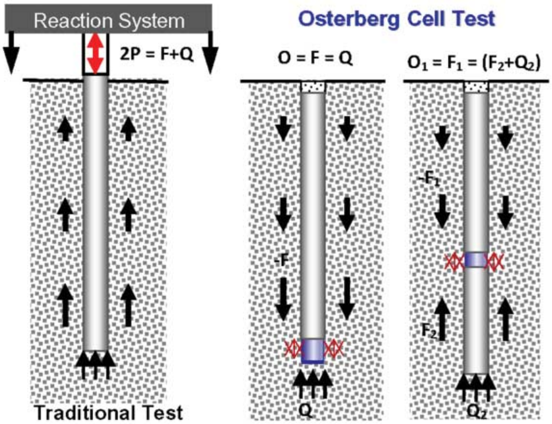

Figure 1 Comparison of loading techniques

With a conventional top-down test, the maximum travel downwards is not immediately limited as there is scope to adjust the hydraulic jack by packing to allow further downwards travel. This option is not available using an O-cell arrangement. In either case, it could be considered that the test is completed once the foundation element has been fully mobilised and with sufficient data to fully characterise its behaviour. For a traditional top-down test, this would require the full shaft element to be mobilised before any of the end bearing is revealed, whereas in the O-cell bidirectional test, this would be achieved once one of the elements, above or below, had been fully mobilised.

Completion of a bi-directional test is determined by one of two things, maximum travel of the loading arrangement or maximum capacity of the foundation element either above or below the arrangement. Conversely in a top-down test, the test would be limited to when the capacity of the reaction system is reached or the foundation element is mobilised fully.

2 INSTRUMENTATION REQUIREMENTS

In a traditional top down load test, the pile head and the load applied are the two critical issues to record with respect to time. The O-cell bi-directional test requires nothing different, only there are two elements being loaded, and their displacement vs load and time also need to be recorded. It is required to measure the compression of the upper element to determine the movement of the top of the loading arrangement at the O-cell level, the addition of further telltales to the toe of the pile and other instrumentation within the test piles is common place. Since the loading is performed within the founding strata of most geotechnical interest, fitting strain gauges is also a regular occurrence.

3 LOADING INCREMENTS.

There are two main types of static load test. The preliminary test, where the test pile is expendable and is designed to reveal the geotechnical behaviour of the shaft, and a proof test which is undertaken to verify the structural ability of the shaft to meet load settlement criteria.

Each of these test types has an associated specific loading schedule in the test specifications.

ASTM [2] includes a preferred method of the 'quick test' where loads are applied for a minimum of 4 minutes and a maximum of 15 minutes at each stage using the same time interval for all loading steps. This standard has regularly been adopted directly for bi-directional testing where requested and is particularly suitable for tests on working piles where confirmation of structural performance is required and there is no requirement to provide geotechnical information. The test is performed in the undrained condition and is used to confirm the test shaft is capable of achieving the required test load and will comply with load-settlement criteria. This test is especially suitable where the loading assembly is placed within the rock socket. Since this test is performed in the undrained condition, no consideration is given to creep or long term movements that may be incurred when testing in softer soils. ASTM [2] also includes a similar testing specification for the fully crept drained condition.

ICE [1] and other codes take the fully crept drained condition as the prime condition for their specifications on testing.

When attempting to produce a test specification that will allow the load displacement behaviour to be analysed, it is appropriate to hold each and all load steps according to a consistent set of rules so that the final displacements can be associated for each load applied – this can be:

- to hold each load for a fixed duration consistently;
- to hold each load step until a predetermined settlement rate has been achieved; or
- hold the load for long enough to be able to analyse the displacement time behaviour to determine the settlement for each load (this becomes independent of the manner in which the testing specification has been scheduled).

ICE [1] suggests for a single cycle proof load test; the load is applied in steps of 25% of the design verification load with a minimum hold time of 30 minutes and dependant upon creep criteria to 100% design verification load, where the load is held for a 6 hour period. The load is then increased to 100% design verification load + 25% of the specified working load and held for 1 hour. The final loading stage to 100% + 50% specification load is then held for 6 hours.

The test may also be performed in two cycles, the first cycle being loaded to 100% design verification load then returning to zero before completion of the second cycle to 100% design verification load + 50% specified working load.

The merit of doing two cycles of loading should be considered carefully [3], the unloading and reloading load-displacement behaviour does not add anything to the understanding nor to the information that can be retrieved from the pile behaviour.

The maximum loading for a preliminary test is not specified in the code and is left to the specific project specification to determine but the increments to 100% DVL + 50% SWL are the same with loadings above this value in increments of 25% SWL until the desired maximum loading.

The increment size and holding times of these load steps are specifically designed for application of the load at the top of the foundation element. The ICE specification takes into consideration that the end bearing would not be mobilised in the early stages of the testing and that the load would take time to be applied fully at the bearing strata. One issue associated with such time periods is, that at lower loads, pile movements rapidly approach stability but as the loading increases, stability is more difficult to achieve within a given timeframe [3]. When the shaft friction is fully mobilised and the end bearing dominates the load-displacement behaviour, the mobilisation of the end bearing is a key component dominating the settlement rate, then the time taken to reach the required settlement rate becomes protracted and it is for this reason that it is recommended to limit the duration at any one load step to 3 – 6 hours as the displacement – time data can be analysed, with high quality results, to find the projected settlement [4].

Applying the above specification to a traditional top down static test will provide equally spaced load steps and allow a load-displacement curve to be produced where creep has been allowed for. The use of only 6 loading steps for a proof test and approximately 8 to 12 steps for the preliminary test can be sufficient in a traditional top-down loading test. However, it is preferred in an O-cell bi-directional test to have additional loading steps in proof tests so that the addition of the upward and downward load-displacement characteristics, required in order to produce the equivalent top down load behaviour anticipated, are sufficient without the need for extrapolation of one set of results. If the upward and downward behaviour can be modelled using techniques such as Cemset® [5] using hyperbolic functions, a minimum of 8-12 successfully completed loading steps can be suitable.

It is worth noting that an O-cell bi-directional test can be applied to a "proof" loading test and after its completion grouting of the separation of the two elements can readily restore the compressive structural integrity. However, it should also be noted that such a test can also reveal more of the geotechnical capacity than traditional top-down loading. Further, the top-down loading is often limited to 150% of the working load for structural reasons, but because a bi-directional loads in two directions, the structural stresses are only half and a proof loading bi-directional test can reasonably be applied to 300% of the working load.

It is considered that 10 to 12 steps can produce sufficient data to assist in the analysis of the results for the interpretation of embedded strain gauges using tangent stiffness modulus [6]. The increments need to be of a sufficient size to distinguish the load steps and allow discrete data points to be plotted. It is recommended that bi-directional proof and preliminary tests should be planned to allow a minimum 12 steps to the expected maximum loading, with extra steps of the same size being added in excess of this for preliminary pile tests seeking the ultimate capacity.

The Cemsolve pile behaviour analysis technique developed for traditional top down tests, can be applied to each element of a bi-directional test and permits interpretation of friction and end bearing from load-settlement results from each element to model both the upper "normal friction" elements and "friction and end bearing" of the pile elements above and below the O-cell arrangement. By addition of the behaviour of each element, these can be combined using Cemset to predict the equivalent top-load response from bi-directional test results [7].

An example of a Cemset analysis of a bi-directional test is presented as Figures 2 to 4. The model uses single or twin hyperbolic curve fitting to find a unique solution. Confidence in the accuracy of the model matching the results is increased with a greater number of data points obtained from increasing the number of loading steps.

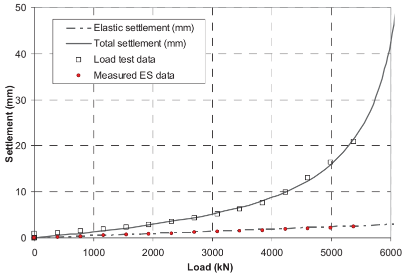

Figure 2 Upward Cemsolve® analysis and plot.

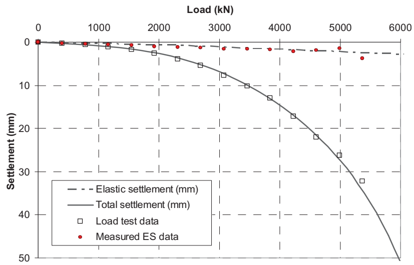

Figure 3 Downward Cemsolve® analysis and plot

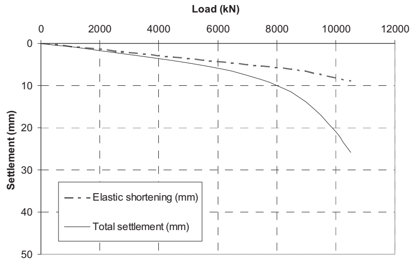

Figure 4 Combined behaviour Cemset® prediction.

4 SETTLEMENT CRITERIA.

The ICE settlement criterion is given as:

- For pile head displacements of less than 10mm, each load increment shall be maintained until the rate of settlement is reducing and is ≤0.1mm/hour.
- For pile head displacements between 10mm and 24mm, each load increment shall be maintained until the rate of settlement is reducing and is ≤1% x pile head displacement/hour.
- For pile head displacements of greater than 24mm, each load increment shall be maintained until the rate of settlement is reducing and is ≤0.24mm/hour.

If sufficient data is recorded, the displacement-time can be analysed to find the final settlement using such techniques as Timeset®[4], thus providing a reliable means of assessing the fully drained long-term pile behaviour without the need for protracted hold periods.

The bi-directional technique can apply the load directly to the bearing strata. In some circumstances the O-cells are positioned lower down the shaft and either at or near to the base of the shaft. In these cases, the end bearing is engaged at much lower loads than those applied from the top. The resulting downward movement would then be a function of end bearing settlement and not shaft creep related. The higher settlement rate of 0.24mm/hour as defined in the ICE specification would be more appropriate.

The settlement or creep movement in the upward direction is generally expected to be dominated by shaft friction since there is no end bearing component. An upward rate of 0.1mm/hour would then be applicable for any movements. Any creep would also be expected to stabilise quickly and long holding times are not thought necessary. This is particularly true of piles in rock and soils with high friction capacities.

Expansion of the O-cells, compression and head movements are used to determine the magnitude and direction of the movements. The measurement of the expansion of the O-cells is provided by accurate instrumentation attached to the lower and upper bearing plates. Since the O-cell expansion gauges are the most sensitive measurements of the instrumentation system, these are recommended to be used as the preferred method of assessing settlement rate in an O-cell bi-directional test. The combined upwards and downwards settlement rates are measured in combination.

The specified 1 hour minimum holding time in the ICE specification is generally appropriate for assessing settlement rate, however with regular digital data collection, if little or no movement is detected this can safely be reduced to 30 minutes without compromising the quality of data. In addition to the minimum period, having a settlement criteria specified allows the time period to be extended to allow creep and end bearing settlement to stabilise within acceptable parameters.

In general, a rate of 0.25mm/hour or 0.3mm/hour for expansion is normally recommended as the creep criterion for O-cell bi-directional testing, without being dependant upon the location of the jacks within the shaft. These rates allow for a combination of upward creep and downward creep/end bearing settlement, the higher rate being more applicable when the O-cell assembly is positioned near the base of the foundation element.

With the bi-directional test, it is possible to continue testing once the lower element has been fully mobilised. If sufficient data has been achieved to deduce the ultimate end bearing capacity, the end bearing behaviour can then be ignored and the test continued using the end bearing as reaction to obtain information regarding the skin friction parameters in the upper element. In this case, the settlement rate below the O-cell can also be ignored and the test continued using the upward movement as the determining factor of settlement rate rather than the overall expansion. In this way, the full stroke of the O-cell can be utilised.

A maximum hold time of 3 hours per step is recommended. It has been considered that three hours of high quality data is sufficient to perform a projected final settlement value that would occur if the load was held indefinitely, using displacement-time analysis.

This hold time is in excess of the ASTM standard 2 hour hold maximum, and is in line with the ICE specification if the reduced increment loading is considered. Provided the settlement is stable and within the creep criterion, a protracted holding time at either 100% or 150% DVL is considered unnecessary.

5 COMPARISON OF TECHNIQUES AND TEST RESULTS

Several comparisons between the O-cell bi-directional and the top down static testing techniques have been performed where the loading specifications for both methods have been different. In all cases, differences in the loading schedules have not resulted in significant differences in results obtained and the comparisons have been favourable as would be expected even when the foundation elements have been pre-loaded.

6 CONCLUSIONS

Both the ICE SPERW 2007 and the ASTM D1134D-07 specifications are applicable to bi-directional testing since the test is essentially full scale static load tests. Certain modification of the specifications is required to allow the bi-directional technique to meet its full capabilities as a geotechnical tool successfully. Adaptations to other National and International standards can be made by following the same guidelines illustrated in this paper.

Settlement rates need to be considered in both the upward and downward directions, where end bearing may be immediately engaged at the first loading increments.

Loading stages should be sufficient to allow for more precise analysis techniques to be employed. Acquisition of good quality data is essential to the application of these techniques.

Loading schedules that combine both a fixed hold period and a settlement criteria should be avoided as comparisons on the obtained load-settlement graph may be misguided.

Use of analysis tools such as Cemset® require good quality well defined data that can be obtained by adaptation of the relevant standards to bi-directional testing.

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