INNOVATIONS IN STATIC LOAD PILE TESTING AND ANALYSIS

The testing of piles should yield a unique result. Since displacement is time related in all soils, an accurate displacement-time model is required to allow correct interpretation of settlement behaviour.

Test equipment and an analysis system have been developed that allow the unique definitive load-settlement characteristic to be established, using any reasonable test schedule for any static load pile test. All aspects of the analysis techniques can be applied to any size and type of pile.

The equipment is basically a computer controlled loading and pile head displacement measuring system.

The analysis involves a time-displacement model which accurately characterises the development of both end bearing and shaft friction to derive the final settlements under each and every load. These settlements can then be used to determine the unique pile behaviour and the distribution of load.

The method employs the major elements that control pile cehaviour. Soil stiffness and strength, together with their development in time are vital to understanding pile performance.

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1. INTRODUCTION

While the recorded test results of a static load test may be a factual record of the pile displacement during the test, it should be realised that the test specification has a significant influence on the recorded results. It is not the definitive pile behaviour which has been measured. Since the behavioural characteristic of the pile is unique, interpretation of the results becomes necessary to remove the effects of the test method, sequence and time taken. This problem is exacerbated in some forms of pile load testing to the extent that accurate evaluation of the pile behaviour may be impossible.

This paper outlines new developments in pile testing and analysis aimed at overcoming these difficulties and asserts that every pile, at the time of testing, has a single and unique behaviour which can be determined by carefully controlled load application and pile displacement monitoring. The method described is based on Terzaghi's[1] definition of ultimate bearing capacity. This definition is unequivocal and may be expressed mathematically as the asymptote of the load/settlement curve.

2. TYPE OF TEST

Perhaps it is self evident that if a pile test is carried out by long term application of load, over a range of loads, during which the force applied is constant so that displacement ceases *completely, then the unique load behaviour of the pile would be* discovered.

All pile test methods have to compare with this standard. For example, the Continuous Rate of Penetration test (CRP), which involves pushing the pile into the ground at a constant rate, was not designed to produce the unique pile characteristic. Even in its declared aim of determining the ultimate capacity, a number of authors[2] confirm that it generally overestimates pile capacity.

Quick Maintained Load (QML) tests, which are common in American *practice, present the same problem, as apparently do all Dynamic* Load Testing systems.

The behaviour of a correctly constructed pile is controlled by its interaction with the surrounding soils. It is therefore fundamental that the properties of the soil are taken into consideration; the primary components governing the behaviour of the soil being strength, stiffness and time.

It is therefore found necessary initially to take the time effects into account before attempting any assessment of pile load/displacement analysis. These effects are generally not addressed in short duration tests and consequently pile performance is overestimated in most cases.

It is perhaps fortunate that most British Engineers have remained faithful to conventional Maintained Load testing, which in the event proves to be the basis of the developments described here.

The test equipment and analysis system, recently developed and introduced by Cementation Piling and Foundations Ltd, is compatible with most static load test specifications and allows accurate characterisation of the time elements and subsequently, characterisation of the load/settlement behaviour from relatively short duration maintained load pile tests.

3. DEVELOPMENT OF THE MODELS THAT CHARACTERISE PILE BEHAVIOUR

It is worth reviewing the requirements for any pile/soil modelling technique:

1. Any mathematical model needs to characterise accurately the pile behaviour in time and under load.

2. It must be possible to model the displacement/time behaviour accurately so that with sensible load holding periods the final settlement at infinite time under a given load can be determined with precision.

3. The load/settlement behaviour must be related to an accurate model which can follow the relationship at each and every load stage up to the ultimate load bearing capacity, determining the maximum settlement at any load.

4. The models must encompass the soil parameters, including those relating to strength and stiffness along the pile shaft and beneath the pile base, and the associated time constants.

5. The models must be suited for both pile design and back-analysis of test data.

6. They should employ typical pile head displacement data so that they may be employed to back analyse commonly available information from well carried out tests.

7. They should enable the time dependent characteristics of different soils to be determined so that a minimum test duration at any given load can be established. This is an important feature which in practice is often neglected.

Mathematical models have now been developed, based on hyperbolic functions, which fully satisfy these requirements. One component of the model deals with shaft friction development and a second component, with the behaviour of the base of the pile.

The parameters pertinent to the models are described below:

- Ds - Equivalent diameter of the pile shaft.
- Db - Equivalent diameter of the pile base.
- Us - Ultimate shaft friction load
- Ub - Ultimate pile base load
- Ws - Asymptote of shaft displacement at given load
- Wb - Asymptote of base displacement at given load.
- Lo - Upper length of pile carrying little or no load by friction
- Lf - The length of pile transferring load to the soil by friction
- Ms - Flexibility factor representing movement of the pile relative to the soil through friction.
- Eb - Deformation secant modulus for soil beneath the pile base at 25% of ultimate stress.
- Ts - Shaft material time constant to reach 50% of final settlement for a given load.
- Tb - Base material time constant to reach 50% of final settlement for a given load.
- Ec - Young's Modulus of elasticity of the pile material.
- Ke - Factor positioning the effective centroid of the friction transfer diagram

4. ASSESSMENT OF PILE BEHAVIOUR AGAINST TIME

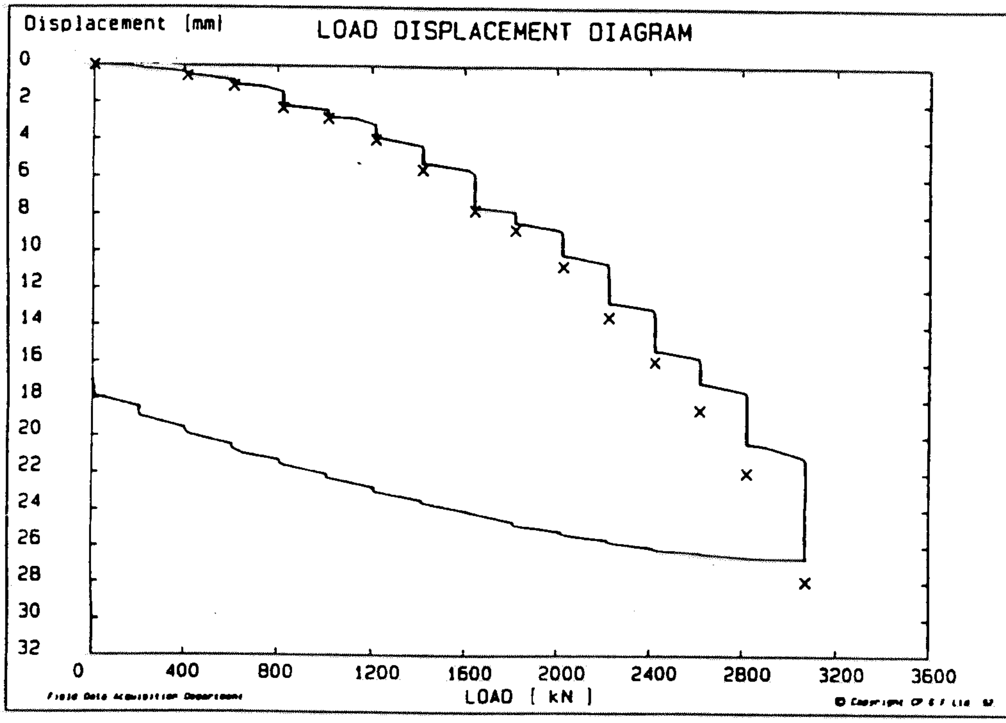
The final pile settlement at a given load is clearly that which would occur at infinite time, when the settlement rate is zero; in other words, it is the asymptote of the displacement/time characteristic. This is the value of settlement of interest as it is representative of the working conditions of the pile. Since it is neither practical nor desirable that tests should take long periods, alternative methods are employed which extrapolate, from the recorded data, to determine the asymptote of the settlement/time relationship.

Until recently the favoured methods were based on determining the slope of the plot of settlement against time on a semi-logarithmic scale or on a time/displacement scale. These techniques only allow the shaft and base settlements to be accurately distinguished when one or other is insignificant. This is rare and therefore under very few circumstances is there an accurate assessment of the final pile behaviour under a given load.

An algorithm which accurately characterises both the base and shaft time elements has been developed and is contained within a new computer program (TIMESET) which has been found to track field results with remarkable accuracy. This algorithm, being based on hyperbolic functions allows the asymptote for any load stage to be determined.

An example of a pile test result, obtained using high grade monitoring and control equipment is illustrated in Figure 1. The application of each load was held constant for durations between 30 minutes and 6 hours and the measured load/displacement is plotted as a continuous line. The final settlements calculated for each load are indicated as separate points.

This method of analysis allows unambiguous interpretation and is particularly suited to cases in which the load applied has been maintained effectively constant within each load step.



x - Calculated final settlement. FIGURE 1

Since the advent of fully computer controlled static load tests, in which the data recorded is more accurate and considerably more frequent than hitherto, and the load applied is maintained practically constant, the analysis of the displacement/time data can now be carried out immediately using TIMESET with a degree of accuracy that is remarkable and unsurpassed.

The asymptote of the displacement/time behaviour represents a fully drained/consolidated condition and is independent of any previous lower loads applied to the pile before the one under consideration; if the previously applied load has been higher, plastic deformation and history of the soil elements involved may preclude accurate prediction of compatible final settlement.

The model illustrates quite graphically why pile testing methods, of short duration, reveal pile behaviour in an undrained or partially drained state and offers an explanation for the widely recognised overprediction of pile performance.

Figure 2 shows displacement/time data recorded with a computer controlled testing system for one specific load holding period in a test together with the analysis. The separate components of the time relationships for the shaft and base are obtained by mathematical optimisation and are illustrated as broken lines on the figure. The pile displacement/time model is the sum of the two components Ws and Wb.

As can be seen, the data points, which are plotted continuously, are virtually indistinguishable from the results obtained from the mathematical model. The quality of modelling has been found to be consistently good for all soils analysed to date.

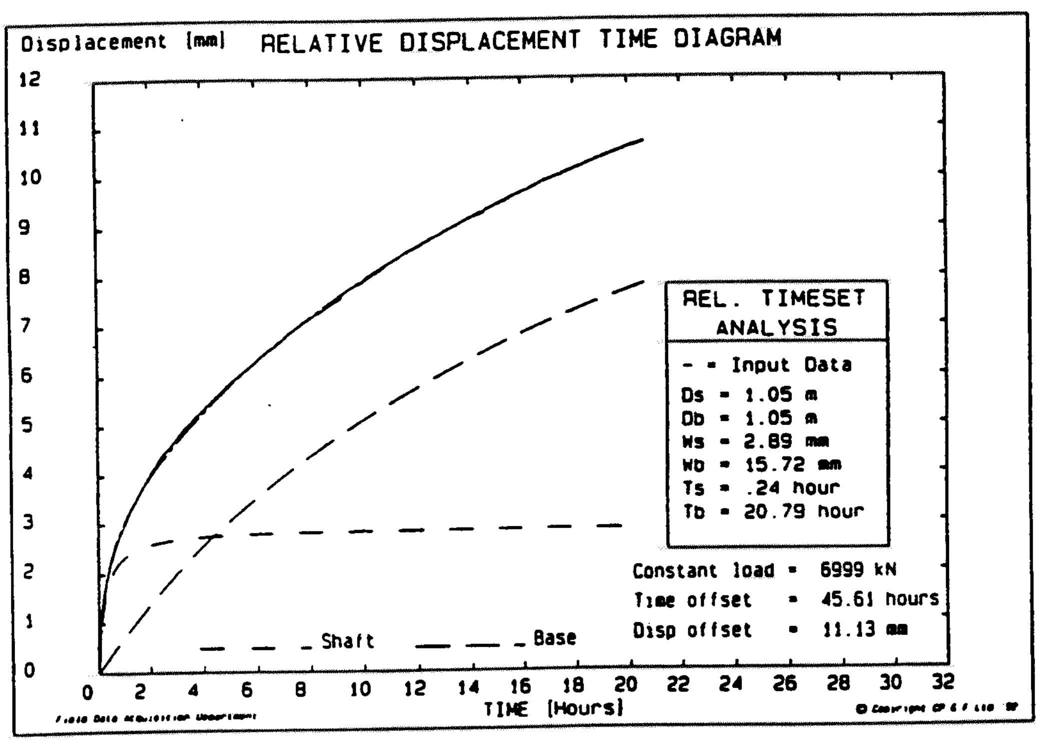


FIGURE 2

5. ASSESSMENT OF PILE BEHAVIOUR UNDER LOAD

The interpretation of pile settlement/load relationships has, until now, been a matter of some controversy. Many empirical rules have been developed in this field, probably as a result of differing ground conditions in various parts of the world.

One of the best methods available has been to employ the method developed by Chin[3], in which, when settlement is plotted against settlement/load, the slope of the latter part of the data was taken as a good indicator of the ultimate capacity.

Two main features have militated against the method proposed by Chin, namely that, because the means of plotting implies a simple hyperbolic function, it fails to give a good result in cases where there are really two strong hyperbolic functions present, one for the shaft and one for the base. The other reason lies in the definition of ultimate pile capacity[4]; it being argued that some engineers want to be able to define whatever 'ultimate' criteria best fits their structural requirements. Under these conditions 'serviceability' states should be defined.

True ultimate states cannot be defined arbitrarily or be based on mechanical dimensions of the pile alone. From a mathematical point of view the correct definition for foundations has to be the asymptote of the settlement/load relationship. From this asymptotic definition most other definitions of 'pile failure' can be derived.

The CEMSET[5] method of prediction and the program CEMSOLVE, specifically developed for back-analysis of single pile behaviour under load, overcome these limitations by identifying the fundamental hyperbolic functions that characterise the shaft friction and end bearing separately. They define asymptotes for the ultimate capacities, and then include a sensible elastic shortening model of the pile material.

Where possible, the settlement for any given load used in any form of back analysis should be independent of the duration of the test at that load stage; this is achieved by determining the asymptote of the displacement/time characteristic and can be calculated using the program TIMESET.

Illustrated in Figure 3 is an example. This shows the CEMSOLVE back analysis of the pile settlement data in Reference 2. The load test in this particular case was carried out manually, so minor deviations from the model should be excused. This pile was instrumented so that the elastic shortening and the characteristics of the base settlement could be separately determined. The figure illustrates how good a match can be obtained for the total behaviour, the elastic shortening and the base relationship.

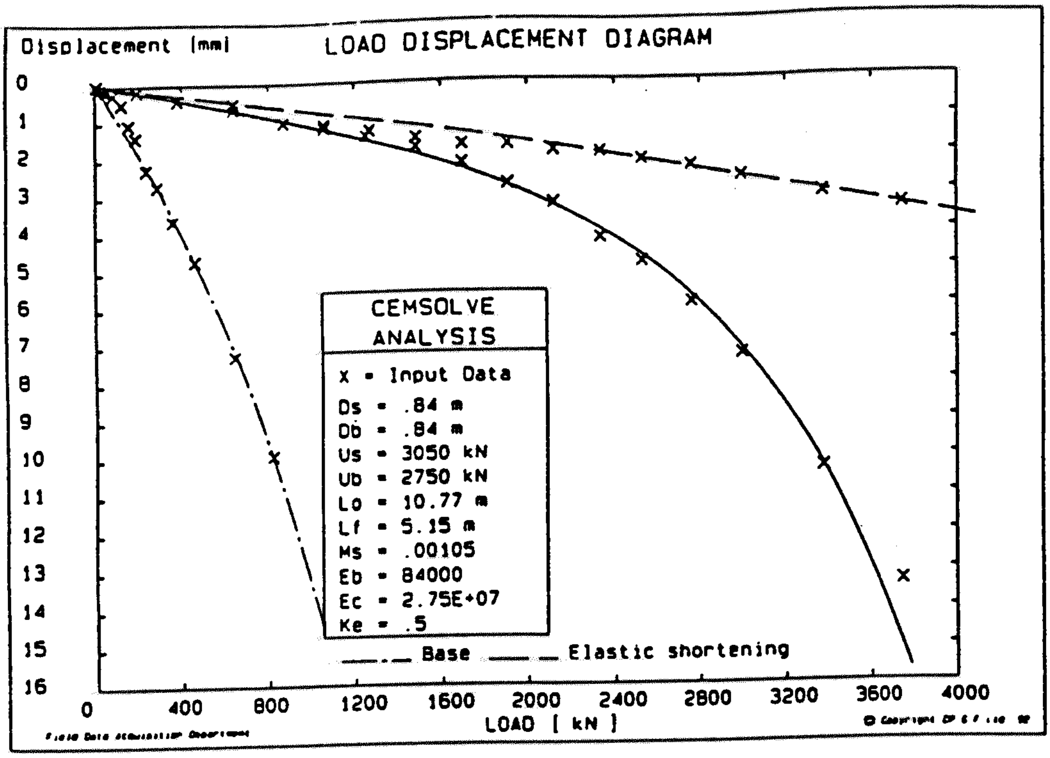


FIGURE 3

In parallel with the development of this system for analysis of pile test data, significant improvements to the data collection were also developed. As a result, a computer controlled static load test system was produced.

Illustrated in figure 4 is the back-analysis of the data shown in figure 1. The correlation between total settlement at each load and the line generated from the numerical model is excellent and typical of the results that can be obtained from a computer controlled load test.

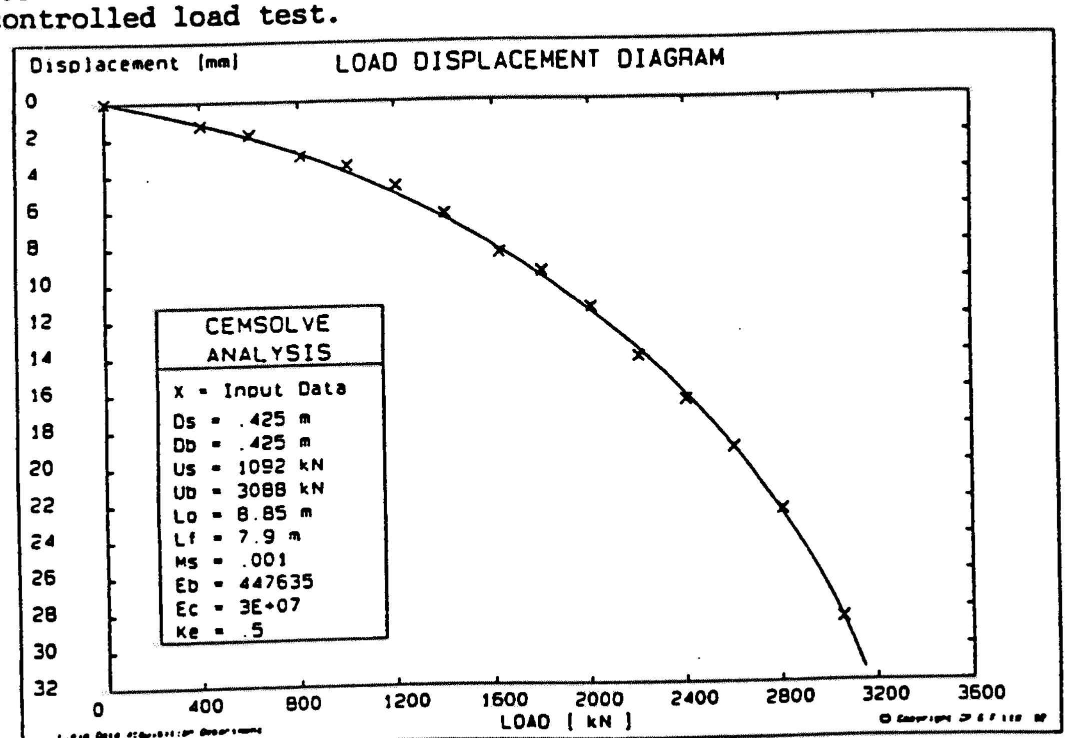


FIGURE 4

ACCURACY OF THE MODELS

Subject to the limitations detailed in this paper and reference 5, the models return a high level of accuracy in all of a wide range of ground conditions which have been encountered, provided the settlement and applied load have been well recorded and sufficient data is available. Results from static Maintained Load tests are compared against the model solutions in the program CEMSOLVE and show correlation coefficients that are far superior to those obtained with any previous forms of analysis. In excess of 400 pile load tests have now been analysed in this way with outstanding success. No case has yet been found in which the mathematical models do not represent with high accuracy the measured pile behaviour.

Piles in the same ground conditions but of differing diameters have also been studied. Behaviour of soils around piles of differing diameters can be readily characterised. For load/settlement analysis, the potential for installing smaller diameter test piles to confirm the pile design and obtain all the relevant soil parameters is now a genuine reality.

Such is the accuracy of the modelling techniques that they have been extended to characterise the unloading behaviour of the pile and subsequent reloading with good results.

6. TEST EQUIPMENT

The basic equipment consists of several displacement transducers to monitor the pile head movement and electronic load measuring equipment, all of which are linked to a data logging system. The microprocessor, which regulates all the functions, also checks the load applied to the pile at intervals of only a few seconds and effects any changes required by controlling the hydraulic pressure feeding the jack. The equipment has been refined to minimise any external influences that might affect the measured pile behaviour.

Some of the advantages of employing this equipment are as follows:

i) Simultaneous readings of all transducers are made by choice at intervals of between 2 seconds and 10 minutes.

ii) Printing and plotting of all data is available directly from the computer: minimising clerical effort for producing reports.

iii) Data are already compatible with a suite of programmes for back analysis, allowing accurate and reliable interpretation of the results and characterisation of the dominant materials that surround the pile.

iv) Automatic system control allows for unattended operation if required. This is particularly suitable for overnight tests, although security attendance may be required.

From a designer's viewpoint, the system allows the most cost effective piling system to be identified; e.g. from initial preliminary test pile results the pile parameters can be optimised for both minimum cost and maximum performance. Its use therefore also extends potentially into the field of piling equipment design.

LIMITATIONS

It comes as no surprise that if a test pile is not moved sufficiently, few of the pertinent characteristics can be accurately defined. Thus, provided the piles are made to mobilise a significant part of the base capacity, and overcome the skin friction, the back analysis using these models can reveal the significant characteristics of pile/soil behaviour and the distribution between skin friction and end bearing capacity. This allows either confirmation that the design was good or diagnoses the area in which the design was deficient or was over conservative.

The calculated load distribution obtained becomes increasingly inaccurate the less is the information obtained from the base behaviour. Under these conditions, the best estimates can be obtained by reviewing a range of parameters that would provide a satisfactory characterisation of the settlement behaviour.

The method of analysis is not intended to provide an accurate measure of the elastic shortening of any test pile. There are better and more suitable methods of determining this parameter.

It should also be realised that any results obtained from a static load test are pertinent to the conditions prevailing when the pile was tested and any long term effects (eg structural soil changes) cannot readily be identified; for example, a single isolated pile may be tested, but the subsequent installation of other piles around it can have significant effects on the original pile performance. Also, where the mechanical properties of the materials or time characteristics of the pile or of the soils change either with time, moisture content, or general consolidation of an area, these may not be assessed.

It should be noted that the TIMESET modelling described is most suitable for use where the pile test load has been maintained constant and where sufficient data points have been recorded to allow the model to optimise a best fit to the data.

8. CONCLUSION

The analysis system, while being suitable for use with practically any test specification, allows the most effective test specification to be selected.

Test equipment has been developed and is offered to the industry which maximises in a cost effective way the data that can be retrieved from a load test. The techniques require just pile head displacement under load to allow the analysis to be completed. No sensors are required within the pile.

The time and load settlement modelling performed using the TIMESET and CEMSET/CEMSOLVE algorithms indicates that the method of pile behaviour analysis is reliable and superior to any existing method. Its revelations may have far reaching consequences in foundation engineering.

Although it is often implicit that specified test methods or testing practices reveal "useful information", it is apparent that the methods described in this article extend well beyond the realms of normal expectations.

Because the unique pile behaviour under load can be determined, it is an invaluable tool for design, analysis and diagnosis. The method is simple to operate and greatly improves the understanding of pile and soil behaviour.

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