

# Pile settlement behaviour: An accurate model

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**ABSTRACT:** A mathematical model is described which accurately characterises the settlement behaviour of piles under load. It can be used for pile design or as an analytical tool to diagnose the pertinent pile/soil parameters. From this model most other definitions of bearing capacity can be derived. The soil characteristics derived are related to recognised physical properties.

The shaft and toe capacity can be determined together with elastic shortening from just pile settlement measurements made at the pile head, provided the pile movement is sufficient to mobilise a significant part of the toe characteristic.

The dynamic pile behaviour is discussed, and reviewed against the parameters governing static behaviour to indicate whether any correlation between different types of test can be expected. It is concluded that it is fortuitous if static pile capacity is correctly predicted with dynamic tests, they may however serve as a useful, cost effective, quality control test.

## 1 INTRODUCTION

It is curious just how much effort has been placed over the years on correlation between dynamic pile test results and static pile behaviour. This paper addresses the evaluation of the unique pile behaviour under load by measurement of the pile head movement during the application of constant loads. The analysis of the pile head movement with time allows the maximum pile settlement to be determined and can provide an insight into what a dynamic test can reveal.

The original objective was to develop a more complete method for the design of piles based on field measurement experience. It soon became clear that the current soil investigation methods do not reveal all the significant soil parameters and that a very appropriate solution would be to derive these from test results. It is the development of these methods and some of the consequences that are reviewed here.

While the fundamental formulae for stress wave analysis in a pile may be quite valid, the issue presented here is to reveal basic behaviour of the soil surrounding a pile and the implications this has on some pile testing techniques.

## 2 UNIQUE PILE BEHAVIOUR

A major problem concerning pile capacity or pile failure is that of definition. Recent research shows clearly that the ultimate load of a pile cannot satisfactorily be defined in any arbitrary way which can be universally applicable, since it depends not just on pile dimensions but also on soil stiffness.

Terzaghi's definition identifies the total bearing capacity as the load corresponding to the value at which the curve changes to a vertical tangent on the load-settlement plot. This definition is readily understood and can be used to derive other definitions if required. Mathematically it accurately defines ultimate load as the asymptote of the load-settlement curve.

Once a pile is installed, its mechanical behaviour under load is unique and most pile testing techniques wish to reveal this specific behaviour in the most cost effective manner, either by measurement of the pile movement under applied load or by measurement of some associated properties that may be correlated or interpreted in such a manner that pile performance may be inferred.

It is to be expected that any results

obtained from a pile test are pertinent to the conditions prevailing when the test was performed and that any subsequent variation of the mechanical properties of the pile or of the soils may not be detected.

In the quest to determine the unique pile behaviour it is necessary that the result be independent of the type of test employed and this is where the complications start. Until recently, only a few heavily instrumented, long duration, static load pile tests revealed something close to the unique pile behaviour, and therefore validation of the various alternative testing techniques has not been feasible.

If a static incremental load pile test is employed, considered to be the most comprehensive pile test, careful post analysis of the pile head movement is necessary to ensure that the result is independent of the test load sequence.

A method of analysis has been developed which allows both the test sequence and the test duration to be addressed. The

final pile settlement at a given load will be that at infinite time. This is the settlement of interest as it is representative of the long term working conditions of the pile. Since it would be unreasonable to maintain loads so long, an accurate method has been developed which allows extrapolation from the recorded data, to determine the asymptote of the displacement time relationship for each load and will be referred to as settlement at the load applied.

The algorithm employed in this method (TIMESET), accurately characterises both the base and shaft time elements and, in the first instance, allows analysis of load displacement data to be done to time independent data points

The example in Figure 1, illustrates a relative TIMESET modelling of the displacement of a pile under constant vertical load, to determine the pile settlement at the given load. This will be the sum of scale offsets plus  $W_s$  &  $W_b$ , which describe the asymptotic values of the two functions.

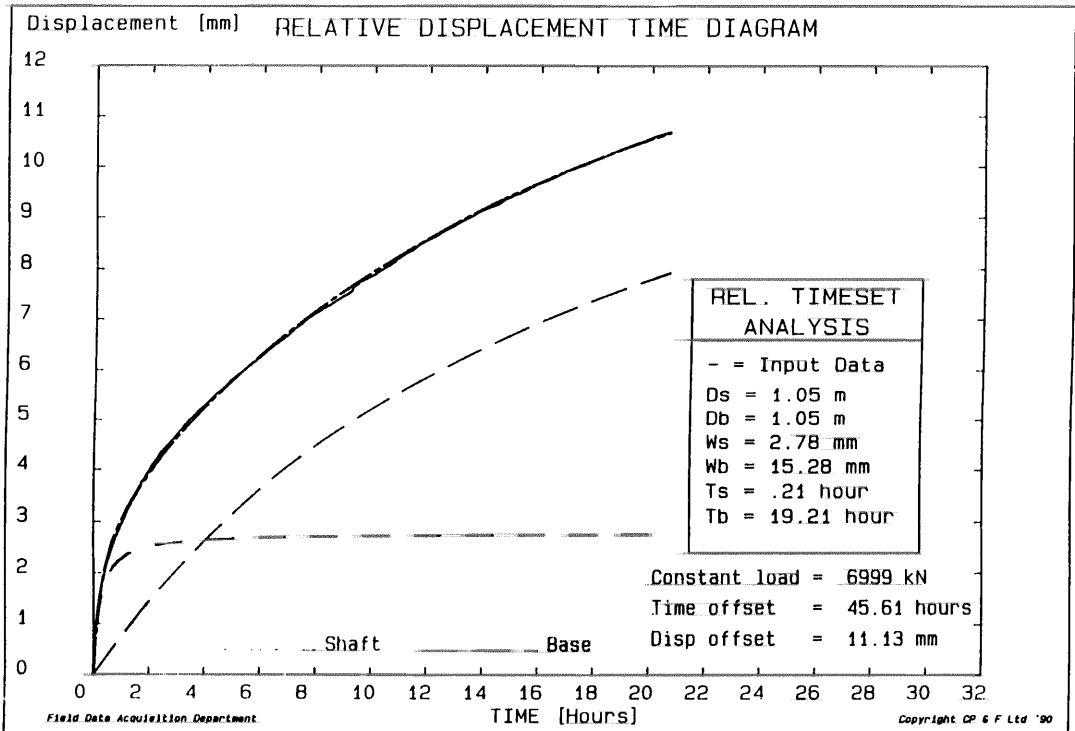


Figure 1

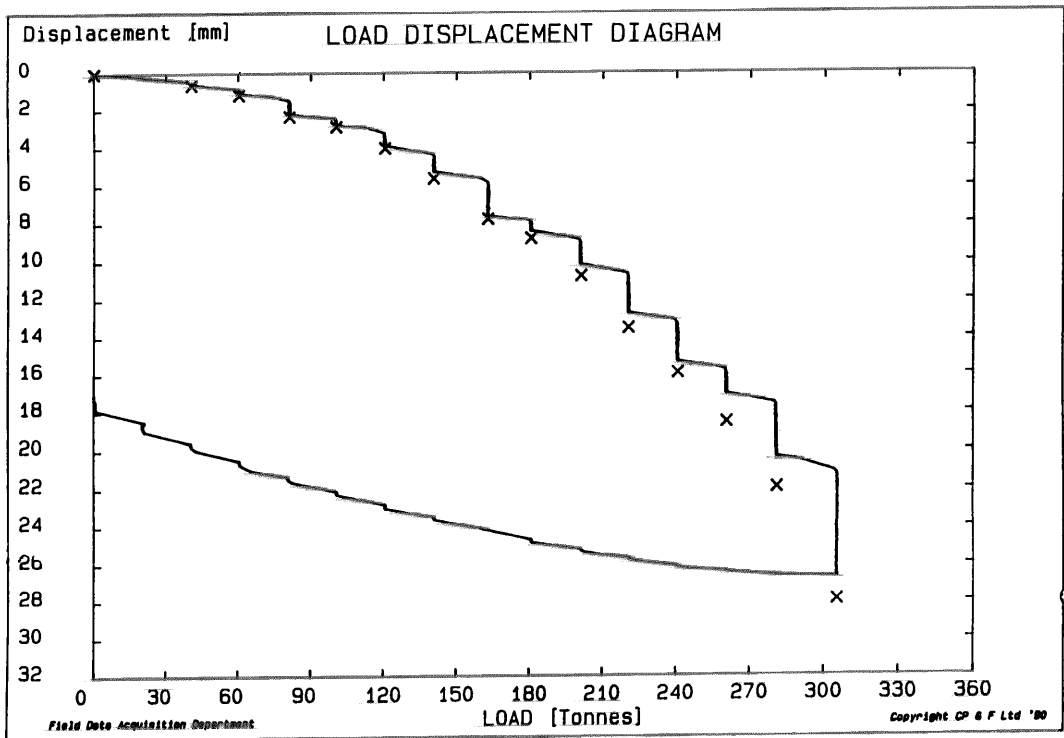


Figure 2

Figure 2 illustrates the load settlement points determined by TIMESET, indicated by an "x", and superimposed upon a conventional load-displacement diagram from which the settlements were calculated.

The analysis of load-settlement behaviour can now progress using the ultimate pile settlement for each load. A method of analysis has been developed specifically, CEMSOLVE, which allows the base and shaft settlement characteristics to be distinguished, together with the pertinent parameters associated with each of these. So powerful is this method of analysis of pile settlement under load that it is also used for pile design (CEMSET) (Reference 1).

The back analysis system is based on optimisation of the hyperbolic functions which characterise individually the shaft and base performance and on determining the most effective elastic shortening model which replicates the pile settlement determined for each load.

An example of unique pile behaviour is included as Figure 3, in which the settlements from Figure 2 have been

analysed using the CEMSOLVE technique.

When these hyperbolic functions are combined and the elastic shortening is added, an extraordinarily accurate model is produced. No pile/soil combination has yet been found in over 400 cases examined which fails to comply with the model.

The most significant aspect of this modelling technique is that all the fundamental components that contribute to the overall pile behaviour can be identified, provided that the pile has been made to move sufficiently and the base characteristics are revealed.

### 3 TIME DEPENDENCY OF THE PILE BEHAVIOUR

It is evident that the changing displacement, with respect to time, of the pile head under maintained load is due principally to changing properties of the soils that surround the pile. This can be attributed to the dissipation of excess pore water pressure that resulted from a change of load applied to the pile.

The computer program TIMESET models the measured pile head movement under constant

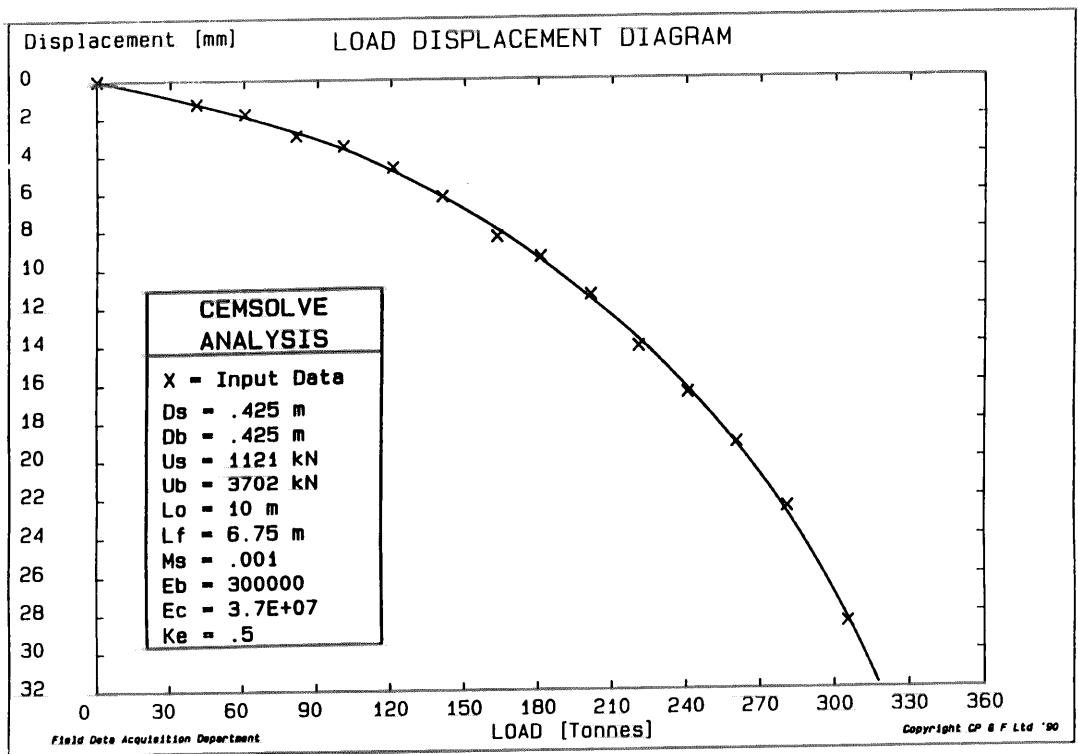


Figure 3

load against time from the moment the initial elastic shortening takes place to time equals infinity. This is accomplished by representing the shaft and base behaviour as hyperbolic functions and the elastic shortening, for simplicity, as a constant.

The example included in Figure 4 is based on measured pile head displacement from  $t=0.3101$  to 24 hours, at a load of 4242 kN on a 27 m, 750 mm diameter pile in clay. The modelled behaviour is barely distinguishable from the measured data.

The accuracy with which measured data can be modelled with the TIMESET algorithm is so good in every one of a large number of cases and in a wide range of soils that data and model may reasonably be described as identical. Approximately 2500 constant load applications have been reviewed and the excellent modelling of TIMESET is repeated every time.

The TIMESET and CEMSOLVE methods may be used in conjunction to solve any particular pile test result with good accuracy provided high grade test results are available. Indeed the problem may be regarded as a three dimensional

representation of single pile behaviour, the dimensions being Time, Load and Settlement.

Figure 5 illustrates an example in which the unique behaviour of a pile has been determined using the CEMSOLVE analysis method based on ultimate settlements determined for each load. The estimated elastic shortening and displacement of the pile head in time have been modelled using TIMESET. Although the patterns are theoretical, they illustrate the pile displacement that would have occurred at each time interval if the load was instantaneously applied without any previous load. The revealing aspect of this example is that as time approaches zero, the predicted pile behaviour gets closer and closer to the elastic shortening. At  $t=0.01$  hour they are indistinguishable.

If a constant vertical load were applied to a pile head instantaneously, complete elastic shortening will be dependent on the time for the stress wave front to travel the full length of the pile and any wave reflections dissipated. The elastic shortening for a given applied

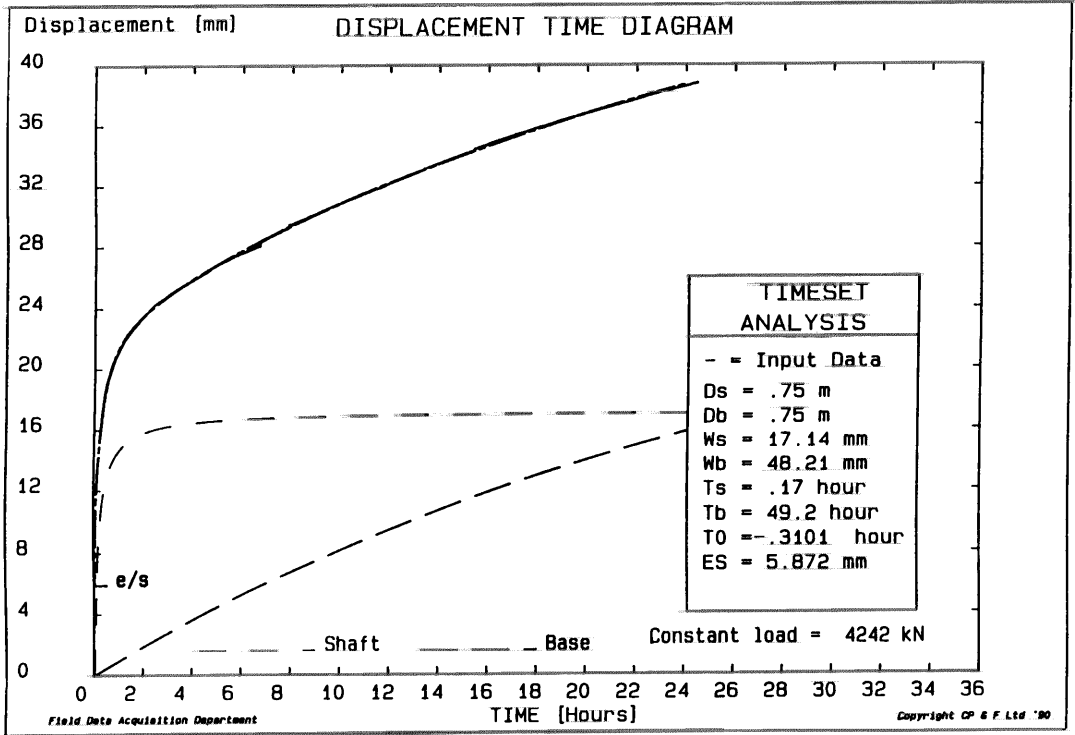


Figure 4

load can be assumed to be relatively constant thereafter. This forms the basis of the TIMESET model which reveals that only a small fraction of the shaft response, and even less of the base response can be detected within the first seconds of application of load to a typical pile.

Considering the test durations of QML (Quick Maintained Load) tests and CRP (Constant Rate of Penetration) tests and observing the TIMESET predicted settlement at say around 1 hour, it can be seen from Figure 5 that the resultant theoretical pile behaviour may still be far removed from its unique characteristic and therefore that these rapid tests need interpretation to ensure that the pore water pressure dissipation and any other time dependent characteristic are taken into account. Otherwise the pile performance and its capacity will be overestimated and this means that pile settlement for a given load will be underestimated. In practice this is readily confirmed as such short duration tests reveal even less pile displacement than that predicted by this theoretical model. (Reference 2).

#### 4 DYNAMIC PILE BEHAVIOUR

A dynamic pile test may conveniently be defined as one in which only temporary elastic shortening takes place and full, elastic shortening of the length of the pile does not occur. By virtue of this definition, such a test must rely on stress wave propagation and the measurement of subsequent reflections resulting from a single blow. This aside, if such a short duration test can reveal any of the time-settlement behaviour, it can only be a very small part. In essence it appears that only some undrained or partially drained failure mechanism allows permanent pile movement.

It is therefore apparent that any pile test that uses the pile 'set' caused by a high energy impact or series of impacts cannot allow the increased pore water pressure, resulting from any blow, to drain and therefore cannot predict either settlement or the relevant drained soil parameters that will determine the pile capacity.

If the resultant stress waves from a single blow are analysed, the interaction

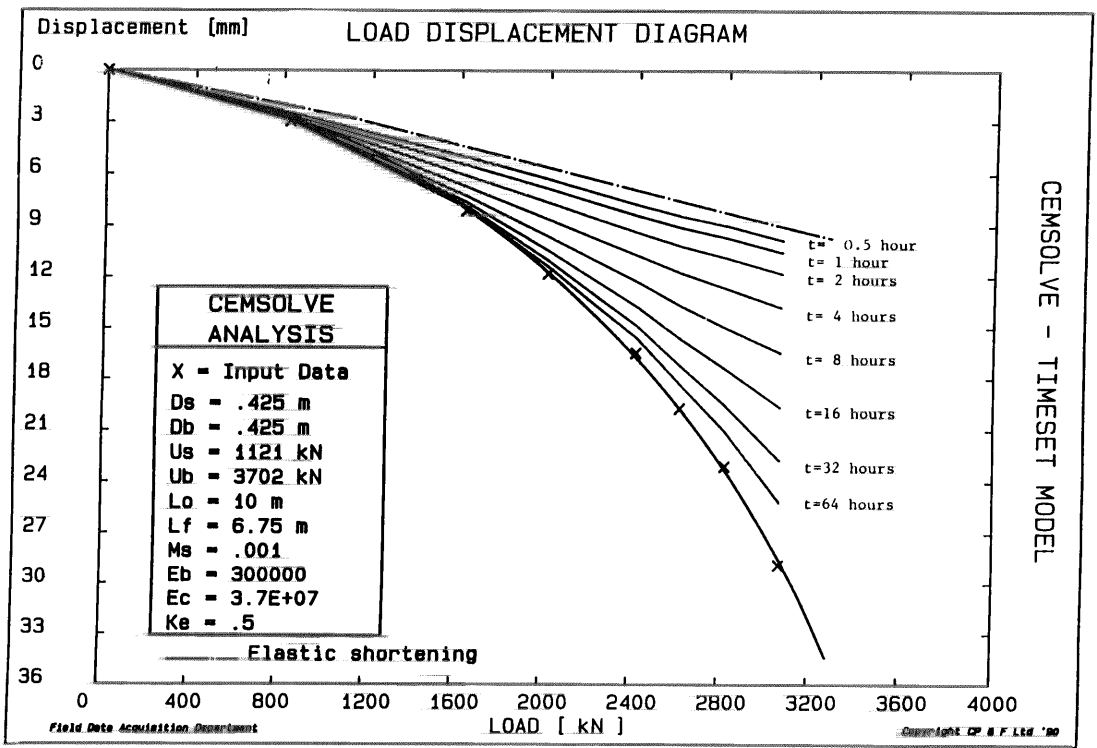


Figure 5

between the pile and surrounding soils can be revealed to the depth of penetration of the test.

Some techniques of dynamic testing claim to reveal soil stiffnesses, it is perhaps a worthy reminder that what can be identified is a parameter associated with the dynamic test and not the drained soil stiffness. The author advocates that what is revealed with such a test can be defined as the non-linear acoustic properties of the pile/soil system, which could only fortuitously resemble the soil stiffnesses revealed with a conventional load test. It is also invalid to believe that any component of the "non-linear acoustic properties" can be equated to the pore water pressure difference between dynamic and static soil behaviour, as the final drained soil characteristics remain unknown in a dynamic test.

Dynamic test results are often presented in the form of load displacement diagrams which have been composed by adding a portion of the calculated dynamic parameters to a supposed elastic shortening calculated from assumed pile/soil properties. It is therefore no

surprise that load displacement results from dynamic and static tests can appear to be very similar for test loads well within the pile capacity.

At impulse loads close to the ultimate load, a dynamic test is unlikely to even indicate that this condition has been reached. If the load is of sufficient magnitude to cause permanent displacement of the pile it is worth reiterating that the dynamic soil failure mechanism is significantly different to a static failure mechanism due to the excess pore water pressure and it is therefore important to consider any previous loads applied. This implies that the dynamic testing schedule will be significant in any method that tries to estimate the ratio of dynamic and static capacity.

As a consequence of this, it is found to be imperative that the validity of the correlation between results from a dynamic test and a static test are always addressed. This means that detailed knowledge of the soils surrounding the pile is fundamental to any assessment of dynamic test results, a practice that is forgotten all too often.

It should be noted that fore-knowledge of the soils alone can be insufficient because pile installation disturbs the ground and different piling techniques can significantly affect the behaviour of the surrounding soils.

With current technology and techniques, the means for correlating dynamic and static test results either in overall performance or split into individual shaft and base components is becoming clearer but is far more complex than would otherwise appear.

As the correlation data are accumulated the effectiveness of dynamic testing may be better understood. Until then the author believes that the dynamic testing technique is appropriate as a cost effective substitute for proof load testing provided evidence of static behaviour for that length and type of pile in the same soils is available. It is also apparent that using a dynamic test to determine an accurate value of static load capacity is too optimistic regardless of pile failure definition chosen.

## 5 CONCLUSIONS

While an engineer is at liberty to specify the type of test he wishes, to a large extent the accuracy of the results he receives, in terms of pile behaviour, are a direct function of cost. A well specified, correctly performed, static test with good back analysis remains the most complete and tangible assessment of pile behaviour.

Hyperbolic functions model pile behaviour with respect to time and load with remarkable accuracy. The merits of using a hyperbolic function to model the dynamic parameters in the stress wave analysis programs is yet to be discovered. It would be no surprise to find that the hyperbolic model was appropriate.

The lack of consistent correlation between static load tests and dynamic tests to determine pile capacity does not seem so much to be a function of adding more coefficients to the computer program as of investigating and understanding the behaviour of the soil surrounding the pile. It is therefore considered necessary that dynamic pile behaviour must be correlated with static test results for practically every specific site and pile type application. This calibration of dynamic tests is still essential to ensure reliable interpretation of test results.

## REFERENCES

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- 2) Burland J.B. and Twine, D (1988) "The shaft friction of bored piles in terms of effective strength", Deep Foundations on Bored and Auger Piles, A.A., Balkema.