

A method of analysis of stress induced displacement in soils with respect to time

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ABSTRACT: A fundamental parameter associated with the behaviour of soils under load, often neglected, is time. The overwhelming evidence now accumulated indicates clearly that this parameter, although widely recognised in consolidation theory, can be as significant to the behaviour of foundations in all soils, as the ultimate soil strength and the soil stiffness.

The analysis and prediction of single pile displacement behaviour is considered and it is demonstrated that, provided the applied load is maintained at a truly constant value, hyperbolic functions may be used to characterise the individual constituents of the time related behaviour.

Extensive use of this technique has confirmed its validity in a variety of soils to the extent that theories currently available for consolidation settlement and creep may be reviewed in the light of this simple behavioural characteristic.

The algorithms employed are suitable for modelling the displacement behaviour from the onset of load to infinite time for all types of piles and surface foundations. Understanding the soil deformation within a proper time framework allows the subject of pile instrumentation and testing to be further developed and extended.

1 INTRODUCTION

Until recently, analysis of the soil displacement-time characteristic under load has been hindered by the quality of the data recorded and the accuracy with which the load has been held constant. This has hitherto impeded the development of suitable behavioural models.

Some theoreticians postulate that it will always be necessary to bury hydrostatic sensing devices in the ground surrounding a pile or that undisturbed soil samples are removed for laboratory analysis, before pore water pressure dissipation or creep may be properly considered. For foundation problems in particular, the ideal scenario under which to test the soil for these parameters is in situ. Although the soil properties are often difficult to identify separately, their effect on foundations can now be recorded with great accuracy. The technique described has been developed specifically for pile load tests, but

other types of foundations exhibit the same fundamental behaviour.

Computer controlled static load test systems such as those developed by Cementation Piling & Foundations, record displacement of the pile head and the axial load applied with electronic sensors. The system also provides for hydraulic control of the jack or jacks to maintain the load applied within very tight preset limits. The load applied is checked every few seconds and any corrections required are carried out automatically, thereby allowing the basic time behavioural characteristics for a given load to be revealed.

It has previously been realised that the behaviour under load and in time of single stress elements can be modelled accurately using hyperbolic functions. The specific case of modelling pile behaviour is similar, but there are two very separate characteristics to consider, one is related to the shaft behaviour and

the other to the base behaviour. For the complete modelling of the pile response it is only necessary to take into account these two separate hyperbolic functions and the elastic shortening of the pile under load.

The behaviour of a pile under load has been accurately characterised with the CEMSET algorithms⁽¹⁾, in which two hyperbolic functions characterise the stress-strain behaviour of the shaft and the base separately.

The analysis of pile displacement in time, under constant load, is a significant improvement to pile behaviour analysis and prediction and becomes an essential component of any load behavioural analysis. It is found that once the underlying pile behaviour is recognised, both the quality of the measuring system can readily be reviewed and improved, and the interpretation of the pile response is enhanced. The current state of development of the relative displacement-time model is described here.

2. DEVELOPMENT OF THE MODEL FOR PILES

The initial requirement was to establish a universal mathematical model that would give a consistent means of analysis of static load test results. It was considered necessary to remove the deformation dependency on the duration of the application of the load, particularly since different loads are often held for different periods. Also, it was necessary to establish and take into account the effect of lower previously applied loads as these influence the pile displacement behaviour in time.

The rate of change of displacement of the pile head, when subjected to a constant load, is generally decreasing in time and it is therefore to be expected that at some time this will approach zero. This is the final settlement that we wish to determine, as it is representative of the long term working conditions of most piles.

Some authors⁽²⁾ choose a "practical" lower limit for this "zero rate of change" as 0.25 mm/hour or some other arbitrary value, but this kind of definition bears no relationship to either the size of the element under test nor the final settlement that may be achieved. Therefore this approach does not assist in

the understanding of the basic time dependency of consolidation or creep and any direct assessment of the pile behaviour under load from the recorded load test results will generally show an enhanced pile performance.

If static load pile test results are to be analysed consistently and accurately, this time element needs to be addressed. The final pile settlement at a given load is required and has been defined as the displacement achieved at infinite time, and it is the asymptote of the displacement time characteristic. The method developed allows the extrapolation from accurately recorded pile head displacement under constant load to infinite time and to zero time, equivalent to the instant the load would have been applied in full.

In the early days of analysis of computer controlled pile load test results, and in the absence of any better techniques, Chin's method⁽³⁾ was employed. This suggests that a single hyperbola may be used to characterise the pile behaviour and can be made to fit the data. However, it is found that the early part of the behaviour appears to depart from such a model and only after several hours, for a pile of average size, does the behaviour approximate to a hyperbolic function.

It is clear that this shortcoming, often encountered with the Chin method of plotting time/displacement vs time, and determining the slope, is that only one characteristic is being determined, either that of the base or that of the shaft and only when one of these becomes constant or is insignificant, does the single hyperbolic model fit⁽⁴⁾. It is very evident that in reality two separate functions exist and that the slope of the time/displacement plots is an inappropriate method for distinguishing them.

Evidence of this problem with modelling displacement-time behaviour with a single hyperbola is found in several references which generally remark that the settlement behaviour approaches a hyperbolic function after some time⁽⁵⁾. While this is a valid statement, it is often the situation that two components dominate the displacement behaviour in time and when two hyperbolic functions are employed the behaviour can be modelled with remarkable accuracy. In the particular case of piles these two components are expected and are present in

most practical cases.

If two separate functions are used to model the measured pile behaviour, this double hyperbolic solution is seen to be capable of matching measured results with high accuracy for any pile shape or size in practically any soil conditions, where piles are likely to be used.

3. FUNDAMENTAL TIME CHARACTERISTICS

The dissipation of excess pore water pressure as a function of time is the fundamental basis of Terzaghi's theory for one dimensional consolidation⁽⁶⁾. It is sometimes said to be simplified⁽⁷⁾ in terms of assuming that permeability and compressibility remain constant and attempts to modify the classical theory have often been made to take account of these simplifications. In any event, it is possible to show that a single hyperbolic solution may be derived from the fundamental equations⁽⁸⁾⁽⁹⁾.

Consolidation in most cases involves the diffusion of water through the soil matrix; however, it also appears to involve the redistribution and spreading of stresses between particles in the founding strata. This causes particle deformation and, if the soil is saturated, also has the appearance of pore water pressure dissipation. Recent test in clay indicated that this hydrostatic excess continues to be dissipated even one year after the surcharge load is applied.

This effect is considered by some authors to be secondary to the fundamental consolidation principals. It is however known that consolidation extends beyond the simple dissipation of pore pressure and also involves structural changes within the soil of considerable importance. This is frequently referred to as "creep", whether the material possesses pore water or not. It is a time dependent effect which becomes particularly evident and of great significance at high stress levels. In saturated soils it is found that no marked transition is detectable in the displacement/time profile induced by constant total stress, and therefore the "creep" and "consolidation" are likely to be one and the same effect. In general, the phenomenon observed in foundation behaviour, should perhaps only be called creep.

It is often perceived that creep is a

continuing process in time with no definite end, this would be consistent with the evidence we have accumulated; although perhaps it should be qualified; while creep may continue to infinite time, its effect is diminishing and tending towards some ultimate condition.

If pile behaviour is considered, under constant axial load, it would be reasonable to expect its response in time to be a result of first mobilising the skin friction and subsequently the base reaction. The loading of the base is generally subject to the time taken for the inflated capacity of the shaft to shed this excess capacity; therefore the load applied to the base will follow the same time characteristics as the shaft mobilisation; and consequently, to distinguish the fundamental base behaviour this shaft time effect also needs to be taken into consideration. This effect is apparent in pile load tests in which elastic shortening has been carefully monitored.

As might be expected, the conditions surrounding a pile prior to the application of a new load are all significant and it is found necessary to evaluate the pertinent parameters independently of previous lower loads. In order to do this it is necessary to extrapolate back to zero time-dependent displacement (elastic shortening in the friction free length of pile⁽¹⁾ is considered immediate) and zero time for instantaneous application of the full load. This adds some degree of complexity to the total model but the remarkable feature is that the double hyperbolic model can still be used with superb accuracy. This model is based on the hypothesis that there is no instantaneous elastic strain other than in the friction free pile length.

In order to attribute time constants to the soil surrounding the pile, the geometry needs to be taken into consideration, and results need to be normalised to reveal independence of load applied or total displacement obtained. Development along these lines is continuing and a data base of time constants for different soils is being accumulated.

This paper does not intend to address the fundamental consolidation or creep behaviour in terms of soil parameters surrounding the shaft and under the base.

The complexities detailed above inhibit complete description here. The objective is to highlight an accurate technique for modelling the relative displacement behaviour in a simple way. From this, realistic time constants are obtained directly for design predictions and analysis of the asymptotic values.

A computer assisted analysis program (TIMESET) has been developed specifically for piles. The half final strain time $[T_{50}]$ has been used to define the time lapsed until 50% of the movement due to friction or end bearing has occurred and a simple hyperbolic function is used to characterise each element of the pile behaviour. Only these time constants and the asymptotic values need to be determined to allow the complete behaviour under constant load to be modelled.

4. BEHAVIOUR OF PILES IN TIME

It is significant to note the simple form of the model employed to characterise the relative displacement:

$$\Delta_s = \frac{W_s t}{T_s + t} + \frac{W_b t}{T_b + t} \quad (1)$$

where t is the time elapsed from the application of load, W_s and W_b are asymptotic values for the shaft and base mobilisation respectively and T_s and T_b the half strain times.

The shaft component, because of its minimal volumetric change, invariably takes effect significantly faster than that of the base and therefore, provided the pile head displacement is recorded for sufficient time, the two functions can be separated uniquely.

It is also interesting to note that the modelling of the relative displacement recorded under constant load shows some variations of the time constants, particularly for the shaft. This is to be expected, as the events prior to the behaviour observed is of great significance, e.g. what was the previous load and its duration and how fast was the new load applied. These are very significant aspects to be considered if rupture of skin friction is to be avoided. However, for the base it is found that, provided the ultimate capacity of the shaft has been exceeded, the normalised half strain value time t_b remains relatively constant and only the

asymptotic value W_b changes from load to load.

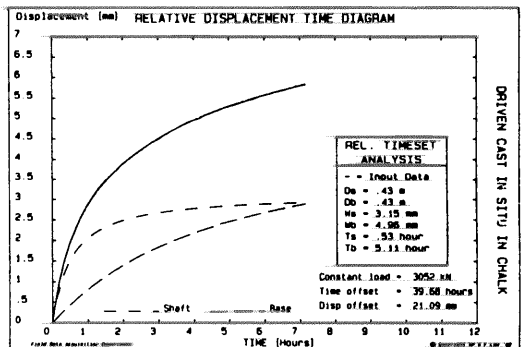
This relative TIMESET model is intended to allow rapid identification of the governing time parameters to allow extrapolation to determine the asymptotic value. It does this with remarkable accuracy on all occasions, provided the fundamental characteristics of the soil do not change during the test. To date over 10000 constant loads have been applied and analysed this way with unambiguous success.

The relative distribution of the behaviour in time between shaft and base is predominantly determined by the time taken to effect reactions from the shaft and the base as a result of the load applied. While in general it is found that different soil layers may surround the pile, in practice the founding strata at the base will normally dominate the behaviour. A secondary effect is the time for the full elastic shortening of the pile to develop. The normalised time constants for this effect are the same as those for the skin friction and therefore need not be identified separately. Fortunately, these simplifications are valid in all cases studied.

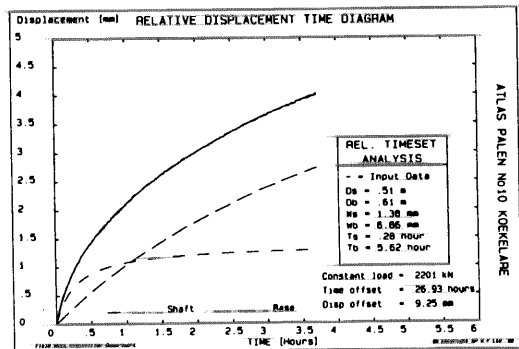
5. APPLICATION OF THE METHOD (TIMESET)

As indicated above, the technique has been specifically developed for pile behaviour analysis under constant load. Some examples are included below to indicate that it is generally applicable and not associated with certain soil types. The examples show how accurately the model tracks field data, even for small displacements, and shows the resulting time constants calculated to be the best fit for the model.

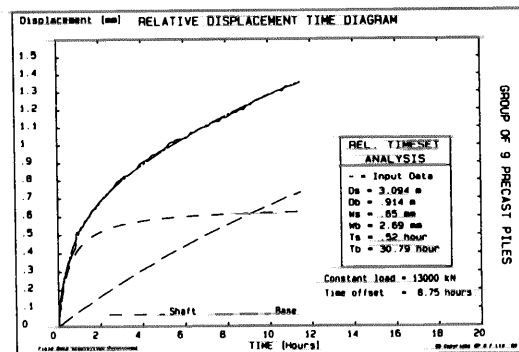
EXAMPLE 1: CHALK.- Driven cast in situ pile of 17 m. length founding in Chalk.



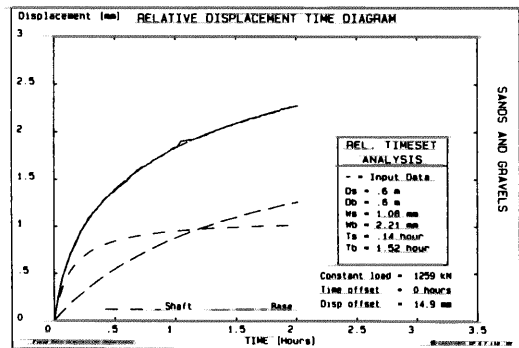
EXAMPLE 2: CLAY.- Atlas pile; tested at Atlas Palen, Koekelare, Belgium. Approximate pile length is 13 m, with an estimated pile diameter of 0.51 m. and tip diameter of 0.61 m. The founding stratum is generally clay. This is, perhaps, one of the more complex pile types to analyse: however it displays the characteristic behaviour in time.



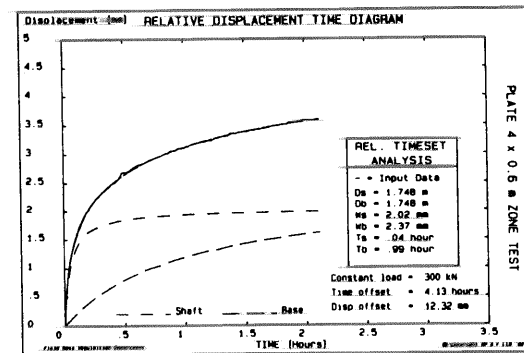
EXAMPLE 4: PILE GROUP.- This is an interesting application where a pile cap was load tested to 13000 kN total. The cap is 4.5 m square and resting on nine 270 mm square 27 to 29 metre length precast piles, founded in clay.



EXAMPLE 3: SAND AND GRAVEL.- Driven cast in situ pile 10 meters in length, founded in medium dense fine to coarse sand with coarse subrounded gravel and occasional cobbles. Soils above the founding level are similar but of lower density and stiffness. Water table at approximately 3 meters below ground.



EXAMPLE 5: ZONE TEST ON STONE COLUMNS.- Applications of this form of analysis are not limited to single piles. This particular test was to verify the performance improvement of soft ground in which stone columns has been installed. A plate size of 4 x 0.6 m covered two stone columns in clay bound fill on stiff clay. The apparent base and shaft components are probably due to bearing of the plate on the surface and a friction component mobilised by the column head as it suffers downward displacement.



In these examples of pile behaviour the shaft and base are appropriately distinguished by the separate individual hyperbolic functions, regardless of the time taken and events before the load has achieve its constant value. When these functions are added together on the vertical scale they can be made to replicate the measured behaviour.

As can be concluded from the above examples, these time elements are important factors in the behaviour of cohesive soils, and also non-cohesive materials. The time constants derived from optimising the model to the field data can then be used to make accurate forecasts of pile performance at times outside the range of the field results.

6 CONCLUSIONS

The accuracy with which pile displacement under constant load can be modelled is remarkable and excellent for all piles in a great number of different soil types.

Extrapolation to infinite time is performed with the high accuracy essential for any sensible assessment of foundation load displacement analysis of static load test results.

The accuracy of the modelled behaviour is so good, when using computer controlled test equipment, that unduly protracted, long duration hold periods in a static load test specifications become unnecessary.

Pile defects such as cracks can easily be identified within the time relationship because the pile displacement, before closure of the crack, is governed by just the characteristic of the shaft above the relevant level.

In order to make best use of the technique for back analysis of static load test results, it is necessary that the constancy of the load is very good and that the displacement data recorded are of high quality.

The method has proved very rewarding in regard to improvement in testing practice as temperature and stability effects of reference datum system and measurement equipment can be readily distinguished from genuine pile behaviour.

The analysis on absolute scales is complicated only by the need to take account of the elastic shortening. The time constants for the founding materials around the shaft and under the base are revealed. This can aid identification of the soil surrounding a pile.

The behavioural analysis for a single immediate application of load illustrates that significant characteristics of the pile soil system are not revealed accurately in rapid pile load testing techniques. Even constant rate of penetration tests can overestimate the pile capacity because the time effects are not allowed for in full. Dynamic pile tests do not determine any of these time effects: therefore any prediction of long term static behaviour from the measured dynamic response in soil is not possible.

The time effects appear to be related to creep, or in the special case of saturated soils, consolidation and these are indistinguishable. The time related behaviour can be seen in all types of soil where pile displacement can be made to occur under load. It may therefore prove to be a very valuable and revealing tool, illustrating how the structure of soils behaves.

This method of analysis in time, together with the settlement analysis under load (CEMSET), provide the complete tools for back analysis of static load test results to determine the single unique pile behaviour.

The time effects would also have significance on any laboratory soil sample testing, for example drained triaxial tests. It has been reported by several authors that the strain rate effects are generally apparent in a wide range of soils, as the findings also show.

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