Review of foundation testing methods and procedures

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This Paper reviews some of the shortcomings of foundation load testing procedures, considers what would constitute an ideal test, and comments on recent developments in static load testing which increase the technical value. It is concluded that the standard maintained load test, as covered by the Institution of Civil Engineers' *Specification for piling* still represents the best available method, but that it would benefit from some minor amendment. This would specifically require defined constancy of load at each load stage and would permit better interpretation of results. An available model for analysis is discussed.

Introduction

Testing is an important part of the foundation installation process and has been so for a great many years, mainly because of uncertainties in soil parameter measurement and design models. In addition, the ground conditions may vary across a site and the extent of site investigation may be limited. Testing can therefore be a means of confirming the ground conditions and of proving that the design parameters, installation method and technique are appropriate to the prevailing conditions. It serves also to check that any subsequent events are not detrimental to required performance.

2. Although a considerable amount of test data have been recorded in the past, complete analysis has usually been difficult because, in general, the conditions of recording impeded such analysis. Recent developments in static load testing techniques allow better analysis and behavioural models are now available to characterize foundation behaviour both in time and under load in a manner independent of the testing programme.

3. These developments indicate shortcomings in all foundation testing techniques and a need for a method of analysis that provides consistency and accuracy, allowing interpretation of the results to be independent of the method of testing. They also serve as a reminder that the limitations of each testing process should be considered carefully to ensure that misleading interpretations are avoided.

The ideal foundation test

4. When evaluation of foundation performance is required, a large variety of tests of differing types are offered by the industry, and for each type of test the conditions under which the test may be performed can produce significantly differing results. It is therefore important to ensure that the type of test and specification selected are appropriate to the results required.

5. Foundations are generally called upon to carry axial static loads for a long time. In the civil engineering context, during most construction the loads applied to the foundation system gradually increase as work progresses and result in some final, near-constant load being applied upon completion. The best foundation test that could be employed would be one which replicated these conditions as closely as possible. However, for practical reasons it is desirable to carry out tests expeditiously, ensuring that any external influences are minimized, so construction can progress with the minimum of interruption and delay. A compromise has to be found, with the result that the duration of the load application is necessarily curtailed.

Available pile test methods

6. A variety of test methods are to be found in the industry, ranging from full-scale static tests, with application of load and monitoring of pile deformation, to the measurement of associated properties of the pile–soil system, as for example in low-strain integrity tests. The list includes static maintained load tests, load/settlement equilibrium tests (in which a pile is made to settle by stages and allowed to reach an equilibrium load at each before moving on to another settlement value), quick maintained-load tests, continuous rate of penetration tests (CRP), 'statnamic' and pseudo-static tests, dynamic tests (in which a pile is struck by a falling hammer), and integrity tests (which basically use wave propagation and acoustic impedance measurement techniques to look only at structural continuity and implied section variation).

7. Costs in general move downwards through the list, with the highest costs being applicable to large-scale fully-instrumented static pile tests which may cost tens of thousands of pounds, while the simplest integrity tests may cost less than £10.

8. In view of the range of methods and the specific knowledge of different engineers, some may prefer one method to another and, amid conflicting claims, there is often a genuine difficulty in making test programme choices from

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combinations of the various techniques. Sound engineering judgement is required to make a sensible and justifiable choice of tests for a particular site.

9. All testing is aimed at finding out whether installed piles will perform according to expectation and the engineer's task in regard to testing has not been completed until the decision has been made as to how many tests of a particular type are sufficient to show that all is well. The engineer even has the option not to do any testing, but in this case other steps must be taken by way of complete pile installation records and enhanced factors of safety or other redundancy features, to ensure that such a decision is justifiable.

10. Many engineers believe that, in general, pile load-bearing behaviour is absolute and not a function of the test specification applied: this is not correct because test results will be determined by the procedure selected. The true, long-term, pile behavioural characteristic is unique at the time of the test, and this is what pile tests generally should aim to reveal, although often they do not succeed.

Current practices

11. The most visible and tangible proof of pile performance is provided by full-scale load tests. In the United Kingdom, the most common test is the static 'maintained load' test and, indeed, it has not only traditional practice to support it, but is capable of wide application, save in a few specifically restricted cases such as offshore work. It also has scope for extension of its usefulness.

12. In the quest for a rapid substitute for the static load test, a modification was developed as the continuous rate of penetration test.[1] However, it has some disadvantages in practice, which at the very least need consideration at the interpretation stage. It has been shown by Whitaker and Cooke,[2] Burland and Twine,[3] Patel,[4] and others that the effect of the rate of penetration (normally approximately 1 mm/min) is to enhance pile shaft capacities in clay soils, but the same is also probable with regard to friction in a wider range of soils and also to base capacities. The enhancement effect can be reduced by decreasing the rate of penetration to less than around 1 mm/h, thus allowing longer for the dissipation of pore water pressure to take place.

13. Possible enhancement of base resistance has not been commented upon much in the literature, partly because there is some confusion over definitions of failure but, particularly in clay soils where pore water pressures are unable to dissipate rapidly, the results are undoubtedly affected if it is long-term pile performance which is of interest. CRP tests show us little about deformations at specified service loads.

14. All rapid pile testing methods and, in an extreme case, dynamic methods, suffer from similar but rather greater problems in trying to relate true static and enhanced resistances. Depending on the use an engineer wishes to make of them, frequently there is a need for some static correlation testing. Of course, such tests may simply aim at approximate installation control, in which case they are probably theoretically superior to traditional dynamic formulae in most cases. However, it should always be remembered that if a pile cannot be moved far enough into the ground under any type of loading, then its ultimate load cannot be determined—only the maximum mobilized load can be found.

15. The traditional static load test still remains the most informative and reliable pile testing method. It has much to commend it and, with careful, accurate measurement and load control, it can contribute greatly to the understanding of pile behaviour, even to the extent of revealing the important soil properties governing foundation settlement.

Refinement of specifications for static maintained load tests

16. Although several engineering practices have their own individual specifications for maintained load tests, the most commonly applied procedure in the UK is presently that recommended by the Institution of Civil Engineers' (ICE) specification.[5] This calls for the load to be applied in stages of 0·25 × the design verification load (DVL, see ref. 5, clause 10.3), and commonly is geared to proof load tests to 1 × DVL + 50% of the specified working load (see ref. 5, clause 10.3), although there is provision for it to be extended to higher loads when appropriate. The loading stages are variable in duration and the requirements are clearly stated. The Authors have developed an improved system and consider the ICE's specification now to be capable of further development, with minor modification as follows.

Load control

17. Loads are required to be held constant. This is a problem if manual load control is exercised, largely because the reason for this requirement is often not understood. Observation clearly shows that accuracy is not regarded as being very important and that operatives do not restore loads with sufficient regularity. Loads can now be measured and controlled within very fine limits and the equipment used by, for example, the Authors' company, checks and restores load every few seconds automatically. This means that displacement–time relationships can be defined with very high accuracy and the behaviour can be modelled so

that extrapolation of settlement to infinite time is readily possible. In doing this the results become consistent at all load stages, with the settlement being independent of the test duration. These projected settlement results represent 'fully drained' conditions.

Settlement recording

18. Conventional measurement of displacement of the pile head is by dial gauges which are read and the results written down on site. Results are not easily checked for error and finally have to be transferred manually to a report. The problem of potential errors can be solved using electronic displacement transducers, allowing all the data to be logged and stored digitally for computer processing. This obviates the need for double handling of the data, ensures readings are taken when required, and minimizes the chances of error. All plotting of resulting displacement can be carried out on screen in a cabin on the site, so any untoward events become evident at the time. The computer can also be instructed to reduce the applied load at any time for safety reasons if a very large deviation occurs, and to give immediate warning of the anomalous condition (Fig. 1).

Fully drained test results

19. Specifications for the execution of a maintained load test have traditionally involved a programme of load application which employs differing periods of load holding as the test proceeds and often include a cycle of unloading and reloading at the stage when the design verification load is applied. Load holding at each stage is specified either by given time periods, settlement rates or a combination of these requirements.

20. The problem with specified time periods is that, at lower loads, the pile movement rapidly approaches a stable state, whereas at higher loads, when the shaft friction has been fully, or almost fully mobilized and load is being transferred mainly at the pile base, the time required to reach the settlement rate becomes more protracted. The period of observation is often curtailed at this stage simply for practical and cost reasons. It is very difficult from short test durations to define the final settlement and therefore what the fully drained ultimate capacity of a pile is. As the ultimate load is approached, it becomes more difficult to interpret without accurate computer modelling of the displacement–time characteristic and settlement–load behaviour.

21. Justification for the use of computerized systems is easy because errors can be minimized, engineering attendance may be diminished and reports can readily be produced, thereby providing a more cost-effective and safer test. However, care must be taken to ensure the data storage system is secure in the event of power supply failure and that transducers are suitably calibrated.

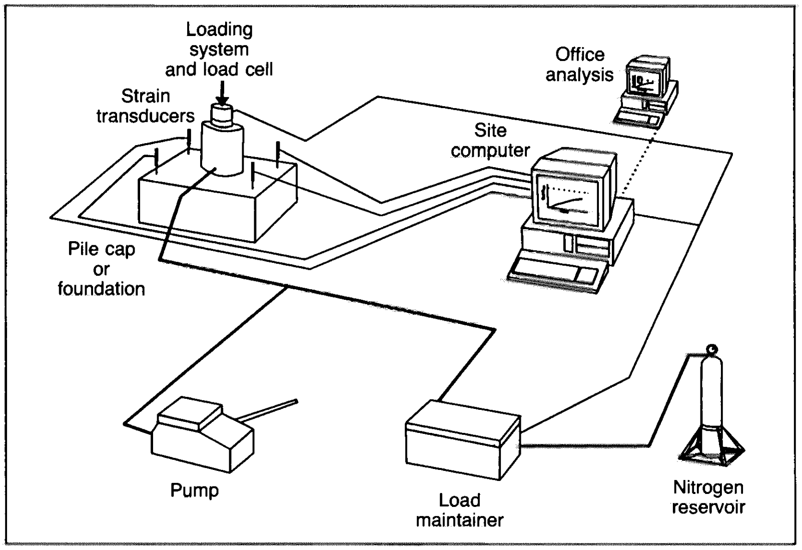


Fig. 1. Electronic sensors monitoring pile displacement and controlling the load applied

22. An accurate method using a computer model called TIMESET[6] based on high grade displacement–time results has been developed which allows each relationship to be divided into components due to shaft friction and end bearing on the basis that each component can be represented by a hyperbolic function. The results from such a technique in undisturbed conditions are so close to observed behaviour in the vast majority of cases and in a wide range of soils, that they may reasonably be described as identical. Temporary deviations sometimes occur due to site traffic or other external environmental factors.

23. Using refined electronically controlled equipment and this interpretation method, a sufficient portion of the time–displacement relationship at a given load needs to be recorded so that the remainder of it may be derived mathematically with accuracy. This can satisfactorily be defined by the point in time when at least 90% of the shaft displacement–time relationship has been mobilized. For most concrete piles of average dimensions, this is between 1 and 3 h, so if the load is held for, for instance, 6 h, the unique solution for each component can be found.

24. The development of base settlement behaviour in time is generally so long that the duration of previous lower loads applied has little influence on the result and it is found that a normalized time characteristic for the base is practically constant from load to load at loads above the ultimate shaft capacity. Therefore, if the normalized time constant can be derived accurately at a higher load, for example, lesser loads may not need to be held for such long

periods. Consequently, only the highest load needs to be maintained constant for long enough to allow the unique separation of the two functions. This allows the duration of the test programme to be minimized without compromising the accuracy of the results. The ideal time for maintaining the single long duration load is overnight when the external influences are generally minimal.

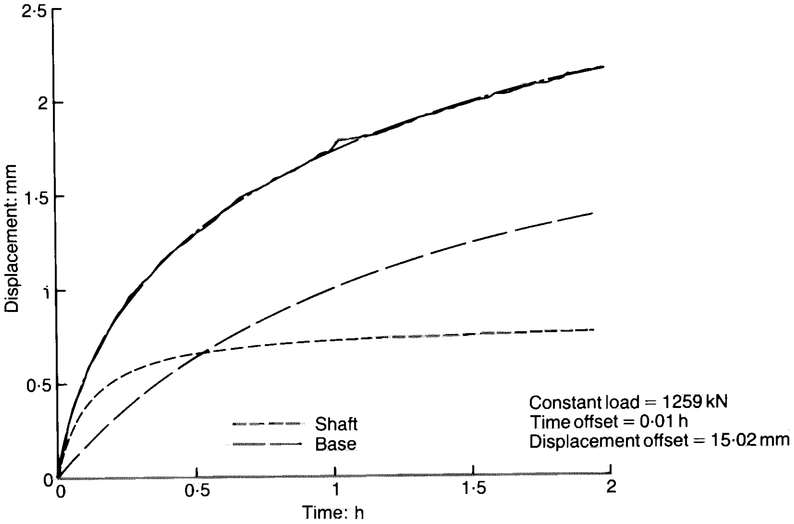
Limiting settlement rates

25. A simple way of controlling the specification for the test schedule is to specify a minimum load duration of around 1 h and a settlement rate of less than 0·25 mm/h, as in the ICE's specification.[5] Although the governing rate should vary from load to load, this specified rate is generally sufficient to ensure that, once creep or consolidation becomes significant, the duration of the load-holding period is automatically extended. A more appropriate procedure may be devised, basing the settlement rate on a proportion, perhaps 5%, of the total displacement recorded since the start of the test, but for practical reasons, with this form of definition a limiting minimum value also needs to be specified for the condition when the total settlement is small at low applied loads. If analysis of the accurately measured behaviour in time, using the computer model TIMESET for example, is available, the duration of application of any load need not normally exceed 6 h.

26. If the applied loads get close to the ultimate pile capacity, it may then be advantageous to reduce the load incremental steps to avoid premature rupture or slip of the skin friction and also to determine limiting rates by practical observation of the displacement–time curves as they develop. However, at this stage, the total test may become unduly protracted.

Fig. 2. Plot of displacement against time and modelled behaviour during constant load application

Parameters required to model pile behaviour in time	Relative timeset analysis
D_s equivalent pile shaft diameter: m	0·375 m
D_b equivalent pile base diameter: m	0·375 m
W_s displacement asymptote for pile shaft friction element of behaviour: m	0·81 mm
W_b displacement asymptote for pile base load element of behaviour: m	2·31 mm
T_s shaft/soil time required to reach 50% of the final settlement at a given load: h	0·12 h
T_b base soil time required to reach 50% of the final settlement at a given load: h	1·31 h



Modelling results

27. An example of the displacement–time results from a constant load stage for a pile is shown in Fig. 2, together with the mathematically derived separate relationships for shaft and base. These results are of great interest since they may be used, for example, to identify the soil type on which the base of the pile sits. As soon as the deformation characteristics can be accurately identified to give a consistent final settlement projection, the test may proceed to other loads.

28. Provided sufficient points on the load–settlement graph are produced so that the relationship is unambiguous, the behavioural characteristics can readily be defined. This might involve eight or more load stages, but where possible, and if good interpretation is required to define all the parameters with reasonable accuracy, the pile should generally be made to settle by something of the order of 10% of the diameter. Although this may not be possible or necessary for piles on or in hard soils or soft rocks, it would be applicable to a wide range of other soils.

29. Proof load tests to 1·5 times the required load would not generally cause sufficient displacement for a detailed analysis, but it is often worth considering an increase of test load to give a more comprehensive view of the pile and soil behaviour. A cost-effective alternative would be to test a smaller diameter pile, installed using the same technique and to the same depth, thus establishing the governing soil characteristics so that they may be scaled to the appropriate pile size.

30. The techniques of back-analysis are very useful and have become valuable when investigating pile failure mechanisms where, for example, closure of small cracks can be identified. The identification of such features is dependent on the accurate maintenance of load at the given stage, and this is an additional reason why refined load control is an absolute necessity. Fig. 3 illustrates the distortion of pile head behaviour that may result from just a 0·5% drop in load.

Loading and unloading

31. It is universally observed that, when a load is removed and subsequently re-applied, the settlement at the reload stage is more than that at the initial stage. A typical result of pile head displacement under the load stages shown in Fig. 4, is illustrated in the load–displacement diagram of Fig. 5; the corresponding displacement–time diagram is shown in Fig. 6. In this example, two of the loads applied are

causing effects in the pile–soil system which differ from other loads in that different stress paths are being followed. It is often the case that the initial load is held constant at such a point for only a short period, whereas the reload stage may be maintained for a much longer period (for example, see the ICE's specification).[5] Experience shows that, for best quality interpretation according to modern methods, it is the initial loading result which is the more valuable and representative. Indeed for most purposes, the cycling of load at such a stage would seem to serve little purpose, but it may be useful in cases where there is some specific reason, as for example in the case of silo foundations. Settlements from initial and reload stages should not be mixed together when plotting results.

Elastic shortening

32. The techniques outlined for the analysis of pile behaviour normally employ just the pile head displacement, applied load and the time data; without the need for expensive internal pile instrumentation. However, where distribution of skin friction along the pile length or detailed assessment of elastic shortening is required, specific sensors need to be used to capture the required data. Most of the methods for determining the full elastic shortening require elements to be cast into the pile during installation.

33. Elastic shortening of the material of a pile is an important element in load–displacement performance, especially at lower applied loads and often up to the specified working load. It is also a significant component in the behaviour of long slender piles.

34. A very useful purpose in analysis can be served by the insertion of a short extensometer into the head region of a test pile at such a level that there is little difference in transmitted load between the top and bottom of the extensometer tube. This can enable the modulus of the pile material to be derived with a reasonable degree of accuracy, although for cast-in-place piles, it may be necessary to do a little excavation after testing in order to check the exact pile dimensions. The elastic shortening information may be used to refine the mathematical separation of shaft and base ultimate loads using the CEMSET method.[7]

Interpretation of pile test results

The TIMESET and CEMSET methods may be used in conjunction to determine the controlling parameters for any particular pile or foundation test result with good accuracy, based on high-grade testing and subject to sufficient settlement data. Indeed the problem may be regarded as a three-dimensional representation of single pile behaviour, the dimensions being time, load and settlement. Basically, TIMESET may be used

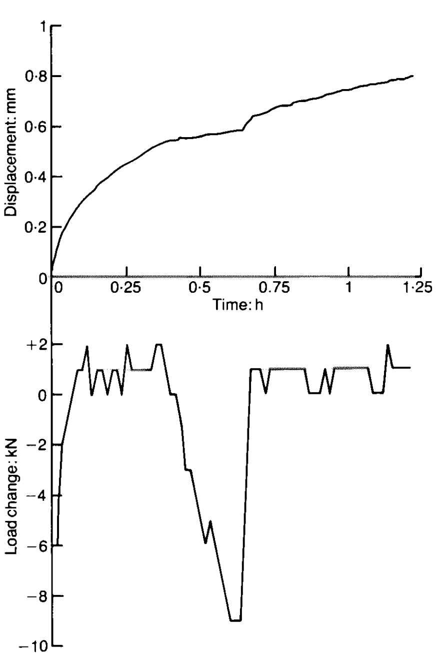


Fig. 3. Variation in pile head displacement with variation of nominally constant applied load (1705 kN)

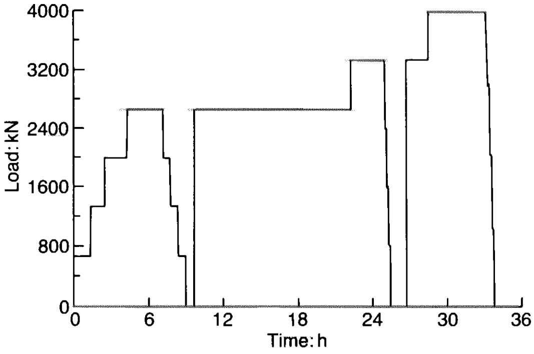


Fig. 4. Typical load–time diagram

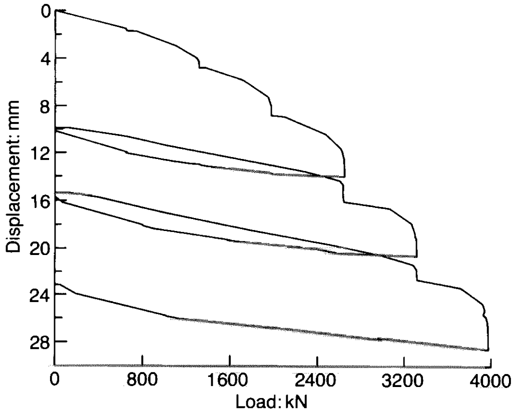


Fig. 5. Typical load–displacement diagram showing unload–reload resulting in greater settlement

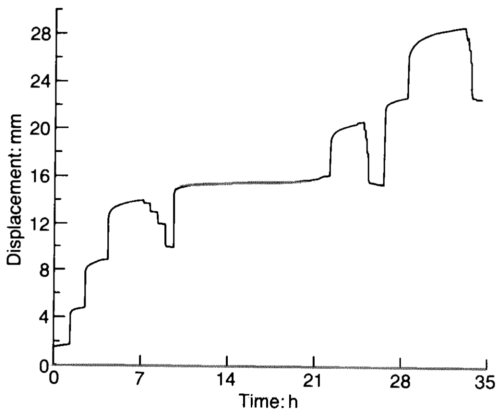


Fig. 6. Typical displacement–time diagram

to determine the final settlement under each load at infinite time, thus removing entirely the time factor from the load–settlement solution and the fully drained load deformation model, CEMSET, may then be used.

(*a*) The TIMESET model has been derived on the basis that any pile displacement–time relationship consists of three distinct components
  (i) elastic shortening—this can be assumed to take place immediately upon application of load (in reality, elastic compression will travel the length of the pile as the final shaft friction develops)
  (ii) shaft behaviour—modelling of shaft behaviour requires a hyperbolic function and is found to conform with many test results, including those from piles tested in tension and
  (iii) base behaviour—modelling is, as above, based on the use of hyperbolic functions.

(*b*) The CEMSET model uses hyperbolic functions to describe the shaft and the base load–settlement characteristics determined by the founding strata and these components are added to the modelled elastic shortening to represent the pile behaviour under load accurately. The characteristic of the base and the shaft responses can be linked directly to the pertinent soil parameters, provided settlement has been such as to mobilize a significant part of the pile base reaction.

Dynamic testing

36. The quest for rapid and low-cost pile tests led to the development of dynamic load testing. In such tests the pile response to a high energy impact blow is recorded. Back-analysis of the data using stress wave theory allows a mathematical model to replicate the measured pile behaviour. The theory assumes that the dynamic and static elements of the mathematical model can be identified individually, and their separation is relied upon for assessing the static component. However, the true displacement of a pile under load, other than elastic shortening, is governed by consolidation and creep, which are significant and very much time-dependent. They cannot be measured using dynamic tests, although, in some controlled conditions, the approximate immediate values they yield may be useful.

37. It is difficult to see how variants on the dynamic method, such as that using progressively heavier successive blows, can provide any advance on the more basic dynamic test. This is because, if a pile has been 'rested' before testing, upon successive restriking it will gradually return to the driving conditions under which only a reduced part of the final static skin friction may be resisting the pile penetration.

38. 'Statnamic' and pseudo-static load tests are those in which a high energy blow of relatively long duration is imparted to the pile. The induced compression is prolonged sufficiently so that the full pile is presumed to be loaded at the same time. The duration is however, still so short (approximately 0·1 s), that the maximum displacement does not always correspond to the maximum force applied and interpretation of the results becomes necessary. The method of assessment of the results, from which it is hoped that the static behaviour may be deduced, is still under development.

39. In interpreting all dynamic load tests some specific difficulties arise. Elastic shortening is often a major component of settlement, particularly for high strength precast piles. The elastic modulus is often derived by wave velocity matching, so that acoustic reflections are made to coincide with recognized or expected soil–pile features. Where these are not distinguishable, the pile length is simply assumed to shorten in accordance with a presumed modulus of elasticity which has not been measured. In addition, with dynamic tests it appears generally that rupture of the soil–pile friction interface takes place and that the dynamic base stiffness, reacting to the impulse, is generally closer to that of water than to that of the soil. The relation between statically developed soil–pile forces and those due to sudden rupture is still poorly documented and has to be empirically based.

40. One is therefore faced with many complex and often currently unanswerable questions in regard to the later generation testing systems, and while it would be unfair not to recognize them as useful, correlation information is definitely required unless, perhaps, there is extensive existing experience in specific cases and applications. One should therefore be cautious about considering a low price to be more important than a correct

answer in respect of the adequacy of static pile capacity determined by a particular test.

Definition of pile failure

41. It is obvious from the large number of tests and test stages analysed to date, that arbitrary definitions of pile failure are but a source of confusion and that the only satisfactory definition to use is that which defines all ultimate conditions by an asymptote parallel to the settlement axis on the load–settlement diagram. This is the definition advocated by Terzaghi[8] which has unfortunately been forgotten by many writers in recent years. While it is true that at large strains pile capacity may diminish because of soil particle reorientation along the pile shaft, this definition still stands and represents real pile behaviour.

42. The derivation of ultimate loads by bearing capacity theory based on plasticity implies an asymptotic definition of failure.

43. All other arbitrary definitions may be made to yield loads corresponding to specific settlements, but the idea that they may have any reasonably universal application has to be discarded. Settlement-dependent assessments may be used as serviceability states and are a function of soil stiffness as well as of ultimate load.

44. True ultimate loads can only be derived if any pile tested is made to settle beyond the stage at which the shaft friction is essentially fully mobilized. It is also necessary to mobilize a reasonable proportion of end bearing. This may mean that to conduct good analysis, settlements in excess of around 25 mm will be necessary for traditional pile sizes and would be considerably more for large or underreamed piles.

45. It may be observed that, even if piles are well instrumented to show the separation of shaft and base load, it is not possible to determine ultimate base load and the stiffness of soil under the base fully without an accurate modelling system, otherwise the contribution from the base behaviour is often found to be underestimated. It should also be noted that piles in certain chalks and other jointed rocks require special consideration and interpretation because of the particular mechanics of rock block displacement.

46. A related issue is that of testing piles to destruction. Unless the structure of a test pile is actually damaged, the ability of the pile–soil system to perform adequately remains. Fears that overloading of the soil by applying more than typical proof load values, may damage the long-term performance of a pile do not appear to be borne out in reality. Indeed a stiffer response will result on reloading. The unload and reload characteristic behaviour can be predicted with reasonable accuracy using the CEMSET model.

Conclusion

47. Research clearly indicates the need for a unique definition of ultimate pile capacity which is asymptotic and emphasizes the role of stiffness in controlling settlement.

48. All pile testing methods for determining bearing capacity, from continuous rate of penetration tests to wave analysis systems, appear to introduce complications related to the inability of soils to reach a stable state in terms of effective stress during the load period. This is not to dismiss such methods as being inapplicable, but the findings from current research emphasize a need for further understanding of basic pile–soil interaction. Even static load test results need some form of interpretation to evaluate the influence of time and soil stiffness on the long-term behaviour.

49. Static pile tests undertaken to yield good quality and useful results, may be carried out according to any maintained load specification which produces sufficient well-defined points on a load–settlement graph to determine the relationship unambiguously.

50. Cycling of load may serve a useful purpose in certain cases. However, it is much to be preferred that pile tests are carried out by increasing load consistently, from stage to stage, until completion. If unload/reload stages are a requirement, then only the first application of load at a given value should be used in analysis of pile performance. The second application of a specific load may be of interest, but it is not to be confused with the initial load–settlement relationship.

51. The final settlement at any given load stage, as analysed by the time-based model described, is independent of any previous loading history. During the application of load, the model can reveal any anomalies in the development of shaft and base capacities.

52. Specifications for static load tests can be improved to reduce both test duration and cycling. Perhaps more importantly, a standard method of interpretation of results is needed across the industry. The methods described above can provide a basis for this.

53. It is useful to consider a practical specification based on the ICE's piling specification as nearly as possible, i.e.

(*a*) without interim load/unload stages
(*b*) with specific times for application of load to include a settlement rate of perhaps 0·25 mm/h, with the possibility of also using variable maximum load holding periods determined according to the observed behaviour
(*c*) with the maintained load test being used to cover *all* test stages and not just up to twice the service load
(*d*) with concentration on holding the last load longer

(*e*) with recovery also specified by rate and
(*f*) with insistence on high quality load control and data recording.

The combination of behavioural models now available can represent the pile load–settlement characteristics with good accuracy. Interpretation of results is practically simplified and the fundamental goal of the pile test can be accomplished.

54. These models can also be employed to study the recovery characteristic of a pile on removal of load, thereby practically eliminating the requirement for confusing unloading and reloading schedules in the pile test specification. They have been found to be applicable to all foundation types so far examined.

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