Piles and Pile Foundations, Settlements of Pile Foundations

Pieux et fondations sur pieux, tassements de ce genre de fondations

GENERAL REPORT

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Introduction

(*a*) The period since 1948 has been marked by an extraordinary number and variety of studies concerning piles and pile foundations, as well as by a major conference on the subject in Paris in 1952. This activity indicates not only the importance of the subject, but also the need and margin for improvement.

(*b*) Notwithstanding the interest in pile foundations, only a few complete case histories have been reported in which the behavior of the finished structure is noted together with the pertinent information about the properties of the subsoil and the design of the foundation. Most of the activity can be divided into two major categories. The first of these consists of the collection of data regarding the bearing capacity of piles in the field or in large-scale tests, combined with a record of the appropriate index properties of the soils, and reviewed with reference to predictions based on static theories or penetration tests. The second category consists of refinements of theoretical concepts, often supplemented by small-scale tests in the field or laboratory. Finally, a few new procedures of construction and a few new types of piles have been introduced or improved.

(*c*) In this report, the Conference papers receive primary attention, but reference will also be made to matters of interest contained in the Annual Reports of the various national societies and to a few significant papers published elsewhere. A selected bibliography of the latter is appended.

(1) Case Histories

(*a*) Two papers have been presented containing the results of settlement observations on completed structures with pile foundations. *Meyerhof* (5/13) deals with the abutments of a bridge established on precast concrete piles driven through about 8 ft. of clay and 8 ft. of loose sand to a stratum of fine dense sand. The results of soil tests, cone-penetration tests and pile-loading tests are reported. The structure settled about 0.75 inch, almost exclusively during construction.

(*b*) The second case history, by *Lumpert* (5/11), refers to a reinforced-concrete coal bin established on uncased cast-in-place (Express system) piles extending through about 40 ft. of soft peats, silts and marls to a deposit of sandy loam on which pedestals were formed. The driving record and the results of a load test on a typical pile are given; no index properties of the soil are reported. The foundation settled rather rapidly for about 8 cm, where it attained a position of equilibrium above and below which it moves in accordance with the load in the bins. The settlement of the structure was about 11 times that of the test pile under the same load.

(2) Field Studies of Bearing Capacity

(*a*) Several of the Conference papers summarize the relations between the behavior of test piles and the results of soil tests. *Nunes* and *Vargas* (5/15) have reported the results of load tests on 11 piles in residual soils in Brazil, together with the results of pertinent soil tests. *Golder* (5/8) has summarized the results of load tests on 18 piles in England, principally in London; most of these records are also supported by adequate descriptions of the corresponding soils. In both papers, there is evidence to indicate a reasonable agreement between the results of the tests and computed values based on statical considerations.

(*b*) *Golder* (5/8) also presents data from 6 locations indicating the practical usefulness of the Dutch cone test in gravels and sands. Further evidence of this type is presented by *van der Veen* (5/16) in a discussion of the point resistances of 19 piles driven through soft soils to sand in the Netherlands. The measured point resistance agreed with that encountered by the cone apparatus within the range of 75% to 180%, with one value of 240% outside this range. The areas of the points of the piles varied from 100 to 3,800 sq.cm.

(*c*) *Holtz* and *Gibbs* (5/10) have presented the results of a full-scale test program to determine the driving resistance and load-settlement characteristics of piles driven into loess with a strong cohesive binder. The effects of soaking the loess were also investigated. The physical properties of the deposit were thoroughly explored and adequately described.

(*d*) A few additional records containing the results of load tests and adequate soil tests have been published during the last 5 years. Reference is made to a limited number of these in the Bibliography.

(*e*) The importance of the records of these field tests, each with adequate descriptions of the subsoil, cannot be overestimated; our fund of general knowledge of pile foundations has been permanently enriched by the systematic collection. Even if no general theories should be developed, such empirical data would advance the art of foundation engineering. Moreover, they will serve to test and define the limits of validity of any theories in current use or likely to be proposed in the future.

(3) Theoretical and Semi-Empirical Studies of Static Analyses

(*a*) The considerable numbers of theoretical and experimental studies of the bearing capacity of footings during the last 5 years have been reflected in further studies of the bearing capacity of piles on the basis of plasticity methods. Similar studies of the theory of cone tests have permitted a more rational correlation of the results of cone and pile-load tests. The paper by *Meyer* and *L'Herminier* (5/12) is an example. It seems to be the concensus of opinion that these methods are promising. In some localities they are supported by sufficient field evidence to permit the conclusion that they are already satisfactory for practical use; this is evidently the situation in Holland, Belgium, and parts of England. An interesting summary of the value of penetration tests, with emphasis on the Dutch cone procedure, was presented by *Kantey* (Ref. 3) in 1951 and was discussed by a number of experienced individuals.

(*b*) There is possibly a trend toward the opinion that better results for piles in granular soils are obtained if the values of the angle of internal friction are computed on the basis of the cone tests and then utilized in the statical computation of the bearing capacity, than if the penetration resistances from the cone tests are considered applicable without modification to the full-sized pile.

(*c*) Not all contributors to the Conference Proceedings agree to the reliability of static penetration tests. Some of the evidence against such tests is presented by *Cambefort* (5/6). Tests on small piles in natural soil indicated that the ultimate point load per unit of area was not independent of the diameter of the pile, as is commonly assumed in the interpretation of penetration tests. However, since the character of the bearing stratum in these tests was quite erratic, there is reason to reserve final judgment until many more similar tests are performed.

(*d*) The division of the supporting capacity of a pile between point resistance and skin friction has also received considerable attention. Several installations have been made of strain gages to measure the transfer of load from pile to soil as a function of the length of the pile. Two installations have been described by *Cambefort*, one for a pile at Gennevilliers (Ref. 7) and the other at Vitry (5/5). Similar tests were made in the United States on the Atchafalaya Floodway in Louisiana (Ref. 4) and at the Q-Street Viaduct in Omaha (Ref. 5).

(*e*) In the Atchafalaya tests, strain gages were established in pairs at intervals of 5 ft. in the vertical direction; the gages of each pair were located at opposite ends of a diameter to permit correction for bending. To provide a check on the average of two gage-readings, two additional gages were occasionally provided on the diameter at right angles. The error in the load in the pile due to scattering in the gage readings was as much as 39%; the error due to bending, if uncorrected, was much larger. For the pile of Gennevilliers, *Cambefort* noted that the load in the pile was a minimum near mid-length and increased substantially toward the point. Since the gages were located along only one element of the cylinder of the pile, the observed effect might have been due to bending. The pile at Vitry furnished very different results; in this case the gages were located along the central axis of the pile.

(*f*) Thus far, all the field tests for determining the distribution of shearing forces along piles have been of short duration. The final distribution may differ radically from that observed in the short-time tests. It appears that long-time tests will be compelled to await the development of strain gages capable of furnishing reliable results for several years under adverse conditions.

(4) Theories and Observations of Pile Groups

(*a*) Several studies have been made of the relations between the capacities of single piles and of similar piles in groups. These include the loading to failure or near-failure of full-size groups on the Atchafalaya Floodway and one group at the Q-Street Viaduct in Omaha in the U.S.A., as well as the small-scale tests reported by *Cambefort* (5/5).

(*b*) All the full-scale tests have several features that make it difficult to draw general conclusions. The spacing of the piles was usually such that group action would not necessarily be expected, the failure loads were not well defined, and the results of the single-pile control tests were erratic. In connection with the Q-Street group, the soil properties were investigated by means of tests somewhat inappropriate to the conditions.

(*c*) The extensive small-scale tests by *Cambefort* (5/5) included complete load and penetration data for piles of several diameters tested singly and in groups of various arrangement. The piles where pushed into a natural deposit of several layers, of which the lowermost seems to have been of quite variable resistance. The program of tests was such that some of the piles were loaded several times in one series of tests; at the completion of the tests, some of the piles had penetrated at least 3 inches below their starting position at which the single-pile capacity was determined. It seems probable that the single-pile capacity was altered during this penetration. Furthermore, the single-pile capacities were extremely variable among themselves. Hence, it is doubtful if any general conclusions regarding group action should be drawn from the tests. The information strikingly illustrates the consequences of the variability in the character of natural soil deposits, and deserves to be supplemented by a tabulation of the appropriate index properties of the materials involved.

(*d*) A somewhat different situation in which the group action of piles must be considered is reported by *Antoine*, *L'Herminier* and *Bachelier* (5/1). A new superstructure was to be constructed on an existing pile foundation established on a thin layer of limestone which rested on a softer layer of marl. Values of the modulus of elasticity and tensile strength of both materials were determined, and the theory of elasticity utilized to investigate the danger of rupture of the layer of limestone.

(5) Dynamics of Pile Driving

(*a*) Dynamic methods of predicting the static bearing capacity of piles continue to interest investigators. By means of tests on cone penetrometers, *Buisson* and *Chapon* (5/4) have found that the scattering in the ratio of dynamic to static resistance can be reduced if the tests are subdivided according to the major categories of soils, especially for large penetrations. Some evidence is presented that a correction may be applied to permit use of the data for full-sized piles. The authors admit the limited nature of the tests and hope for further studies. In such studies, it would be advisable to include the pertinent index properties of the soils, since it is hardly to be expected that all clays, for example, would exhibit similar behavior.

(*b*) An interesting and somewhat different approach to the dynamic problems of pile driving has been made by *Nanninga* (5/14). Here, the attempt is made to develop a pile driving hammer that will be efficient and that will permit more accurate dynamic observations.

(*c*) The vibrational problems associated with pile driving are treated in two papers, one by ***Peter*** (5/16) and one by ***Bendel*** (5/2). The first discusses vibrations due to pile driving at three sites; typical boring logs are given but no index properties of the soil are reported. The second paper presents the measurements of deformations in a party wall close to pile-driving activities. The piles were driven through 7 m of silty sand and peat; the properties of the soil are not described quantitatively.

(*d*) *Grasshoff* considers the nature of the relationship between dynamic resistance and penetration on the basis of model studies in sand. The studies were made on pile-shaped projectiles by means of a high-speed motion picture camera.

(6) Construction Procedures

(*a*) Two Conference papers deal with new or somewhat different types of concrete piles. ***Brown*** (5/3) describes a method for mixing portland cement with soft soils in the ground to form piles. *Cuadrat* (5/7) describes one of several procedures for constructing concrete piles in soft soil with the aid of compressed air.

(*b*) Considerable attention has been devoted in the United States to the control of heaving and displacement associated with the driving of displacement piles into deposits of saturated clay. Methods of pre-excavation have been developed whereby part of the soil in the space to be occupied by each pile is removed, either by driving and cleaning a casing or by a rotary drilling process in which the clay is reduced to a slurry.

(7) Conclusion

(*a*) In addition to the all-important collection of complete case histories of pile foundations and pile tests, the most promising developments during the last 5 years seem to have taken place in the attempts to estimate the ultimate bearing capacity of single piles by means of the results of computations based on the theory of plasticity. The Dutch cone apparatus has increased in favor in Europe. In the Americas, on the other hand, the static penetration tests have not made any significant impression, and there is a prevalent opinion that the lengths and capacities of piles can best be estimated on the basis of detailed soil profiles supplemented by the results of dynamic penetration tests made in conjunction with test borings. In all countries, load tests are considered the final criterion, and all other methods are considered valid only if based on extensive empirical knowledge.

(*b*) The capacity and the settlement of pile groups have received attention to a much smaller degree, and the literature contains only a few articles dealing with the changes on the physical properties of masses of soil during and after pile driving. Since these are important matters, there remains much to be investigated in the complex realm of pile foundations.

Proposals for Discussion

It is suggested that the discussions should be concerned primarily with the following points:

(1) *The state of knowledge concerning the bearing capacity of single piles; the relative merits of various procedures for estimating the bearing capacity; and the basis for further research.*

(2) *The state of knowledge concerning the safety and settlement of groups of piles and pile foundations, and the basis for further research.*

(3) *An evaluation of the relative importance of research into the various aspects of pile foundations, with suggestions as to procedure.*

Sommaire

1° Pendant la période postérieure à 1948 on a constaté une activité remarquable dans le domaine des fondations par pieux et surtout de la force portante des pieux.

2° *Meyerhof* (5/13) et *Lumpert* (5/11) ont présenté des résultats de tassements de pieux ainsi que des informations pertinentes sur les conditions en sous-sol.

3° Des traités donnant les relations entre le comportement des pieux expérimentaux et les essais du sol ont été présentés par *Nunes* et *Vargas* (5/15), *Golder* (5/8), *Van der Veen* (5/17), et *Holtz* et *Gibbs* (5/10). Ces données ont une grande valeur pratique.

4° Des études concernant l'usage des essais au cône statique ont été présentées par *Meyer* et *L'Herminier* (5/12), et *Cambefort* (5/6). L'opinion prépondérante est que ces essais ont une grande valeur pratique. Des études sur la distribution des forces de cisaillement le long du pieu ont donné des résultats erratiques et aucun essai de longue durée n'a encore été fait.

5° Des études sur des groupes de pieux ont été effectuées aux Etats-Unis et par *Cambefort* (5/5). Jusqu'à présent ces résultats n'ont pas pu être groupés sous la forme d'une loi de valeur générale. Une étude sur des pieux reposant sur une mince couche de roche au-dessus d'un sol mou a été présentée par *Antoine*, *L'Herminier* et *Bachelier* (5/1).

6° Des problèmes de battage des pieux ont été traités par ***Buisson*** et ***Chapon*** (5/4), *Nanninga* (5/14), ***Peter*** (5/16), *Grasshoff* (5/9) et ***Bendel*** (5/2).

7° Deux parmi beaucoup d'autres nouveaux procédés de construction ont été présentés par *Brown* (5/3) et *Montagut Cuadrat* (5/7).

8° On peut conclure que le développement le plus important de ces cinq dernières années, a part la collection des divers cas de fondations par pieux, est la tentative d'évaluer la force portante des pieux en utilisant des procédés semi-empiriques dont la plupart sont basés sur la théorie de plasticité. La force portante et le tassement des groupes de pieux n'ont pas été traités de façon aussi approfondie. Très peu de recherches ont été effectuées sur les variations des propriétés physiques du sol pendant et après la battage des pieux.

9° Une brève bibliographie des articles qui ne sont pas présentés dans les Comptes Rendus de la Conférence, est présentée.

Propositions pour discussion

On propose que les discussions soient concentrées sur les points suivants:

1° Les études concernant la force portante des pieux; la valeur relative des divers procédés pour l'évaluation de cette force; et la base à admettre pour des recherches ultérieures.

2° Les études concernant la sécurité et le tassement des groupes de pieux et des fondations par pieux, ainsi que la base des recherches ultérieures.

3° L'évaluation de l'importance relative des recherches sur les divers aspects des fondations par pieux, avec des suggestions sur le procédé à suivre.

References

(*a*) The Proceedings of the 1952 Paris Conference contain a number of significant papers which will not be listed separately here.

The following papers deal with the results of load tests and the pertinent soil properties at the sites:

(1) *U.S. Waterways Experiment Station* (1950): Pile Loading Tests, Combined Morganza Floodway Control Structure, T.M. 3–308.

(2) *U.S. Waterways Experiment Station* (1950): Determination of Required Pile Lengths, Combined Morganza Floodway Control Structure, T.M. 3–317.

(*b*) Cone-penetration tests as related to pile capacity are discussed in the following summary:

(3) *Kantey, B. A.* (1951): Significant Developments in Sub-Surface Exploration for Piled Foundations. Trans. South African Inst. C.E., Vol. 1, No. 6, August, pp. 159–216 including discussions.

(*c*) The action of groups of piles is considered in the following. The first two publications deal with full-scale tests; the last is one of several analytical procedures that have been proposed for taking account of group action.

(4) Steel and Timber Pile Tests-West Atchafalaya Floodway. Proc. A.R.E.A., Vol. 52, 1951, pp. 149–202.

(5) *Schlitt, H. G.* (1950): Steel Pile Tests, Q-Street Viaduct, Omaha, Nebraska. Dept. of Roads and Irrigation, Lincoln, Nebraska.

(6) *Derqui, F.* (1952), Madrid: Calculus of Pile Groups.

(*d*) The transfer of load from pile to soil is discussed in Ref. (4) and (5), and also in the following:

(7) *Cambefort, H.* (1947): Etude expérimentale de la force portante d'un pieu foré. Travaux, July–August (Pile of Gennevilliers).