DIVISION 4

Deep Foundations

Fondations profondes

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ON REACHING THE SIXTH INTERNATIONAL CONFERENCE on Soil Mechanics and Foundation Engineering, the role of the General Reporter becomes at once easier and at the same time more difficult. The task is easier now because the General Reporter has brilliant predecessors as examples, outstanding members of the profession who performed their duty with skill, real understanding of the problems, and loving care. However, it is also more difficult to write the Report now, and for the same reason. My predecessors stated many truths, and outlined, criticized, and evaluated many theories and methods; it is therefore very difficult for the present reporter to add something new. Fortunately, he can share this task with the authors of the papers; it is really their role to add something new to the theories, useful experiences, and data on piled foundations. The General Reporter's role is to summarize, survey, evaluate, and draw the lessons.

Your present General Reporter, in order to make his task easier, availed himself of previous reports and of proceedings of special conferences held to discuss pile problems.* He examined the themes treated, and classified the papers dealing with the different aspects of piled foundations. Before discussing the papers which have been presented at this Conference, the results of this analysis are presented.

As far as I know there have been ten conferences with international participation since the First International Conference in 1936, where the problems of piles and piled construction have been dealt with to a considerable extent. The place, nature, and date of each of these conferences are listed in Table I. I have also given the number and percentage of papers in the division on piles. (The classification of the papers on piles into divisions is explained later in this Report.)

It is evident from the table that the interest in this field is increasing steadily. This is shown on the one hand by the increased proportion of the papers on piles, and on the other hand by the fact that since 1952, there have been

*I wish to thank the many colleagues from whom I received help in this respect.

TABLE I. STATISTICAL DATA ON CONFERENCES

No.	Name of Conference	Place	Year	No. of contributions	Papers on piles: No.	Papers on piles: %	Percentage of papers in the different groups: 1	2	3	4	5
1	First International	Cambridge, Mass.	1936	152	12	8	42	8	50	—	—
2	Second International	Rotterdam	1948	402	32	8	34	19	16	19	12
3	European Conference	Paris	1952	20	20	100	70	5	25	—	—
4	Third International	Zürich	1953	162	18	11	44	22	11	17	6
5	Fourth International	London	1957	179	17	9.5	41	30	17	6	6
6	Symposium on Pile Foundations	Stockholm	1960	14	14	100	29	64	7	—	—
7	Fifth International	Paris	1961	271	28	10	50	25	7	4	14
8	Symposium on Bearing Capacity of Piles	Roorkee	1964	29	29	100	38	21	21	13	7
9	Congreso de cimientos profundes	Mexico City	1964	17	17	100	24	30	6	35	5
10	Sixth International	Montreal	1965	218	28	13	36	25	25	7	7
TOTALS					215	100%	40%	23%	18%	12%	7%

four conferences which have dealt exclusively with the problems of piles. This increasing interest has obvious causes. First, the weight and size of modern buildings and structures continue to grow, and the bearing capacity of the upper layers with average strength is not sufficient to carry these great loads. Also, it is more and more difficult to find a site where the subgrade is suitable for this type of construction. In addition, much of the rapid building development has taken place in areas where the subgrade consists of a thick deposit of low bearing capacity. Examples of such areas are the alluvial valleys of the great rivers, or the extensive areas around great cities covered by old man-made fills. Another contributing cause to the growing use of piles lies in the fact that deep foundations lend themselves to mechanization more easily than do spread foundations, and the increasing shortage of labour and the need for economy make mechanization imperative.

Every year there is probably a rather large number of piles driven unnecessarily to avoid any possible difficulties with the foundations but having little economic justification.

Table I also allows other conclusions to be drawn. Let us examine the frequency of conferences, i.e., the number of years between conferences. This number is decreasing rapidly and if this trend continues we shall soon be discussing our problems at a permanent and eternal conference!

The really important aspects of this statistical study are the distribution of the papers on piles among the different themes and the question of whether this distribution shows any variation with time. In order to investigate this, we must classify the papers in the very complex field of piled foundations under general headings. After surveying the classifications of the general reporters of previous conferences and also those of various bibliographies,* your General Reporter feels that the following classification will be comprehensive enough.

The order of sequence is determined by the number of papers in the different groups. I have, of course, no doubt that the establishment of a perfectly comprehensive classification is by no means easy and that the system presented below has its drawbacks.

1. Investigations of the behaviour of the single pile: bearing capacity and settlements; static and dynamic behaviour. Theoretical and semi-empirical studies, field tests, and model tests. In this group we shall treat separately the papers dealing with sounding devices and methods, and also the dynamic problems of pile driving. Any other study intended to investigate single piles—for instance, the effect of lateral loads—belongs in group three.

2. Investigations of the behaviour of pile foundations; bearing capacity and settlement of pile groups; case histories.

3. Investigations of problems associated with other than vertical loads; field tests; piled anchors.

4. Problems associated with the construction of piled foundations; piling systems; construction methods; driving tests and problems.

5. Special studies and problems.

By far the greatest percentage of papers belongs to the first group. Based on the statistics of ten conferences, listed in Table I, 40 per cent of the individual contributions definitely fall into this category. The second group accounts for 23 per cent, the third 18 per cent, the fourth 12 per cent, and the fifth, 7 per cent. The fact that this last group is only 7 per cent is probably because this classification is rather arbitrary.

*We direct the attention of the reader to two excellent bibliographies: Petermann and Kühn (1965) and Nishida (1960).

If we examine the series of international conferences, we regret very much having to report that the percentage of the papers dealing with field tests and measurements has decreased up to the Fifth Conference; however, it is greater in the present Conference. We also regret the low percentage in the second group because this group is the treasury of well-documented case histories and of evaluated experiences with piles. Measurements made on existing structures on piles and the comparison of the real behaviour with the predictions based on theoretical investigations would give the best basis for the further development of existing theories.

Piling has come a very long way, not only through the thousands of years of human history since lake dwellings, but also in the technological age itself, and even since the establishment of soil mechanics. The piles of the past were 30 to 50 ft long and 1 ft in diameter, but today we have giant piles with a length of 200 to 250 ft and a diameter of 10 ft. The use of piles has become more varied and complex than ever before. Methods of construction underwent rapid change and evolution; the timber piles and the handpowered drivers of the past have given place to very complicated machines and highly specialized methods.

It is always important, when dealing with bearing capacity and settlements in piling problems, to consider the construction methods and the manner of installing the pile. These factors certainly influence the real bearing capacity of the pile. The differences in this respect between bored and driven piles are well known and the differences are even greater in the case of some special pile systems.

The ancient method of foundation construction with piling has solved many problems for the benefit of mankind in the past, and it could adapt itself elastically to the changed conditions and tasks, and so prove that it was the most economical deep foundation. However, in spite of the great practical importance of piles and piled foundations, there are only a few developments in present theoretical and practical research that can provide guidelines for future investigations. We have to keep in mind that the design of piled foundations will be always one that requires experience and sound knowledge of the behaviour of subsoil materials before and after pile driving. Purely theoretical methods are not likely to give a correct and complete answer.

BEHAVIOUR OF SINGLE PILES

Pile foundations were originally designed on a purely empirical basis, but the design procedure is now on its way to becoming a method that can be judged, designed, and controlled by scientifically sound theories. Even if we cannot reach this goal completely it must be our aim in our endeavours. Progress is, however, very slow and by no means continuous. There is no doubt that many "superstitions" of the past either have been eliminated or are on their way to being eliminated; all these ideas could not be replaced immediately by sound theories which would make rational design possible. We are now collecting the data that will furnish the basis for such realistic assumptions.

We only know of a few attempts to solve the basic problem of describing the behaviour of a single pile under the action of a load acting along its axis. The first investigations in this field were published about ten years ago: they were partly theoretical studies, partly results of model and field testing. They were centred on the manner in which piles transmit their loads along the shaft and at the pile tip into the surrounding and underlying soil. The theoretical investigations assume, of necessity, simplified soil conditions and soil properties and their results are, therefore, contributions and attempts only. They created, however, great hopes that a synthesis will soon be found that will fulfil the needs of practice.

There is no doubt, therefore, that real progress in the understanding of the mechanism of pile loading will be furnished by the analysis of the forces and stresses in, around, and beneath the pile, whether or not these investigations lend themselves to testing. In this field of research, begun no more than ten years ago, the present Conference makes further advances. Nowadays, research in this field is served by two powerful tools: first, the use of electronic computers to solve intricate mathematical derivations by means of numerical methods; secondly, modern measuring devices and methods which furnish data on forces and stresses.

Thurman and D'Appolonia (4/21), investigating the behaviour of single piles, make use of the theory of elasticity. They claim that the stresses in the soil mass around the pile remain under the limit of proportionality even when the pile load approaches its ultimate value. Plastic deformations occur only under the pile tip. These assumptions do not hold simultaneously; the strains on the pile shaft and in its vicinity are elastic, if the resistance of the soil layer around the pile point is considerable, and subsequently the penetration of the point is small. The displacements along the shaft then come partly from the penetration of the pile point but, for the most part, from the compression of the shaft itself. In this case, the degree of mobilization of the shearing stresses on the surface is actually small and the assumption of a linear relation is justified. The authors neglect the compression of the piles and assume a failure condition along the shaft. However, the paper definitely adds to our knowledge of this fundamental problem and we hope that the assumptions can be improved later. Effective use of the computer will undoubtedly lead to significant results.

Similar theoretical apparatus had been used to solve the same problem by *Salas et Belzunce (4/18)*. They make use of Mindlin's solution for stresses due to a point load in the interior of a semi-infinite half-space. A computer was used to solve the problem numerically. They assume an elastic half-space; the pile itself is replaced by a section of a vertical line along which vertical line loads are acting. There is an essential difference between these two papers in that Salas and Belzunce do not assume displacement between soil and pile shaft, that is, the value of adhesion is always greater than the shearing stress. The paper presents a summary of a detailed research report and furnishes numerical solutions for three cases.

In the first case the rigid pile is embedded in a homogeneous material and suffers a given penetration. According to the solutions, the force in the pile is rather independent of Poisson's ratio and increases towards the pile tip. This result differs from the computed stress distribution obtained in previous similar investigations and it probably comes from the assumption of adhesion. There is obviously no adhesion in granular soil and not necessarily any in cohesive soil. If we have a sufficient amount of adhesion, then, there is no "skin friction." In the first case mentioned above there is no point resistance either and the load on the pile head will be transmitted through gradually decreasing shearing stresses acting on the cylindrical surface around the pile axis. The vertical and horizontal stresses due to the weight of the half-space and the matter of whether or not the pile, with the calculated forces, is capable of carrying and distributing the stresses produced are not considered. The assumptions are probably responsible for the fact that the calculated curves do not give realistic results.

This conclusion is substantiated by the test results presented by *Kérisel, et al. (4/9)*. These tests are a worthy continuation of the researches presented by the senior author to the Fourth Conference. The present study is concerned with tests carried out with model piles in sand and shows, above all, the extraordinarily great effect of density on pile penetration and also on the value of the surface friction. The previous tests were carried out in dense sand and now they have been repeated in loose and medium dense sand. From the results of these tests and from theoretical considerations, de Beer (1965) showed that the ultimate point bearing capacity at a given depth depends on the lateral dimensions of the point. This effect may be considered by transposing sounding test results.

In some tests the sand was placed around a pile and in others the pile was pressed into the sand. The point resistance and the surface friction were measured separately. In other tests the compression and expansion during loading and failure were measured. All these tests and measurements furnish additional information on the investigation of stresses around the piles, a problem which was successfully tackled previously by Meyerhof (1960). In the tests of *Kérisel, et al. (4/9)* the importance of the compressibility of the sand has been confirmed.

When we investigate, either by tests or theories, the relations between pile load and settlement, we must not forget that it has been proven that the number and extent of loadings and unloadings carried out during a loading test greatly influence the general course of the diagram. This fact has been illustrated by the precise measurements of Habib (1953) and Cambefort (1964). The pile section immediately above the tip cannot adapt itself to the repeated quick changes in the direction of the frictional forces. Consequently, during the unloading process residual forces remain in the pile shaft and they will influence the process of reloading. *Cambefort (4/3)* has dealt with the analysis of the loading diagrams of piles pressed into sand and, on the basis of simple assumptions, he has presented methods for their interpretation. His statement about the unequal distribution of the surface friction on some sections of the pile shaft during the course of pile penetration is reasonable and very interesting. The length of these sections must depend on the loading too.

As all these tests were made in dry sand, the pore pressures were obviously of no concern. However, if we drive piles into a saturated clay, pressures will originate in the pore fluid. This is the central topic of the paper presented by *Lo and Stermac (4/13)*. The paper is very important and interesting and gives excellent information about pore pressures during driving both for single piles and pile groups. The theoretical investigations are concerned with normally consolidated clays. The field tests indicate a fair agreement between theoretical and measured values. The conclusions, although cautiously stated, present a good qualitative picture of the phenomenon. It is hoped that the next step will be the performance of tests in overconsolidated clays and the establishment of a method which would give information about the way these pore pressures influence the bearing capacity and the consolidation process of a given pile foundation. It is also important to record the conditions before pile driving as proper evaluation will require knowledge of these stresses.

A similar problem was treated earlier by Nishida (1963) who derived a theoretical expression for the initial pore water pressure in fully saturated clays due to the skin friction of a cylindrical pile. By assuming a certain distribution of the surface friction, he determined the principal stresses in the soil and, by making use of Henkel's equations, the pore pressures. It would be desirable to compare the values obtained by Nishida's theory with those measured by *Lo and Stermac (4/13)*.

In the opinion of your General Reporter, the four papers discussed above indicate more than anything else the direction to be followed by future research. Both theoretical and the experimental investigations have to be enlarged and as stated by Kérisel (1964) we shall arrive at a proper solution if we apply the Cartesian method: that is, if we work out some details but at the same time never lose sight of the general problem. This solution will describe, then, the behaviour of the pile in a manner that can be used in practice. This means a method which, for a given soil profile and certain physical characteristics, enables us to predict both the probable loading diagram of the pile and the distribution of the pile load along the pile as a function of the total load. The theories which are available today make either too many assumptions and deal with excessively idealized cases, or contain too many empirical elements and constants in their formulae.

Until we find this solution we must be content with simpler and less complete methods in the design of pile foundations, so much the more because we do not have this solution for the simpler case of spread foundations either. as the computation of settlement does not furnish the total load-settlement diagram. These simpler methods of investigation do not pretend to predetermine the loading diagram, but instead are intended only to give some characteristic points on the loading diagram without asking for the value of the settlement. The great majority of the theories and methods in this group determine the limiting state of equilibrium and the ultimate bearing capacity beyond which the load cannot be increased because of the large settlements.

Many theories in this group use crude simplifications and assumptions not justified by theoretical considerations and/or not proven by appropriate tests. The first objection that could be raised is the fact that, in most cases, there is no general failure. The loading diagram does not have a vertical tangent and the end tangent is a slanting line.

Here we have to mention the investigations carried out by Vesić (1963). He tried to determine the phenomena of failure in sand. He introduced, in addition to the modes of failure named after Terzaghi (general shear failure and local shear failure respectively), the term "punching failure." In this case, the penetration of the footing is made possible by the vertical compression of the soil and later, by the lateral horizontal displacement, without mobilizing the total shearing strength. The character of failure depends on the density of the sand, on the foundation depth, and on the width of the footing. Vesić presented a diagram in which he defined the fields of these failures as functions of the variables mentioned above. Based on the numerical values given in this diagram, it is evident that we always have a punching failure with piles, without a vertical tangent of the load–settlement diagram.

A further error in principle arises because many theories calculate the surface friction and the point resistance separately as limit values, and, subsequently, without taking the settlement into consideration, these values are added and the sum is regarded as the ultimate bearing capacity. The theories often neglect the axial symmetrical character of the problem and calculate, for example, the normal stresses on the pile shaft with theories assuming plane strain. Thus, the application of theories of limit equilibrium may not be regarded as a sound method; even if some of the above errors are eliminated, they do not indicate the future direction for theoretical evolution.

The separation of point resistance and surface friction, and possibly the neglect of the latter, is fully justified, if we have to deal with the bearing capacity of caissons or shells and heavy sinking wells, but not in the case of piles. This is the problem attacked by *Berezantzev (4/2)* in his paper. An essential feature of the case investigated by him was that there are no lateral outward displacements during the construction period and the soil around the pile does not become compacted during the sinking of the caisson. The surface friction can correctly be neglected in his investigations. He reaches exceedingly instructive quantitative conclusions in comparing the driven pile and the sunk open caisson: their respective behaviours show marked differences. In the latter case the settlements are much greater and the loading diagram is a smooth curve without resulting in a critical load. He concludes that we must not use the same criteria to determine the bearing capacity, and that the settlement has to be the determining factor. He determines the limiting value of the load acting on the base surface; the safe value of the stress will be given by the extension of the plastic zones beneath the base, which will be limited to a certain degree. This method of calculation, formerly quite common in soil mechanics (Puzyrevsky, Fröhlich, etc.), represents a rather rough approximation. It completely separates the ideal elastic and plastic zones, assuming a very simplified loading diagram; the extent of the sliding zones is fictitious. However, the model tests performed by Berezantzev revealed that there is a correlation between the relative settlement and the extent of the sliding zones.

The manner of developing the theory further has been pointed out by the author himself: a solution of the combined problem of the theory of elasticity and the limit equilibrium theory is necessary. This is, actually, the requirement whose importance was stressed above.

Williams and Colman (4/26) describe large-scale field tests carried out in the highly overconsolidated and stiff, fissured London Clay in order to investigate the load-carrying capacity of piles with enlarged bases. During the tests they measured the settlements and also the load carried by the enlarged base. They found that the resistance acting along the pile shaft was fully mobilized at small values of the settle settlement. The surface friction reached its ultimate value and, on additional loading, only the point resistance continued to increase. These tests and many others published in the literature confirm that the initial resistance to deformation is predominantly from surface friction, but that, for larger settlements of the piles, as ultimate load is approached, point resistance becomes the dominant factor in the total resistance. This behaviour has been stated by Rutledge (1957) in connection with the paper by this General Reporter presented to the Fourth International Conference.

The authors were able to establish some design criteria, based on their tests in London Clay, by using tolerable values of the settlement under the working load and taking into consideration the peculiar properties of London Clay. The load-settlement relations of the shaft and the base which are shown to be markedly different have been expressed by empirical formulae.

The same soil conditions and the same kind of piles served as materials for the tests of *Whitaker and Cooke (4/25)*.

The load carried by the enlarged base was measured by load cells and the behaviour mentioned above appeared here again as shown by Fig. 5 of the paper. The tests furnished very valuable numerical data on the effect of the enlarged base.

In the third group of the papers included in the first category, we first have the problems of sounding. The general use of the sounding method for the purposes of subsoil exploration will be discussed in another division. Here we intend to talk about its application in the design of pile foundations.

Much has been said about sounding and it is difficult to add anything new. Your General Reporter feels that, for well-known geological conditions, a standardized sounding method always carried out in the same way is an excellent tool for performing subsoil investigations economically. The reliability of the design can be increased if we can obtain a correlation with the real behaviour of piles based on sufficient statistical data.

Three papers dealing with this matter have been presented to this Conference; they also introduce new methods of sounding. *Shashkov (4/19)* presents a combined procedure which aims at reducing the minimum number of costly pile load tests. The method is novel and very interesting: one drives two rods into the ground, one with a wide cone and one with a smooth point. After driving, the rods are tested under a static vertical load. Correlation with the results of many pile-loading tests gave good results. The conclusion, that the specific resistances of piles to vertical loads depend upon the properties of the soil surrounding the pile and not upon the diameter of the pile, very likely holds, to a certain extent but only for specific soil conditions.

Ménard (4/15) shows the use of the test results obtained with his well-known pressuremeter. He intends to give methods furnishing bearing capacity and settlement, and he presents, as a summary, many empirical rules with which to do this. The detailed descriptions of tests, test results, and derivations have been published elsewhere. The General Reporter is somewhat skeptical regarding the instrument's use for settlement calculations; he believes that the procedure may serve this purpose by giving a relative comparison on the compressibility of the different layers.

Begemann (4/1) proposes to use the friction jacket cone (see also his paper published in Division 1 of this Conference) to determine the maximum pulling force on a single tension pile. The adhesion jacket cone measures both the cone resistance and the local friction in various layers. The ratio of these is related to the type of soil encountered.

It is worth emphasizing some of Begemann's important results. The effect of the type of soil is very significant; the pulling force cannot be calculated from the data on the local friction resistance. Numerical calculations have been made possible only by a correlation obtained from large-scale field tests. After repeated loading and unloading there is a marked decrease in the value of the adhesion. The same result was observed in many earlier investigations; the tests of Habib (1953) mentioned earlier confirm this effect, for instance. It would be desirable to supplement Begemann's paper by a description of the soil conditions and the numerical values of the soil properties. This would also help in applying the method in other circumstances.

In the field of investigations aimed at the determination of the behaviour and bearing capacity of single piles, the papers presented to this Conference point out the right path for research, at least as regards the methods used. No mention has been made of the pseudo-theoretical pile-driving formulae and this supports the opinion held for a long time by your General Reporter that there is, in general, no possibility of predicting the future behaviour and settlements of a pile under static loads from pile-driving formulae. However it is absolutely reasonable and right to collect and statistically evaluate many well-documented cases, pile-driving records, load test results, physical characteristics of soils, data on soil profiles, and results of soundings. In this respect a properly organized collection and evaluation would add tremendously to our knowledge. I propose, therefore, to the International Society of Soil Mechanics and Foundation Engineering that a subcommittee be set up to work out first the principles and the form for the data, and that the collection and evaluation activities be organized with the help of the National Committees. The reports of this subcommittee could be discussed at subsequent Conferences and the discussions would surely provide guidance for research. The subcommittee would work out recommendations for test-piling and loading-test procedures, as its first task.

THEORETICAL AND EMPIRICAL INVESTIGATIONS OF THE BEHAVIOUR OF PILED FOUNDATIONS AND PILE GROUPS

Piles are always used in groups but in spite of this it is only recently that we began to investigate the bearing capacity of pile groups by making use of the methods of soil mechanics. The "efficiency formulae" of the past solved the problem in a mechanical way and neglected its essential elements. It is true that the settlement of one pile depends only on the soil surrounding the pile, but the settlement of the complete pile foundation depends on the number and spacing of the piles, on the method of construction, and, above all, on the compression of the layers underneath the pile tips. Today the results of theoretical and empirical investigations are available. The majority of these investigations, however, relate to idealized and simplified conditions, and to soil profiles that are not very often confronted in practice, or for which one would not use a piled foundation. Although there are some well-established results which have been translated into standards and foundation codes, the number of cases for which definite rules can be given is small.

There is, first, the suggestion made by Terzaghi for pile groups in clay: it gives the ultimate bearing capacity of an entire pile cluster including the soil located between the piles, provided that the probable failure will come about by breaking of the foundation as a unit into the ground. Another rule states that groups composed of piles driven in sand may have a greater bearing capacity than the sum of those of the individual piles, provided that the spacing of the piles is smaller than a given upper limit. In more complicated cases we are compelled to use some rough guesses. It has not yet been clarified whether there are great differences when the pile cap rests on the soil rather than being supported by the piles only.

With respect to the theoretical investigations we may mention the work of Nishida (1963), who calculated the superimposed stresses on the basis of the theory of elasticity and developed some statements of principle. Then, there are many methods which determine the forces in the piles by the statistical investigation of the entire pile foundation (for instance, Ostenfeld, 1922; Nökkentved, 1929; Vandepitte, 1957). The role of these theories and methods in soil mechanics is similar to that of the theories of elastically supported, load-bearing structures, using a coefficient of subgrade reaction. The simplifying assumptions make a clearcut mathematical solution possible, although the assumptions are far from reality.

We have no papers giving solutions based on the theories of elasticity or statics among those presented to this Conference; those contributed concern case histories and semi-empirical methods characteristic of soil mechanics. *Cambefort (4/3)*, in the paper discussed earlier (*supra*, p. 258), publishes some data on the behaviour of pile groups in sand. The same problem has been attacked by *Kishida and Meyerhof (4/10)*: they applied centric and eccentric loading to their model groups. They arrived at a theoretical equation for the bearing capacity in sand, including the lateral forces on the sides of the groups, and in addition for individual pile failure the uplift resistance of piles, taking it as a block which is capable of undergoing rotations. The lateral forces will increase to the maximum value, corresponding to the coefficient of passive earth pressure. The authors state that there is no increase in bearing capacity in dense sands because of the dilatation of the soil around the pile due to driving. Your General Reporter believes that this dilatation is limited in reality to a rather narrow zone around the pile which cannot influence either the bearing capacity or its increase. The critical void ratio decreases with increasing vertical pressures and, consequently, the dilatation will be rather small.

Among the papers of the second group are four dealing with the behaviour of pile foundations in clay. Let us take a look at this field; we have mainly case histories.

Yu, et al. (4/28) present the settlement records of fourteen structures founded on piles. Precast reinforced concrete and cast-in-place concrete piles of about 20–30 m and bearing on a relatively stiff clay layer are in general use in Shanghai today. To compute the settlement, the pile foundation was assumed to act as a deep foundation without making allowance for shearing stresses acting on the sides of the pile-soil block. The measurements covered a period of 3–7 years and the extrapolated final settlements have been determined from the consolidation curves. The accuracy of computed settlements was very satisfactory. The absolute value of the settlement is quite high and there is no indication whether the piling acted as a settlement reducing agent or not. The authors suggest that piling slows down the rate of the settlements, thus allowing the different parts of the structure to adapt themselves by creep to the deformations without the damage often caused by non-uniform settlements. This study and the paper by *Mohan, et al. (4/17)* both prove the classical thesis that relatively short piles have very limited value in minimizing settlements as in such cases the whole foundation acts as a large spread foundation. The fact that the settlements of the structures investigated by *Yu, et al. (4/28)* could be computed with reliable results as settlements of a spread foundation gives further support to this statement.

The settlement in the case described by *Mohan, et al. (4/17)* was also calculated on this basis. The damage due to excessive settlements could be repaired in a manner normally associated with spread foundations. Both these excellent and well-documented papers present very valuable numerical proof of some known theses.

In the case described by *Gibbs and Merriman (4/5)* a very large number of piles was driven in a soft clay. The effects acting during construction were important and the amount of the settlement caused by them was greater than the settlement due to the weight of the structure itself. The backfilling of the foundation pit which had been excavated with gentle slopes had very important effects: these were so extensive that they encompassed the entire pile foundations. It would be interesting to see the distribution of the settlement among its various causes. The paper proves, however, that the piles reduced the settlements by transmitting the loads to a deeper and somewhat stiffer layer. The detailed and precise settlement observations extending over a long period greatly enhance the value of the paper.

Lambe and Horn (4/12) discuss similar additional settlement. On the M.I.T. campus, piles were driven in the vicinity of an existing building. The authors measured the pore water pressures, and the heave and the settlement of this building. The relatively high pore water pressures dissipated rather quickly, but the settlements were much smaller than would be expected from the large excess pore pressures. The authors ascribe this result to the disturbance of the samples and to the rigidity of the structure. Moreover, the pore pressures measured outside of the building were higher than those under the structure.

Some of the papers in this group bear out the opinion set forth by the previous general reporters that piles driven in clay are of limited value in reducing the settlement of a structure.

The paper by *Henry et Paubel (4/6)* deals with a matter somewhat different from those discussed above. A watertight enclosure of unusual size for dewatering operations had to be made. The conditions were much more severe than those usually encountered along the Rhone River. The authors investigated several possibilities and chose, with appropriate explanation, an enclosure made of cast-in-place concrete piles which formed a tight wall, 15 m in depth, around the pit.

INVESTIGATION OF PROBLEMS ASSOCIATED WITH OTHER THAN VERTICAL LOADS, FIELD TESTS, AND PILED ANCHORS

In this group I shall first discuss the investigation of the effect of horizontal forces. Within this section we find papers on theoretical derivations, on model tests, and on the results of field measurements.

For the case of a pile head loaded with a general system of forces, *Davisson and Robinson (4/4)* have carried out a theoretical investigation on the basis of the classical assumptions. They use the concept of subgrade modulus and consider first a constant value for the modulus and secondly a modulus varying linearly with depth. Bending and buckling are treated also. The authors present the results in a simple and practical form, and give simple, straightforward procedures for utilizing the possibilities offered by the analog computer.

Kubo (4/11) made model tests with piles loaded by lateral forces. He replaces the usual $p = ky$ equation with a more general relation: $p = kx^m y^m$. This equation is completely empirical; it contains, however, all the equations proposed so far. The curve that gives the relation between k and pile width is very interesting, as is also the structure of the equation furnishing the effective length of the horizontally loaded piles. Unfortunately, his standard curves, calculated on the basis of the model tests, were not available for the General Reporter. He was somewhat surprised to see a correlation between the N value of the standard penetration tests and the subgrade modulus. A statistical relation between constants of different static and dynamic natures probably has a regional validity for given geological conditions.

Węgrzyn (4/24) also treats the same problem on the basis of model tests. He introduces into his investigations the angle of rotation of the pile head and concludes from his tests that the ratio of the horizontal displacement to the tangent of this angle is constant. This conclusion, according to which the depth of the maximum bending moment is constant, corresponds to the theoretical results obtained by *Davisson and Robinson (4/4)*.

The paper written by *Heyman (4/7)* presents the results of field tests carried out in the investigation of laterally loaded piles. The author successfully utilized an exceptionally advantageous construction situation. The measurements made a very precise solution of that particular practical problem possible and also led to some results of fundamental importance. Your General Reporter feels that the paper may serve as a model for similar field tests and scientific evaluation.

Heyman (4/7) emphasizes that the measurement of the horizontal displacements is very expedient in order to calculate the bending moments in the pile. Also, these measurements may assist in investigating the validity of an assumed equation for the relation between horizontal force and displacement. *Van Milaan et Lousberg (4/16)* recommend an excellent instrument to measure these displacements. A light ray in the pile and an interference pattern serve to measure the deformations. We hope that we shall soon hear of many measurements performed with this instrument.

The problem of the effect of lateral forces induced many research workers to undertake theoretical and empirical investigations.

Johannessen and Bjerrum (4/8) deal with vertical forces caused by the compression of the soil surrounding the pile, that is by negative skin friction. The authors computed the average stress in the pile from the observed compression of the pile. They assumed that the adhesion was proportional to the effective stresses in the surrounding soil. However, it is unlikely that the compression of the pile—about half an inch at the pile head—could cause full mobilization of the adhesion over the total length of the pile, particularly along the lower part of the shaft. This is also shown by the very low value of 0.20 for $K \tan \phi_a'$. It is also probable that the value K did not remain constant in the course of the compression of the soft clay. This paper has the great merit of furnishing numerical data with which to judge this phenomenon, which has been treated quite often but always in a qualitative way. It also helps future theoretical investigations.

The last paper to be discussed in this group is a contribution to the behaviour of an unusual pile, the so-called "cuff pile." *Van der Veen (4/23)* describes this peculiar kind of pile which has been adopted to utilize a particular soil profile. It was interesting to plot, based on the data given in the paper, a diagram showing the ratio of the surface friction and point resistance *versus* pile load. It differs greatly from that which was derived theoretically by the General Reporter in 1957 (Kézdi, 1957) and verified by many measurements. This is caused by the fact that surface friction will not be mobilized on the section above the enlarged cross-section, partly because of the pile driving and partly because of the enlargement. It is probable, therefore, that the "cuff pile" will be advantageous when the surface friction on the upper part is small or negligible, or when the prevention of negative skin friction is intended.

CONSTRUCTION PROBLEMS

There are only two papers in this group. One of them, by *Wu (4/27)*, develops the theory of vibro-sinking, applying it to precast reinforced pipe piles which are used extensively in China today. The author begins with the measured values of acceleration, average sinking velocity, and stress in the reinforcing bars of the wall. The model that serves to set up the governing differential equation is rather complicated; the solution requires extensive mathematical treatment. The General Reporter agrees with the assumption related to the viscous damping on the wall surface. Also it would be difficult to find a more appropriate assumption for the point resistance; the one used by the author considers even the hysteresis loop. The author evaluates the highly mathematical solution in practical applications and his equations also furnish the soil constants that make the calculation of vibrosinking possible. Based on these theoretical derivations, the design of pipe piles of large diameters will be more reliable.

The heads of precast concrete piles often suffer damage during driving. This damage may be caused by insufficient strength of the concrete, or by overdriving. It then becomes difficult to connect the pile with the main construction; overdriving also means the waste of energy. To avoid this damage, *Széchy (4/20)* hopes to assist the practice by proposing a graphical method that uses the ratio of the elastic penetration and the set of the pile.

SPECIAL PROBLEMS

The General Reporter found only two papers which did not fit into the preceding groups and which therefore form a separate group—special problems.

The first of these by *Trofimenkov and Mariupolskii (4/22)* deals with the bearing capacity of screw piles. Their comprehensive testing programme, which included loading tests, pulling tests, loading with pulsating and also alternating forces, using both single piles and pile groups, and the performance of an unusually large number of tests in each group (about two hundred piles were tested), is very impressive. It made possible the construction of formulae and design diagrams for this kind of pile. The design diagrams take into consideration both the bearing capacity of the surrounding soil and the allowable deformation of the pile. It is interesting to see that the loading diagram never goes over to a vertical tangent, not even in the case of pulled piles. I also would emphasize the interesting result that the greatest pulling force did not differ for vertical and inclined piles.

Because of the usually very simple way of installing these piles, they deserve much greater use in the future. The bearing capacity could be even increased by bringing some fluid for soil solidification through the stem down to the plate. The most important field of application will be their use for tension piles and anchors.

In the *Proceedings* of the Paris Conference, Széchy (1961) gave an account of his findings with model tubular piles and pointed out that there was no appreciable difference in bearing capacity between open and solid bottom piles. Petrasovits (1964) made further investigations with this special type of pile and carried out many model tests. He proposed that the inner surface of the pile be shaped conically, and presented for this case the solution of the stressed state in the inner earth plug which forms during driving, and he gave a formula for bearing capacity. Proposing some interesting practical techniques, the author proved the great economy connected with the use of pipe piles.

Locher (4/14) gives an account of a peculiar and, at the same time, ingenious solution for a pile which was made up of cast-in-place and precast sections. The paper may serve as a firm reminder to many members of the profession that the application of soil mechanics does not always require the use of a highly mathematical solution. Nor does it necessarily consist of mechanically substituting numerical values into complicated formulae. Profound knowledge of the basic principles facilitates the preparation of a design which not only eliminates damages and failures likely to occur with standardized solutions, but also may help to find substantially more economical design. Your General Reporter gladly shares this opinion. This kind of union of theory and practice may serve as an example for civil engineers practising in the field of foundations.

On reaching the end of my report I feel bound to quote some sentences from the first Report ever written on pile foundations for an international conference. At the Cambridge Conference (1936) Crandall wrote the following words which are well worth consideration even after thirty years and which I feel deserve to be included here.

> The use of pile foundations used to be a simple problem and one to which engineers could always resort when in doubt or difficulty. Pile driving was then a pleasant and profitable pastime. Today the problem is becoming so complex and involved that the use of piles may soon have to be abandoned. In the past it was so easy to drive piles to some resistance by some formula, multiply the number of piles by this resistance and thus obtain a foundation. Today we know that our formulae were faulty, that the resistance of one pile is not indicative of the resistance of the entire group and that the entire group with its surrounding soil mass may be constantly settling. Such is progress.

We did not abandon the use of piles—I guess we never shall—and the somewhat skeptical tone of the text, listing almost all of our present problems concerning piled foundations, would lose its bitterness and become a more pleasant one by following the progress achieved at international conferences held since 1936. However, if doubts, skepticism, and discontent are the guarantee of progress—and they certainly are to some extent—then we are, even today, justified in hoping and expecting that this progress will be realized in the near future.

CONCLUSIONS AND ITEMS FOR DISCUSSION

I strongly believe that the establishment of a reliable design procedure for piles, based on an understanding of the behaviour of different piles under different soil conditions, is the most important step to be taken. I think that any detail that adds something to our knowledge in this field is to be welcomed. I suggest, therefore, that the following problems, listed in order of importance, be discussed.

1. Stresses and deformations in and around piles during vertical loading, in different soil profiles. (Model tests, field tests, theoretical investigations, and measurement on structures during and after construction may all be included, provided that they represent a further step towards further generalization of the rules.)
2. Interactions between pile groups and soil, with reference to the pile caps; investigations regarding the relative importance of factors influencing the bearing capacity of pile groups. Problems of pile groups, although put on discussion at two previous conferences, need further clarification. The influence of the manner in which piles and structures are coupled on the bearing capacity is of great importance; moreover, we have to list the factors that are of primary concern in this problem.
3. Review and criticism of the use of coefficients of horizontal subgrade reaction, in connection with laterally loaded piles. Laterally loaded piles aroused great interest at the present Conference; the approaches to the problem were quite similar. I think, however, that the usual assumptions for the subgrade reactions are worthy of discussion, to further the development of a better approximation, with the help that modern computers could give always in mind.
4. The most important features of pile-loading tests to be included in recommendations on their use and evaluation. Reviewing the papers of the first group, I suggested that a committee be formed on pile-loading tests. Any experience reported, opinions stated, and suggestions made would certainly help the work to be done by this committee.

CONCLUSIONS ET SUJETS DE DISCUSSION

Je crois fermement que l'adoption d'une technique éprouveé pour le calcul des pieux, basée sur une compréhension du comportement de différents pieux sous diverses conditions de sols, soit la mesure la plus importante à prendre. Je crois que tout renseignement susceptible d'accroître nos connaissances dans ce domaine doive être accueilli. Je suggère, par conséquent, que les problèmes suivants, inscrits par ordre d'importance, soient discutés.

1. Contraintes et déformations à l'intérieur et autour des pieux durant un chargement vertical sous diverses conditions de sols. (Les essais sur modèles, essais sur le terrain, recherches théoriques, et mesurages des structures durant et après la construction peuvent tous être inclus, pourvu qu'ils constituent un autre moyen d'aider à généraliser davantage les règles.)
2. Interactions entre les groupes de pieux en fonction des capuchons de pieux. Recherches sur l'importance relative des facteurs influençant la capacité portante des groupes. Bien que les problèmes des groupes de pieux aient été discutés lors de deux congrès précédents, ils exigent, néanmoins, d'autres éclaircissements. L'influence exercée par la façon dont les pieux et les structures sont accouplés, sur la capacité portante, est d'une grande importance; de plus, il nous faut énumérer les facteurs qui jouent un rôle primordial dans ce problème.
3. Revue et critique de l'emploi de modules de réaction horizontale du sol relative aux pieux chargés latéralement. Les pieux chargés latéralement ont suscité un vif intérêt durant ce Congrès; le problème fut aussi abordé de la même façon. Cependant, je crois que les hypothèses courantes sur les réactions dans les soubassements méritent d'être étudiées afin de permettre une meilleure approximation, sans toutefois oublier l'assistance que les ordinateurs modernes pourraient apporter.
4. Les caractéristiques les plus importantes des essais de chargement de pieux devant être incluses dans les recommandations se rapportant à leur emploi et à leur évaluation. En revisant les communications du premier groupe, j'ai suggéré qu'un comité d'essais de chargement de pieux soit formé. Ce comité serait certainement secondé dans sa tâche si toute expérience, opinion et suggestion lui étaient transmises.

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