NEGATIVE SKIN FRICTION AND SETTLEMENTS OF PILED FOUNDATIONS

FROTTEMENT NEGATIF ET TASSEMENT DES FONDATIONS SUR PIEUX

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FOREWORD

When, a little more than a year ago, Prof. Marsal suggested to us that we should act as Organizers for this Speoialty Session, we thought that one of most important purposes to be achieved was to gather up a large amount of references on experiments in development at present. It was our aim also, to make it possible for specialists working on the subject matter of the Session to attain a proficuous intercourse of data investigation. The idea of publishing a volume that would comprehend all these investigations, not reduced to the specific subject only but including different aspects in relation to the general behavior of piles and piled foundations, was thus conceived. Professor A.J.L. Bolognesi, Bs. As. University and Prof. O. Moretto, La Plata University, consulted on the subject, bore this point of view too and accepted to act as advisers during preparatory period of Specialty Session. The mostly efficient collaboration of the Engineering School of Buenos Aires, who issued the special volumes, which included 18 papers written by distinguished specialists, by the first fortnight of August, made it possible to attain the afore mentioned purpose and, at the same time, to demonstrate that a large group of young men were developing important contributions to the theme. The Session was thus organized to obtain brief personal participations that would put forward many different points of view with respect to the problems involved with the purpose of providing information to all those who were interested and, at the same time, to invite to post-Session discussion on the different points arisen. Organizers expect to publish a second volume including these post-Session papers whose content will prove to be of great value to the bibliography on the subject.

Due recognition must be given to Professor T. W. Lambe for his acceptance to act as Chairman and his collaboration in conducting the Session, which has been highly intersting and valuable.

Introduction.-

The prediction of a single pile or a pile group behavior under loading is related to an adequate knowledge of the subsoil characteristics and the actual distribution of efforts due to the interaction between soil-single pile or soil-pile ground which governs the relations between loads and foundation settlements.

The change of soil properties due to piling and its stress-strain-time variations proves the proper design of piled foundations to be one of the most difficult problems in Soil Mechanics not enterely solved hitherto by a single calculation method.

As a general procedure, it is assumed that one part of the load acting on a pile is transfered to the soil along the pile shaft and the other part is resisted by the soil located beneath the pile point. The subsequent consolidation phenomena modify the primary load distribution as well as the stress-strain characteristics of the soils located along the pile shaft and in the zone of influence under the point. These phenomena may be caused either by an increase of the resulting total pressures - in the case of external loads - or by a change of the pore-pressure in the soil mass due to driving, phreatic level variations or pumping from wells under practically constant total pressure. In both cases the effective pressure varies with time. In addition, the heterogenity and anisotropy of soils involved in every piled foundation increase largely the number of parameters to take into account for a quantitative analysis and makes the interpretation of the process even more difficult.

The magnitude and direction of a load transference along the pile shaft depends on the relative movements between soil and pile. These movements, in turn, are influenced by the nature of the soil strata located under the point of the pile. The negative skin friction occurs when the soil moves downward with respect to the pile shaft.

Negative skin friction.-

Numerous contributions on this subject have been made in the last decade. However, the use of the different theories or the application of existing experimental data convey, in some cases, to quite different results.

The difficulty lays, not only in the elaboration of an adequate mathematical approach, but in the correct application of the parameters obtained using field test experiences too.

The conclutions arrived at by distinguished specialists and published previously to the Conference are not commented here, since the purpose of this Report is to deal with papers submitted to this Specialty Session.

A. Verruijt (Paper 5) puts forward an elastic method for the calculation of negative skin friction on a single pile. Negative skin friction is due to the consolidation of a layer composed of homogeneus, elastic material loaded on the surface by a uniform vertical load. The point of the pile is embedded in a rigid base.

Friction forces are computed in two different cases by the use of a differential equation of elastic equilibrium, which allows to calculate the vertical displacements of the compressible layer in several points: a) in the case of assuming perfect adhesion between pile and soil and b) in partial slips, in the case that the soil remains in contact with the pile only throughout a limited length of the pile at the lower part of it.

The method assumes the existance of a natural level in the compressible layer. This level ie the boundary between an upper zone where relative vertical displacements take place and a lower one in which these movements are null. The method allows the computation of the negative skin friction in terms of the uniform vertical load, for different values of friction coefficient, Poisson's ratio and the relation between the thickness of the compressible stratum and pile diameter. An example and its results as compared with those obtained using De Beer's and Zeevaert's solutions and the experimental data published by Brons, Amesz & Rinck are included in this paper.

Begemann (Paper 1) develops a method to evaluate the negative skin friction on a single pile driven through a profile formed by an stiff upper layer of sand under which a soft clay stratum lays. Both layers rests upon a compact formation which can be penetrated by the pile point. The author obtains an expression which allows to estimate what part of the load acting on the upper layer is transfered to the pile by using the formulae of Timoshenko for a concentrated load on an infinite plate on an elastic foundation. On the other hand, using its own cone method, he computes the maximum pulling force of a tensile pile with a length equal to the thickness of the stiff upper layer.

The maximum load to be transfered to the pile can be obtained according to the Theory of Elasticity by a formulae expressed in terms of: the modulus of linear deformation and the Poisson's ratio of the upper layer, the initial effective pressure and the consolidation coefficient of the soft clay, the geometrical pattern of the problem and the upper layer settlement. If the latter is formed by dense sands a relative soil-pile settlement of 4 mm is considered enough to develop the maximum friction along the pile shaft.

Comparing numerical results obtained using both solutions, the author concludes that the maximum friction calculated as a tensile pile always gives the smallest value and therefore the negative skin friction can be limited to the pulling resistance of a pile embedded in the sand upper layer. At the same time he recommends to adopt as negative skin friction 75% of the total pulling force computed using the cone method, since the process of pile extraction takes place under a relative movement velocity greater than those existing in a long term process. Finally, the author compares the results obtained by using the method and experimental values reported by Brons, Amesz & Rinck.

Locher (Paper 8) presents a computer program which can be used to solve Zeevaert's differential equation for the evaluation of negative friction on a group of piles under general conditions assuming constant or variables values of Ko, tg ϕ', c' and γ . He points out that direct mathematical solution of the Zeevaert's equation is only possible in special cases when the soil-pile properties remain constant along depth. A numerical example is included showing how to calculate the negative skin friction on a piled foundation under the load of a building surrounded by a fill. In this particular case he founds no significative influence on the total value of the friction when soil and pile properties are constant over the length of the piles.

Davis & Poulos (Paper 15) present a summary of recent theoretical solutions for the behavior of single piles resting on a rigid base under negative friction. In all cases the soil is supposed to be an homogeneous elastic material, with the modulus of elasticity and Poisson's ration unaffected by the presence of the pile. In the included diagrams negative friction can be computed if the soil and pile elastic characteristics and geometrical pattern are known. They point out the necessity of carrying out loading pile test to determine representative elasticity parameters.

Among the group of papers referring to measurements obtained in full-scale load tests, Brons, Amesz & Rinck (Paper 2) have made an important contribution to the empirical knowledge of negative skin friction distribution along a single pile shaft due to fill loading.

They report the tests carried out in cast-in-place Vibro piles, with a precast unit in the lower part provided with a steel pressure box; 3 piles with identical measurements devices in which provisions were made to reduce friction (one of them with a metalic casing covered by a layer of bitumen 20/30, 10 mm thickness, and the other two with a bentonite slurry 3-4 cm of initial thickness, surrounding the casing); and finally a smooth steel pile with steel wires attached inside the tube at various depths to measure up relative displacements. A complete set of apparatus were installed to register settlements near the piles at ground surface and at different levels as well as piezometers for pore-pressure recordings. On the location of each test pile static cone penetrometer tests were made and undisturbed samples were secured and tested in some places. The results reported include the valued of negative friction and settlement in terms of the time and the values of negative friction related to corresponding soil settlement. The measures obtained are compared with the theoretical values computed using Zeevaert - De Beer's method showing a good agreement. It is interesting to point out that the negative friction in Vibro pile, is of the smae order as the existing in the smooth steel pile. The reduction of negarive friction is 50% in piles with bentonite slury around their shafts and 90% in the pile covered by the bitumen layer.

Fellenius & Brons (Paper 12) report the first results obtained in a program of tests which are being carried out on precast concrete piles driven through 40 meters of normally consolidated clays, 13 meters of silts and 15 meters of sand. The purpose of the soil undrained strength or effective soil pressure immediately after pile driving and its variation with time, relation with settlements and the corresponding downdrag forces, and the effect of driving in negative friction. In future program stages, the authors intend to study the behavior of piles under axial loading and subsequently the effect of a fill placed over the area round the piles.

The piles have been instrumented with load cells designed to resist the dynamic effects of driving. Settlements gages and piezometers have been installed in the ground at different depths and distances from the test piles before driving. The values obtained immediately after the pile driving and in the first 5 months of measurements show interesting conclutions: The soil settlements due to consolidation of soils by the dissipation of overpore-pressures built up by the pile driving are small; the negative friction after 150 days is of the order of 17% of the soil average undrained strength or 5% of the average effective overburden pressure. During oral discussions, Mr. Fellenius reported that the value of negative friction reached 25% of the undrained strength.

With the purpose of controling the effect of downdrag forces, several ingenious solutions have been lately developed based upon the use of composite piles. Correa (Paper 11) describes a new telescopic pile adequate for subsidence conditions such as those existing in Mexico City. The bearing capacity of this pile derives from positive skin friction and point resistance. The favorable effect is obtained by friction between an upper tubular section of the pile and a gravel fill inside which transfers the load to a lower section resting on a firm stratum. When the upper section slides down downdrag effects are avoided and positive friction forces are developed in the inner face of the upper section. The maximum value of the friction is reached when the downward movement of the upper part takes place at the same rate as the general soil settlement. The author includes the results obtained in a model test and recommends the use of the telescopic pile in soils undergoing consolidation where a firm stratum can be economically reached by the pile points.

Sultan (Paper 13) afforded a good contribution with his up to date state of the art on negative skin friction.

Settlements of piled foundations.-

Davis & Poulos (Paper 15), in the already mentioned summary, include diagrams to compute the settlement of a single floating pile and pile groups. In the latter, they compare the results obtained in pile groups with or without rigid caps. The practical use of the solutions are limited, as the authors point out, by a correct experimental evaluation of the elastic parameters used in the equations.

Kézdi (Paper 9) reports a very interesting procedure used to improve the bearing capacity of a group of Franki piles supporting a grain silo. After completion of the piling, the loading tests proved that the actual bearing capacity of the piles was, in several cases, half of the design value. On the author instructions, it was decided to increase the resistance of the pile group by preloading using the dead weight of the structure and to accelerate the consolidation rate by the use of sand-drains. Special devices will be placed on the pile heads before filling the silo cells to transfer the load to the piles. Since the total final settlements after preloading were of the order of 20 mm, the piles were probably submittet to the maximum negative friction before the filling of the cells. The friction will turn out to positive when the piles are loaded. The discussion of final results will be, undoubtely, an important contribution.

Vardé, Núñez, Bolognesi & Moretto (Paper 16) describe the experience acquired in the design and construction of three large tanks piled foundations in clay. Tanks are 160' diameter, 72' high, 40,000 m^3 capacity each. The authors report data obtained from soil investigation, loading pile tests and control measurements during construction and after erection of the tanks. The authors report data obtained from soil investigation, loading pile tests and control measurements during construction and after erection of the tanks. The foundations consists in a 25 cm. thick slab with square column capitals and a marginal beam resting upon 540 precast reinforced concrete piles. In tank N° 3, which erection is being carried out at present, several piles located along a tank radius were instrumented with strain-gages to determine experimentally the point load and the firction load distribution in the pile group. Quick response piezometers were also installed at the center of the foundation at different depths to follow the development of pore-pressures upon loading. The results to be obtained during hydraulic loading of the tank will be reported in future papers. The authors hope that they will contribute to a better understanding of pile group behavior.

Nishida (Paper 14) presents a theoretical solution to estimate the pile group effect on sands. He defines a failure zone around piles as a result of massive piling. The radius of this zone depends on the pile spacing and the soil modulus of elasticity. He assumes that the soil located out of the failure zone remains in elastic state.

The bearing capacity and the settlement in pile foundations are dependant on the mechanical properties of the soil which is affected by stresses in the soil. The paper gives a method to estimate these stresses in order to study pile group behavior in cohesionless soils.

Cassan (Paper 17) describes a method to determine the settlement of a single pile in an homogeneus material with a linear stress-strain relationship, using the subsoil characteristics provided by "in situ" pressurometric tests. The parameters used in computations are a function of the deformation modulus. Comparing the results obtained with the experimental values of 9 tests, the author finds a relation between actual and computed deformations in terms of the normal stress on the piled head. He also presents a relation between the normal stress in pile head and in pile tip in terms of the relation $\frac{h}{D}$, length to diameter of the pile.

Reséndiz, Auvinet & Silva (Paper 18) make a very complete report on the behavior of the Mexico City Sport Palace foundations. The circular structure, 180 meters diameter, transmits to the soil a load of 22,000 tons through 1,400 piles. The soil formation is the typical in Mexico City where exists a regional subsidence, due mainly to pumping from wells, at a rate of approximately 15cm per year. The contribution includes a detailed description of subsoil strength and deformation characteristics which allow to evaluate the phenomena studied by the authors. The foundation was designed to accomplish with the following requirements: to avoid differential settlements due to local subsoil irregularities, to avoid larger settlements in periferical piles than those to be experimented by the central piles due to negative skin friction, and to obtain a rate of the structure settlement of the same order of the general subsidence movements.

The piles are precast reinforced concrete piles of square section 40 x 40 cm They were built in sections joined together by the welding of terminal steel plates. The piles are provided with a 4" diameter metalic pipe in the lower part with the purpose of controlling the relative pile-soil movements under loading to achieve the foundation design requirements already mentioned. The pore-pressures, the soil deformation development, the construction effect on the horizontal and vertical soil movements, the foundation displacements, the behavior of piles during driving and its stress-strain characteristics, were registered during and after construction work. The vertical movements recorded show a good agreement with the foreseen behavior. The results of 35 loading pile tests are included and classified according with the different shapes of the load-settlement curves.

As an important conclution, the authors remark the time influence in the negative skin friction development and the effect of bulging ground movements due to piling which cause tensile efforts on the piles. These efforts are capable of breaking the welded joints, or of taking apart the point of the piles form the bearing stratum or avoiding the effect of the negative friction. The general behavior of the foundation is, hitherto, very satisfactory with a good correlation between the design previsions and the experimental measurements.

Effect and distribution of the load on piled foundations.

Tavenas (Paper 4) describes the technique used and results obtained in pile loading tests carridi out in sands on 4 different types of piles: precast concrete piles, steel piles, timber piles and cast-in-place concrete piles.

The precast "Herkules" piles and the "H" steel piles were instrumented to determine the distribution of stresses for each stage of the tests. In these piles, it is possible to register the variations of the bearing capacity, the point resistance, and the skin friction in terms of the embedded pile length. According with the measurements recorded, the bearing capacity is not a linear function of the piles embedded length. A critical depth can be defined under which the increment of resistance is relatively small.

The results indicate a greater friction value in the timber piles, due, perhaps, to a different shape factor. The experimental data show the variation of the skin friction and point resistance in terms of the pile settlements. In the Herkules pile the friction increase linearly up to a value of approximately 540 p.s.i. corresponding to a settlement of 0.175 inch. For further settlements the friction keeps almost constant.

In the steel "H" piles the analysis of results is more difficult due to the influence of the soil located between the flanges at the pile tip. The maximum measured skin frictions range between 330 and 500 p. s. i. It is not possible to determine a precise limit value due to the shape of the skin friction - displacement curves. Equally, critical point-resistance values can not be defined, although a linear increment is observed up to a settlement of 0.15" where soil rupture starts. The results agree with the observations made by Kerisel and Vessic in laboratory conditions. The author defines a critical depth at a ratio D/B = 23, below which ultimate point resistance and skin friction are constant. He confirms that for a given type of soil-pile system exists a constant relation between point resistance. This relation in a function of the relative density of the sand before driving. Finally, he remarks that the H pile behaves as a displacement pile at shallow depth and as a non-displacement pile at great depths.

Renau & Enderli (Paper 6) report the results of a loading test on a bored great diameter piles with the tip inserted in crushed shales. When the pile was finished, a central boring was made trougnout the pile and 5 Carlson extensometers were installed inside to determine the friction along the shaft. The samples obtained from the boring were tested to determine the concrete elasticity modulus. In addition, two deep plate tests were carried out. The authors present the curve stress-settlement obtained in a plate, 200 mm diameter, placed at the bottom of a cased boring of a slightly larger diameter. They propose the systematic execution of buried plate tests to define the diameter -settlement correlation, similarly to that existing for shallow foundations.

De Beer & Wallays (Paper 3) report the experimental data obtained in pulling load tests made on precast concrete piles, cast-in-place piles and bored piles, and compare their results with those obtained in static-cone penetration tests. One bored pile, 600 mm diameter, was installed at Zelzate using a turn-grab boring equipment and bentonitic mud. The tip of the pile reached a dense sand layer at 26,30 m deep. The pile was submitted first to a compression load test, up to 300 tons, and then to a pulling test up to 250 tons. The authors include a detailed analysis of the load-pile ascendant movements curve. The critical tensile load is computed using the Van der Veen method. Five cast-in-place piles, 6.30 meters long, were driven at Anvers. Four of them were made using Franki technique in all of which, except one, and enlarged base was built. In the 5th pile, the 5 mm thickness casing was left in the ground. All piles, except the one encased, reached 90 tons in pulling tests without showing failure. Two piles were tested once more, after removing the sand, up to a depth of 5,75 m by air-compressed action. The critical tensile loads were obtained using the same method as before. Several penetrometric cone tests were made before and after pile installations to verify the driving influence in sand density. In addition, the extraction forces were measured during the pulling of penetrometer pipes to study the influence of compression-pulling loading sequence. The authors find a correlation with some of the Mazurkiewicz experimental conclutions.

Finally, the piles were submitted to repeated cycles of extraction. The measurements indicate that the pile vertical displacements increase remarkably with the logarithm of n, number of extraction cycles. The authors conclude that extraction pile resistance can be evaluated safely from the friction measured in penetrometric cone tests; the installation of bored piles using bentonite does not seem to have influence on friction resistance; the pile critical pulling force diminish with cyclical tests, and this critical force can be evaluated more accurately using secondary extraction values. The allowable pulling load is determined by the concrete fissuration in piles driven or bored in cohesionless soils.

Guy de Castro (Paper 7) reports obtained in load tests carried out in reinforced concrete piles driven in sandy soils. Axial compression, pulling, single and combined bending tests were performed and measurements recorded discussed. In the case of horizontal load the author compares the results with the solutions of Winkler, Mallock & Reese and Biot.

Various.-

Lowery, Hirsch, Edwards, Coyle & Samson (Paper 10) make an study of the use of computer solution of the wave equation to predict driving stresses in piling and to estimate static load bearing capacity of piled foundations.

Oral discussions.-

The Session was held on August 28, acting as a Chairman T. W. Lambe.

The following topics were discussed in the first part of the Session: a) magnitude and distribution of friction immediately after construction; b) changes with time due to negative friction or other causes.

The expositors were : O. Moretto, B. H. Fellenius, K. F. Brons, J. J. Correa, H. G. Poulos, P. Girault, M. Bozozuk, Bello, B. B. Broms, L. Zeevaert, Focht, Van Vem Whele, Fuentes, Flores, Muratti and Enríquez.

The second part was devoted to the discussion of settlement of piled foundations. The expositors were: A.J.L. Bolognesi, E.E. De Beer, H. Cambefort, F.A. Tavenas, L. Fernán dez Renau, O.A. Vardé, A.S. Vesic, A. Kezdi, D. Reséndiz, E. D'Appolonia. The Session was closed by Dr. T. W. Lambe's remarks.

Written discussions will be included in a second volume to be published by the Facultad de Ingeniería de Buenos Aires.