The Effects of Horizontal Loads on Piles, due to Surcharge or Seismic Effects

Les Effets sur les Pieux des Charges Horizontales dues aux Surcharges ou aux Actions Sismiques

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I. INTRODUCTION by Dr. K. Aoshika

The Specialty Session No. 10 was concerned with the effects of horizontal loads on piles, due to surcharge or seismic effects. Special emphasis was put on the problem of horizontal loads induced in piles through the surrounding soil due to asymmetrical lateral surcharges in the vicinity of piles as well as to the effects of horizontal dynamic loadings and of earthquakes.

Organization of the Specialty Session on this theme was fully justified, as in the past the horizontal loading induced in piles due to asymmetrical surcharges has often been overlooked, leading to severe damages to piles and consequently to the structures. There are also examples of severe damages caused on piles by earthquakes. The Tokyo Conference was certainly an appropriate place for exchange of ideas on these problems, because Japanese hosts have a great deal of experience and have made several theoretical approaches.

By the request of the Organizing Committee Prof. E. De Beer of Belgium took the task of organizer of this session and Prof. E. Nonveiller of Yugoslavia accepted to act as co-organizer. Dr. Aoshika (Japan) was appointed as a secretary and Dr. Sawaguchi (Japan) acted as his deputy.

The objective of this session was to make clear where we stand and to exchange views on these problems. In order to achieve this objective both the organizer and the co-organizer have agreed to plan this Specialty Session No. 10 in the following manner.

1. Dividing the session into two parts. The first part was devoted to the static problems and the second part was devoted to the dynamic problems.
2. Providing two state-of-the-art reporters. The static part was delivered by Prof. E. De Beer and the dynamic part was given by Prof. H. Tajimi of Japan.
3. Call for papers. Abstracts were collected before October 1, 1976 and full papers were submitted by January 31, 1977 to each of the corresponding state-of-the-art reporters to be included in their reports.
4. Inviting altogether four selected papers from outstanding experts.
5. Publication of the proceedings of this session which include the state-of-the-art reports, the four selected papers, all the written contributions, oral and written discussions and the final remarks.

In the afternoon of July 14 this session was held from 3.00 pm to 6.30 pm with over 500 participants which filled the hall to its capacity. The program of the session was arranged and progressed as follows.

1. Introduction and state-of-the-art report on static problems by Prof. E. De Beer.
2. Two selected contributions on static loading, one by Prof. Jamiolkowski of Italy, concerning the Soil Modulus for laterally loaded piles, the second of Prof. Fukuoka of Japan, new President of the International Society of Soil Mechanics and Foundation Engineering, concerning the practice in Japan for prevention of landslides by steel pipes.
3. State-of-the-art report on dynamic loading by Prof. H. Tajimi.
4. Two selected contributions on dynamic loading, one by Prof. F.E. Richart of the United States concerning the stiffness and damping of a pile system, and one by Prof. Minai (Japan) concerning the mathematical formulation of the effects of dynamic lateral loads on piles.
5. Short presentation of written contributions by Dr. Franke, Germany; Prof. Uriel (for Oteo), Spain; Prof. T. Matsui, Japan; Prof. Sommer, Germany; Prof. Kishida, Japan; Mr. G. Vogrincic (for Sovinc), Yugoslavia; Mr. K.R. Datye, India and Dr. F. Tatsuoka, Japan.
6. Oral discussion by Prof. B.B. Broms (Sweden).
7. Closing remarks by the co-organizer Prof, Nonveiller.

All the papers contributed to this session are listed below.

List of papers

State-of-the-art reports

1. Piles subjected to Static Loads by E. De Beer.
2. Seismic Effect on Piles by H. Tajimi.

Static Loading

3. The Effect of Horizontal Loads on Piles due to Land Slides by M. Fukuoka.
4. Soil Modulus for Laterally Loaded Piles by M. Jamiolkowski and A. Garassino.
5. Bending of Piles due to nearby Surcharges in Elastic Soil by I. Cañizo and M. Merino. Cañizo and M. Merino.
6. Horizontally loaded Pile in layered Soil by C.M. Dordi.
7. A qualitative View of lateral Displacements of Poles and Piles in Sand by J.M.O. Hughes and P.R. Goldschmith.
8. A Field Study of laterally Loaded Piles by T.S. Ingold.
9. The Effect of Piles in a Row on the Slope Stability by T. Ito and T. Matsui.
10. Large Deflection of a Single Pile under horizontal Load by H. Kishida and S. Nakai.
11. Bending Moments Prediction in Piles subjected to horizontal Soil Movements by R. Marche and C.E. Schneeberger.
12. Horizontally loaded Piles, Deformation Influence by C.S. Oteo.
13. Large Diameter Bored Piles for Abutment by H.G. Schmidt.
14. Creeping Slope in a Stiff Clay by H. Sommer.
15. Pile bending Induced by Unsymmetrical Surcharge on the Soil Around a Pile Foundation by M. Wallays.

Dynamic Loading

16. Notes on Stiffness and Damping of Pile System by F.E. Richart and C.S. Chon.
17. Static and Dynamic Tests of Piles under Horizontal Load by J. Petrovski and D. Jurukovski.
18. Deformations and Efforts in Vertical Piles Due to Seismic Loading by B.Boshinov.
19. Surcharge and Seismic Effect on Piles by A.C. Chaturvedi.
20. Reinforced Granular Columns - A New Design Concept by K.R. Datye and S.S. Nagaraju.
21. Dynamic Response of a Single Pile by J.J. Emery and G.P. Nair.
22. Behavior of End Bearing Piles under Seismic Forces by R.J. Flores Berrones.
23. Effects of Soil Liquefaction on Dynamic Behavior of Pile Foundations by M. Hakuno, T. Iwasaki and F. Tatsuoka.
24. Dynamic Behavior of a Laterally Loaded Pile by T. Kobori, R. Minai, K. Baba.
25. Dynamic Horizonl Loading of a Steel Pipe Pile by I. Sovinc and G. Vogrincic.

All written contributions, oral and written discussions will be published in one Volume. The publication of the Proceedings of this Specialty Session is due to the courtesy of the Japanese Association for Steel Pipe Piles.

A brief review of the recent advances and trends discussed in each of the state-of-the-art reports will be presented in the following along with reviews of the contributed papers.

II. PILES SUBJECTED TO STATIC LATERAL LOADING by Prof. E. De Beer

INTRODUCTION

As clearly put forward by Vesic (1975), a distinction can be made between the two following groups of problems:
1. piles which are expected to transmit lateral loads to the soil;
2. piles which are subjected to lateral loading along their shafts by horizontal movements of the surrounding soil.

In the first group the horizontal load on the piles is the cause and the horizontal soil movements are the consequence; we can call these piles "active piles". In the second group the horizontal soil movements are the cause and the horizontal loads along the pile shaft are the consequence. We can call these piles "passive piles".

Of course both groups of problems are governed by the same series of parameters:
1. the deformability of the pile (E, I, L)
2. the deformability of the soil $K_h = F(z, u, b)$, where b = diameter of the pile and u = displacement of the pile
3. the ultimate resistance of the soil (governed by c_u, c', $\emptyset'$).

In each group a distinction has to be made between the problem of a single pile and that of a pile group.

Active piles

The problems of piles subjected to lateral loads either in clay or in sand, under static loads, of short or long duration have already been treated by several authors (Broms, 1964; Vesic, 1965; Matlock and Reese, 1960; etc.). The most important problem is the correct definition or choice of the parameters characterizing the deformability of the soil layers surrounding the pile.

In his selected paper for this session Jamiolkowski (Paper 4) gives a very complete survey of this problem and its latest developments.

Professor Jamiolkowski reviews the different ways of determining the soil modulus to be introduced in the calculation of laterally loaded piles
- full scale lateral load tests on instrumented or uninstrumented piles (uninstrumented piles are those for which only measurements are made at the head of the pile)
- in situ tests: pressuremeter tests, flat dilatometer tests, plate loading tests, cone penetration tests
- laboratory tests.

Attention is also paid to the ultimate soil resistance. The opinion is expressed that

with the use of the self-boring pressuremeter, the ultimate soil resistance for laterally loaded piles could be predicted with more accuracy.
A clear distinction is made for the deformability parameters governing short term and sustained loading in cohesive saturated soils.

Emphasis is laid on the modification of the soil properties around piles due to pile installation, and which is not put into evidence by soil investigations carried out before pile testing.

Also the influence of cyclic loading both on the modulus and on the ultimate resistance are considered.

To this session, Dordi (Paper 6) has introduced a contribution giving the results of systematic calculations performed for the case of piles running through two layers, each having a constant but different modulus of subgrade reaction, the lower layer being stiffer than the upper layer.

In his contribution, Sovinc (Paper 25) describes the results of the measurements made on a fully instrumented long steel pipe with a length of 33 m and subjected to static and dynamic horizontal loadings at its head.

In order to achieve better guidance for the choice of the parameters of the mathematical model, it is of course of great interest to obtain a better knowledge of the displacement field in the soil around a pile subjected to a horizontal load at its head.

In his contribution Hughes (Paper 7) describes how by a special technique he has been able to determine by means of model tests the three dimensional displacement fields around piles subjected to horizontal loads, for rigid, medium flexible and flexible piles, embedded in dry and saturated sands with different relative densities. The imposed head displacements were rather large 1.3 to 1.8 times the pile width, so that in reality rupture conditions were introduced into the soil. The links between these findings, the full scale conditions and the improvement of calculation methods are still to be made.

Kishida and Nakai (Paper 10) present a numerical solution of the differential equation of the deflection of a single pile caused by a horizontal load, introducing into the differential equation typical stress-strain relationships for sands and clays. These relationships are based on the non linear characteristics deduced from field investigations and laboratory tests. Kishida states that the method is also applied to the problem of the soil-pile interaction under landslides, and thus should also give a solution for passive piles.

The primary objective of the session was to concentrate on the problems of piles subjected to lateral loading by horizontal soil movements.

Structural measures for the prevention or reduction of horizontal loadings on passive piles.

Horizontal loadings on piles along their shafts, are always to be considered as rather unfavourable loads, and should therefore possibly be prevented or at least limited. Such horizontal loads can only be caused by the horizontal movements of the soil, occuring after installing the piles. Thus a first principle is to prevent or at least limit such movements. This can be obtained in several ways, from which some are indicated in the contribution by Franke (Discussion), by Ingold (Paper 8) and by Datye (Paper 20):

1. total or partial replacement of the soft layers by a much less deformable material.
2. by supplying the load prior to the placement of the piles and sufficiently in advance in order that most of the horizontal movements have already taken place.

   The preconsolidation time can be shortened by providing sand drains, wick drains and temporary overloads.
3. transmission of the lateral load, adjoining the pile foundation, by means of piles, lime piles or reinforced granular columns (Datye), through the softer layers to deeper competent layers.
4. construction of the embankment of light weight material.

Theoretical approaches of passive piles. Single pile and pile group.

In order to obtain a theoretical approach of the problem, one can try to solve first the problem for a single pile, and then to introduce some correcting factors for the group effect.

However, if such a procedure is possible for the case of "active" piles, these are piles which have to transmit a horizontal load to the soil, this is much more questionable for the case of "passive" piles.

Indeed in the case of "active" piles the total horizontal load to be transmitted to the soil is independent of the presence of the piles. This horizontal load is one of the data of the problem. In the case of passive piles, the horizontal soil movements make up the data of the problem; however these soil movements are now dependent of the presence of the piles. Where it is possible that the presence of but one pile does not influence the general horizontal movements, it is possible that a pile cluster will be able to completely stop these movements, creating a completely different situation as for a single pile.

In opposition with the case of the problem of active piles, it will therefore, in the case of passive piles, in certain cases be necessary to consider from the beginning the problem of the pile cluster as a whole.

Different calculation methods.

In as far as it is admitted that the soil movements at large are known, different methods have been used to obtain a theoretical solution:

1. the soil is considered to be characterized by a modulus of subgrade reaction, either constant or variable with the depth z and with the relative displacement of the pile versus that of the soil ($u_p - u_s$).
2. the soil is considered to be a linear elastic material or an elastic material.
3. the finite element method for bilinear or a hyperbolic material.

Method of the modulus of subgrade reaction.

Since the linear dimensions of the cross section of the pile are small compared to its length, the pile can be considered as a beam the classical differential equation is written:

$$E_p \, I \, \frac{d^4 \, u_p}{d \, z^4} = K_h \, (u_p - u_s) \qquad (1)$$

E_p = modulus of elasticity of the pile material
I = moment of inertia of the cross section of the pile
u_p = horizontal displacement of the pile at the depth z
u_s = horizontal displacement of the soil at large at the depth z or horizontal displacement which the soil should undergo at the site of the pile, if no pile should be present.

K_h = F (z, $u_p - u_s$) in kg/cm².

There exist computer programs (Baguelin, 1976) to solve the equation (1). The most difficult problem is the knowledge of the value of u_s. When the measured values of u_s are introduced, a fair agreement is obtained (Marche, 1973 and Heyman, 1961). However when introducing theoretical values of u_s large discrepancies with reality can occur.

Baguelin concludes very correctly that for the case of passive pile loading problems, the applicability of his computer program for a pile group is uncertain, because the pile group may cause a barrier effect, which modifies the initial soil deformation curve, to be introduced in the calculations. Fukuoka (Paper 3) utilizes the method of the modulus of soil reaction for determining the load on piles introduced in the soil in order to stabilize creeping slopes.

Calculation based on the assumption of a linear elastic material.

In his contribution presented to this session Oteo (Paper 12) refers to a method applied by Begemann-De Leeuw (1972). In this method the soil is considered to be a linearly elastic material, with a constant modulus of elasticity and with a Poisson's ratio of 0.5.

The method of Begemann-De Leeuw has many limitations because

1. it is based on the assumption of a linearly elastic material.
2. it is based on the stress and displacement fields given by the theory of Boussinesq, which can be very different from reality (Perloff and Harr, 1967).

The deductions made by Oteo and based on the method of Begemann-De Leeuw are of interest, as they show on a qualitative way the benefic effect of the relative deformability of the pile on the moments, but their quantitative significance and applicability are certainly doubtful.

Calculation based on the assumption of an ideal elastic-plastic material.

Poulos (1973) has utilized the method of the finite differences for solving the problem of a single pile installed in an ideal elastic plastic material, whose modulus of deformability E_s and the yield stress σ_{yield} may be variable with the depth z. In order to be able to use the method of Poulos, it is necessary to know:

1. the value of the soil modulus E_s
2. the soil yield pressure σ_{yield}
3. the horizontal soil movements in the absence of pile.

The most critical influence is given by the horizontal soil movements u_s in the absence of a pile.

To this session Cañizo and Merino (Paper 5) give tables which allow to determine the horizontal displacements u_s = f (x/B, z/B) under different elementary vertical load schemes. These data can only have a practical interest if the real soil should be homogeneous, isotropic and linearly elastic which only rarely will be the case.

The finite element method.

The finite element method allows to solve quite intricate problems. The real stress-strain relationships of the soil can be represented by multilinear, for instance bilinear, or hyperbolic approximations. However the difficulty remains that in general it will not be sufficient to consider a pile in a given displacement field, because in general the pile foundation will react to this field, and therefore change the input data. In order to solve quantatively the problem, it is necessary to consider the whole of the loading, the soft layer and of the pile cluster. This of course will in general complicate very much the computer calculations.

When the displacement field is known, exact values can be obtained. Unfortunately this is generally not the case. For instance Marche (1973) tried to retrieve the measured values for a specific pile testing program in Belgium. He utilized the program established by Duncan (1970). By introducing calculated displacements he could not retrieve the experimental values. On the contrary by introducing the measured displacements he got a very good concordance between calculated and experimental values, even for a very large scatter of the other parameters.

As the horizontal soil displacements are a very sensitive function of all parameters and especially of the heterogeneity and the anisotropy, and as the loading on a passive pile is also a very sensitive function of the soil displacements, in order that the finite element method should be able to give quantitative values, it is necessary to introduce as correctly as possible all these data. Furthermore the finite element analysis must embrace the whole of the lateral loads and the pile cluster. Mostly the problem will be three-dimensional. Therefore for quantitative solutions very intricate calculations will be needed. Such calculations can only be justified for very important structures, but will not be applicable for usual problems.

However the F.E.M. can give very interesting qualitative informations concerning the influence of some parameters, when the displacement field u_s is given.

Also Fukuoka (Paper 3) stresses the difficulties and limitations of the use of the F.E.M. for design of piles used to stabilize creeping slopes.

Empirical methods for passive piles.

For most of the usual problems semi-empirical and empirical methods are still used. For such methods a distinction has to be made between the types of problems. The most frequent are the pile foundations of abutments and those used for increasing the stability of slopes or stopping the movement of creeping slopes.

Abutments.

Several empirical methods have been presented by Tschebotarioff (1970), Steinfeld (1971), De Beer and Wallays (1972) and the German Recommendations described in the contribution by Franke (Discussion).

Experimental data show that horizontal movements start to increase considerably when the safety factor F against overall stability drops below 1.4. This is shown in Fig. 1, which gives the variation of a dimensionless displacement factor R against the safety factor F. When the safety factor drops below 1.4, the displacement factor which gives the increase of the horizontal displacement starts to increase considerably. That is the reason why in the method of De Beer-Wallays (1972) a distinction is made between the cases for which F is smaller or larger than 1.4.

In the course of the oral discussion B.B. Broms introduced the use of embankment piles in Sweden for lessening the lateral soil movement around the abutment piles. The embankment piles where designed to carry the total weight of the fill behind the abutment.

Creep of slopes.

A special problem concerns the stabilization of creeping slopes by means of piles or caissons. As in creeping slopes the lateral soil movements are very large, a first idea is that the placed piles or caissons will be loaded by the yielding pressures. This should be the case if the unbalanced force which is the cause of the creep could increase as much as needed to continue the creep, notwithstanding the supplementary resistance created by the presence of piles. However, there is generally no reason that this unbalanced force should increase. Therefore the load on the piles is here again limited to the earth pressure corresponding to this unbalanced force.

The load on piles or caissons will be the smaller of the two following forces:

1. the earth pressure needed to stop the movement
2. the yield pressure.

The problem of the effects of horizontal loads on piles due to landslides, as well in its theoretical as in its experimental aspects, as for the practical solutions

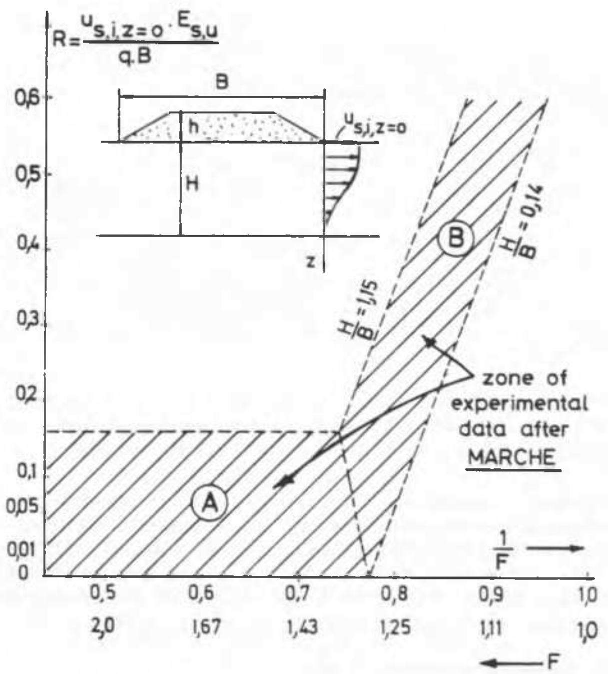

Fig. 1. Experimental relationship between the horizontal displacement u_s and the safety factor F after Marche

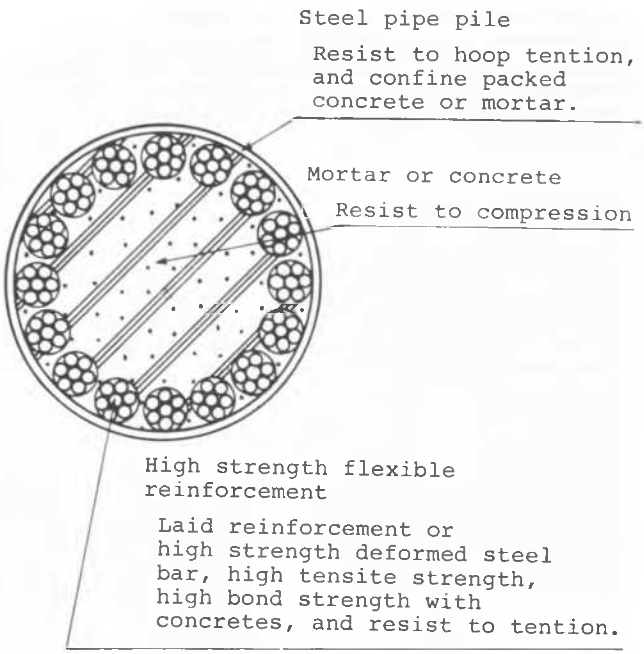

Fig. 2. Cross section of flexible reinforced concrete pile with steelpipe pile (after Fukuoka)

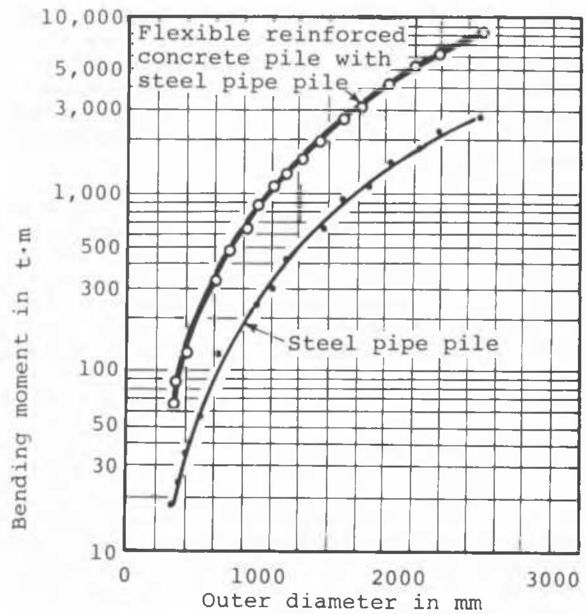

Fig. 3. Relationship between outer diameter of steel pipe and bending moment (after Fukuoka)

is fully treated in the selected contribution by Fukuoka (Paper 3). In this contribution theoretical consideration is given to the relationship between the pressure acting on the pile and its deformation. Also model tests conducted to explore this relationship are discussed. Practical examples of landslide prevention piles, measurements of bending moments in actual piles are given. Examples of special steel pipe piles with high bending resistance are shown (Fig. 2) (Fig. 3).

The problem of the yield pressure has been considered by Ito and Matsui (Paper 9) in their contribution. They determine the forces acting on piles in a row when the soil is obliged to squeeze between the piles. The practical meaning of the result is limited to the value of the acting force needed to induce the creep of the soil.

In solving the problems care will be taken not to accumulate the safety margins as indicated in the contribution by Wallays (Paper 15).

Sommer (Paper 14) brings very interesting experimental results of measurement of the force on caissons placed in a moving slope. The value was much smaller than the predicted yield value of Brinch Hansen and corresponds better to that given by Ito and Matsui.

CONNECTED PROBLEMS AND COMMENTS

There are still several connected problems to be discussed:

1. the yield value of the pile soil interaction
2. the influence of time
3. the combination of active and passive loading on piles
4. the width of the slice influencing a pile
5. the influence of bending moment in the pile prior to embankment loading
6. influence of the pile cluster
7. horizontal loading on batter piles.

SUBJECTS FOR FURTHER RESEARCH

1. The paramount problem is to be able to predict the horizontal soil movements under the influence of a modification of a stress field already existing in the soil. Prior experience shows that it is a difficult problem even for the finite element method calculation. However, if we should know better the relative influence of all the parameters, it must be possible to introduce in the F.E.M. the essential parameters needed to obtain, at least for rather simple cases, correct answers. If the horizontal movements could be correctly predicted, the arsenal of calculation methods is sufficiently developed, in order to be able to solve the problem. Thus the essential point for further research is the improvement of the methods for predicting the horizontal movements.
2. In most of the practical problems, at least in the immediate future, semi-empirical and empirical methods will remain in use. For the semi-empirical methods, a further subject of research is to define simplified horizontal movement diagrams which could be introduced in the already existing calculation methods, in order to obtain safe values for the bend-

ing moment in the piles.

In each case the results of fully instrumented full scale tests are still scarce, and thus a subject of further research should consist in the analysis of the measurements of the action of horizontal soil movements on fully instrumented piles.

III. PILES SUBJECTED TO DYNAMIC LATERAL LOADING by Prof. H. Tajimi

INTRODUCTION

In a seismically active area, there exists an increasing demand for a rational design based on the consideration of dynamic behavior of piles, as predicted in theories, observed in tests and experienced during earthquakes. This situation has certainly motivated the works of ten papers submitted to the section entitled "PILES SUBJECTED TO DYNAMIC LATERAL LOADING" of this Specialty Session; however, much of discussion will be equally applicable to other dynamic loads, such as machine loads and wave forces. The contributions are divided conveniently into several categories.

Seismic response of structures supported on deep foundations are well known to be greatly dependent upon the rigidity of foundations. For instance, rigid foundations resting on the bed rock lying at a certain depth below the ground surface could completely resist the movement of surrounding soil relative to the rock motion. On the contrary, many pile foundations behave rather as flexible and ductile structures, and primarily controlled by the surrounding soils. Therefore, for a more rational design of piles, it becomes an important problem to predict the ground motions to be anticipated at sites of different soil conditions. But, this has not been covered in the discussion of the present session.

Soil-pile-structure interaction analysis.

The stiffness of piles has a significant effect on the soil-pile-structure interaction. Laterally loaded piles are classified according to their stiffnesses into (Broms, 1972).

1) Rigid or short piles,
2) Semi-rigid or intermediate piles, and
3) Flexible or long piles.

The long pile is defined as a pile whose lateral deflection at the ground surface is independent of the pile length when the lateral load is applied to the pile head. In other words, the structure supported on the long piles has the natural periods of translational modes not affected by the pile length, L. From this viewpoint, Flores-Berrones (Paper 22) has classified the long pile by $\lambda > 5.0$, $\lambda = (\beta L)^4$, $\beta = (k_h B/4E_p I_p)^{1/4}$. It corresponds to $\beta L > 1.5$, which was proposed by Broms (1964) for the fixed-headed long pile having a constant coefficient of subgrade reaction k_h with depth.

The analysis methods of soil-pile-structure interaction are fundamentally classified into the following groups:

1) Foundation springs method,
2) Beam-on-Winkler foundation method,
3) Finite element method, and
4) Three-dimensional analysis method.

Herein, 1) and 2) are prevailing for practical purposes at present. The foundation springs method represents the pile foundation compliance by swaying and rocking springs. On the other hand, the beam-on-Winkler foundation method employs a joint model of soil and pile-structure systems, both of which are connected by interaction springs and dashpots. The latter method is more complicated, but is useful for extensive application (Penzien et al., 1964).

Flores-Berrones (Paper 22) discusses the validity of the foundation springs method by analyzing the beam-on-Winkler foundation model. The input motion to the foundation springs is given by the seismic response of the pile head in the soil-pile model without the supported structure. When the pile has $\lambda > 5$, the author points out that the pile follows the soil motion and the input motion can be estimated by the normal response analysis of soil layers neglecting the presence of piles. Additional movement of piles might be caused from the inertia loading on the supported structure. For this reason, the author emphasizes that the foundation springs method is valid only when the effect of the supported structure on the input motion to be imposed on the springs is negligible.

Boshinov (Paper 18) describes an approximate method evaluating the stresses and displacements of a laterally loaded pile with a coefficient of subgrade reaction increasing linearly with depth. The method was developed by use of the variational theorem applied to a hinged or fixed headed pile subject to moment and shear, when acting separately on the head.

In their selected paper for this session, Kobori, Minai and Baba (Paper 24) present the accurate mathematical solutions of dynamic behavior of a laterally loaded pile embedded in a linear viscoelastic semi-infinite medium, on a basis of the three-dimensional wave propagation theory. The governing equations in the frequency domain are satisfied by three scalar Helmholtz-type potentials, and the solutions are expressed by solving the Fredholm-type integral equations of the second kind for unknown coefficients involved in the potentials. The numerical calculation requires lengthly complicated procedures. The results are illustrated for the stiffness functions as defined in Eq. (2) in this report and the distributions of displacements, bending moments, soil pressures and shear stresses along the pile shaft. The general trends seem to be consistent with the discussion presented in the subsequent section.

Emery & Nair (Paper 21) present a finite element dynamic analysis incorporating free field, acceleration boundary conditions, for predicting the seismic response of a single pile embedded in soil. The soil-pile system is idealized as an axisymmetric structure composed of an assemblage of triangular and quadrilateral ring elements. Dimensions of the system are determined by the magnitude as large as free field conditions can be assumed at the boundary. The authors pay a special attention to the spatial variations of seismic motions, taking into account that for sites nearer to the source the direction of shear wave propagation may be inclined and surface waves also contribute. Hence, the input accelerations to the boundary nodes are evaluated by the response of soil layers surrounding the soil-pile system, using wave propagation theory and assuming that the earthquake energy is transferred through soil layers by shear waves and Rayleigh waves. As for numerical results, the authors state that a pile considerably reduces the response of supported structures. In addition, the analysis is capable of predicting the pore pressure development in a saturated soil around the pile. The resulting simulated behavior of a pile-saturated sand system during the San Fernando Earthquake showed that the sand around the pile liquefied. However, when a similar pile-saturated clay system was subjected to the same earthquake, there was no sign of liquefaction. These results are in qualitative agreement with the field observation and seem to provide good evidences indicating that the present method will be useful for more extensive applications.

Dynamic characteristics of a single pile in soil.

It is fundamental to investigate the dynamic characteristics of a single pile embedded in an elastic stratum resting on the rigid base. Many contributions have been made on this subject. The review of these theoretical studies and related experiments gives the following summaries concerning the general trend of frequency response of a single pile subjected to the horizontal excitations. When a sinusoidal varying force $Pe^{i\omega t}$ is applied at the pile head in the horizontal direction and the resulting displacement at the head is denoted by $Y_o e_{i\omega t}$, the P-y_o relation can be written in the form,

$$P = K_{st}(k_{hl} + i\, k_{h2})\, y_o \tag{2}$$

where K_{st} denotes the static stiffness of piles for its real part. The coefficient k_{hl} and k_{h2} are functions of the frequency ω and illustrated schematically in Fig. 4. The valleys appearing in the k_{hl}-curve and steps in the k_{h2}-curve take place at the natural frequencies ω_{gl}, ω_{g2}, ... of the soil layer in the modes of the horizontal translation. In this figure, it is noticed that the value of k_{h2} representing the damping is quite small for $\omega < \omega_{gl}$. Thus, when a pile-supported structure has the natural frequency less than the fundamental frequency of the soil layer ω_{gl}, the damping of the structure becomes very small.

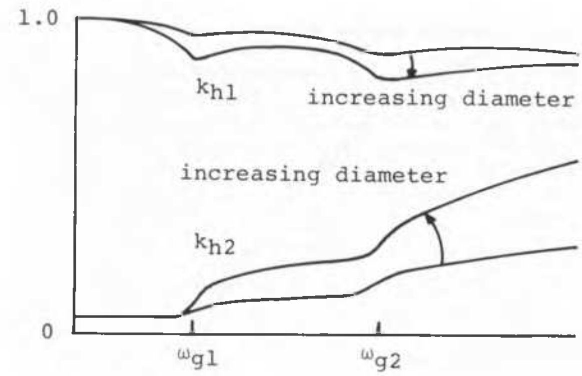

Fig. 4. Nondimensional lateral stiffness functions (from the State-of-the-Art report, 2)

Roughly speaking, the real part k_{hl} is practically independent of both the frequency and the diameter of piles, while the imaginary part k_{h2} increases with increasing values of them. Then, if the stepped curve of k_{h2} is replaced by an averaged straight line, it may be approximated by

$$k_{h2} = k^*_{h2} + \Gamma \frac{r_o \omega}{V_s} \tag{3}$$

where Γ = a constant, r_o = radius of pile and V_s = shear wave velocity as a reference. The first term represents the hysteretic damping and the second term indicates the radiation damping. The radiation damping of a circular footing resting on the homogeneous half-space is given by being proportional to $r_o\omega/V_s$ in the similar fashion (Richart et al, 1970). The comparison of the magnitude of the radiation damping of a pile to that of a footing with the same radius will show that the former is likely to be three to four times the latter.

As another problem, when a long pile without a supported mass is subjected to a sinusoidal, horizontal ground motion, the amplification defined by the ratio of the displacement amplitude of the pile at its head to that of the ground motion at the surface will be given by a function of the frequency, as illustrated schematically in Fig. 5. It shows that the amplification for the small-size pile becomes almost unity, but the amplification for the large-size pile decreases with increase of the frequency.

The selected paper by Richart and Chon (Paper 16) presents an instructive discussion on the effect of a pile cap to a pile-sandy soil system. If the pile cap is in firm contact with the surrounding sandy soil, it develops horizontal resistances both along the vertical faces over the embedment depth and along the base of the pile cap. The stiffness and damping from each component can be estimated by Novak's (1974) expres-

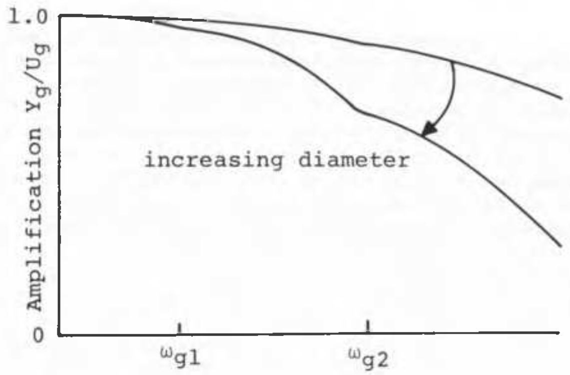

Fig. 5. Amplification of movement at pile head with respect to that at ground surface (from the State-of-the-Art report, 2)

sions. In this case, movement of the base causes the soil surface to move horizontally and the lateral resistance of piles to reduce, because the pile and soil have about the same motion near the surface. On the other hand, if the soil settles away from the base of the pile cap, only the vertical faces are effective in providing horizontal stiffness and damping from the pile cap. Additional stiffness and damping are provided by the pile-soil system, but are reduced again due to decrease of the confining pressure. Thus, the behavior of the pile-soil system is considered as being similar to the case of free-standing piles. In the second portion of the paper, the authors present interesting data on free vibration tests (the plucking tests) of models of free-standing single piles in a sand bin. The model piles had circular and square cross sections of 3 to 4 in. in diameters or widths with 3 to 5 ft. in embedded lengths and each was mounted by a rigid weight at a distance above the surface. The soil models were built under highly controlled conditions with the resulting relative density of about 0.76. Tests were run when the sand bed was just submerged, or when the water had been drained from the bed. The following general observations are made about the measured data. The natural frequency of the system increased with an increase in pile diameter, and it decreased as the value of the initial horizontal static load increased. The damping ratio increased as the pile width increased, but the trend for damping ratio as a function of initial force amplitude were not consistent. The measurements are compared with predictions from elastic theory. It is reported that the measured values of the natural frequency and the damping ratio for piles in drained sand agreed well with the theoretical values, provided that the shear modulus of the soil was assumed to be so low as comparable to that found from interpretation of the static data. The authors conclude that for design purposes, it is necessary to evaluate the shear modulus for the soil under prototype confining stress conditions, then the response of the pile-soil-pile cap system can be evaluated in a direct manner.

Lateral resistance.

The most simple method to estimate the lateral resistance of piles is to use the Winkler foundation assumption (Broms, 1972). The coefficient of the subgrade reaction k_h is obtained from the empirical formulae or the static loading test at the site. The coefficient k_h is not a material constant and varies with the width of pile, the deflection and the depth below the ground surface. Hence, if only the soil data are available, Mindlin's equation is useful to evaluate the coefficient k_h, assuming the soil constants at an appropriate value of the strain level. At present, the most reliable and direct method seems to be primarily the lateral quick loading test of full scale piles, from which the deflections and stresses at the working load are exactly determined.

In order to predict the dynamic response of a 21-story high panel prefabricated building supported on a pile foundation, Petrovski and Jurukovski (Selected paper, 17) performed static and dynamic full-scale loading tests on single piles and four-pile groups simulating the actual foundation. Piles were of Franki type with diameter of 52 cm and were buried down to 15 m deep in a loose sandy soil. The pile cap was first in contact with the supporting soil and thereafter excavated down to a depth of 2 m for the successive tests. An eccentric mass vibration generator was used for the forced vibration tests and hydraulic actuators for the static repetitive load tests, with varying forcing levels. The measured results of force-displacement relationships and soil-pile foundation interaction parameters, as stiffnesses and damping ratios, are described in details, exhibiting the effects of soil nonlinearity developed with increasing displacement of pile foundations. From the test data, the authors determine the stiffness of the soil-pile system for the dynamic analysis in the different stages of force levels. In a future program, the authors intend to check the mathematical model thus formulated by means of the forced vibration test in smaller displacements and the strong motion measurement during moderate and strong earthquakes in larger displacements for the completed structure.

Sovinc and Vogrinčič (Paper 25) give details of full scale test on a steel pipe pile of 508 mm in diameter with 8 mm wall thickness driven into sand and gravel marine sediment. The object of the test was to obtain the design data of piles for the quay structure. The closed-ended pile was driven down to 33 m depth and load tests were carried out at first empty and then on the same pile filled with concrete. The measurements were performed for driving stresses in the pile, stresses in the shaft during vertical loading, horizontal loading, dynamic loading and surface loading around the pile, earth pressures on the pile during driving and intervals between drivings, settlements of the pile head during driving and vertical loading, and deflections of the pile head during static, repeated and dynamic horizontal loadings. All the results are shown in diagrams and could be used with confidence for design purposes.

For a flexible pile, Datye and Nagaraju (Paper 20) report the use of reinforced granular columns, which are of precompressed granular materials placed within confining spiral or ring reinforcements, if necessary, with longitudinal tensile reinforcements. The authors are intending to achieve extensive applications as flexible piles and for ground improvements in soft clay and sandy strata in seismic active areas.

Group effects of laterally loaded piles.

There is no contribution on this subject in the present session. The group effect includes two types of problems. The first type deals with the reduction of bearing load or stiffness of a pile group, compared to the sum of bearing loads or stiffnesses of individual piles. The second type of problem is concerned with the carrying load of individual piles according with the finding that the front pile in the moving direction was subjected to larger soil reaction than the piles behind it. Numerous studies on these subjects have been made in the past decade by both theoretical and experimental methods, for the most part in the static aspect. However, the principal information available on this subject is still largely empirical. As a successful application of theoretical solutions already obtained to the dynamic problem, Novak (1977) has proposed the following equations for simple estimation of stiffness and damping of a group of piles,

$$\bar{K} = \sum_r K_r \,/ \sum_r \alpha_r, \quad \bar{C} = \sum_r C_r \,/ \sum_r \alpha_r \qquad (4)$$

where α_r denotes the contribution of the r-th pile to the displacement of a representative pile in the group: hence, $\alpha_1 = 1$ and the other factors are smaller than unity and decrease with distance between the piles. The values of α_r will be obtained from the theoretical solutions of Poulos (1971), with considerations of the possibility of an increase in soil stiffness due to pile driving and grouping. For an additional type of problem in the dynamical aspect, much remains to be clarified about the behavior of the soil mass enclosed by the pile group, as the soil mass is likely to move together with the piles.

Dynamic behavior of piles in liquefied soil.

When a soil is judged sensitive to liquefaction, a great reduction of lateral resistance and frictional resistance must be considered in the design of piles. Although liquefied soil is often assumed as air or heavy liquid, such an assumption would result in prohibitively expensive design. However, once liquefied, the soil cannot transfer shear waves and consequently shows quite reduced motions. Hence, it is probable that the soil and pile might reach their maximum amplitude of motion prior to liquefaction rather than after its onset.

Hakuno, Iwasaki and Tatsuoka (Paper 23) have conducted a model test of end bearing piles in the saturated sand which was filled in a box on a shaking table and actuated in a sinusoidal motion. A weight was mounted on the piles. In this test, the liquefaction initiated near the surface and progressed downwards, during which the instantaneous natural frequency of the sand layer would gradually decrease towards the zero frequency, as expected in a liquefied state. On the other hand, the instantaneous natural frequency of the pile foundation intially coincided with that of the sand layer and gradually decreased to the natural frequency of the pile foundation submerged in water. As a result, the experiment indicated that when the frequency of input motion is less than the natural frequency of the sand layer in the initial state and is larger than the natural frequency of the pile foundation submerged in water, the sand layer and piles reached maximum displacement in the course of pore pressure development, causing a passing phenomenon of resonance state.

Observed dynamic behavior and earthquake damage.

Many reports have been presented on model tests, full-scale field tests and seismic observations of pile foundations, although they are restricted to small vibrations. Some findings already confirmed may be summarized as follows.

1) It is difficult to get a significant increase in horizontal stiffness of foundation by vertical piles.
2) For small-size piles currently used, the increase of damping is made more effectively by the backfill around the pile cap, because the damping produced by the soil-pile interaction during horizontal vibration is comparatively small. In the theoretical aspect, the stiffness and damping for pile cap-soil systems are fully discussed by Richart and Chon in the present session.
3) When the bottom surface of a pile cap is loose contact with soil as in the case of end-bearing piles, the horizontal stiffness and the damping of a pile foundation decrease considerably with increase of lateral load, because of reduction of pile cap contribution in the total resistance. It causes a variation in the dynamic behavior of buildings on end-bearing piles, depending on the intensity of earthquakes.
4) Piles contribute to increase the rocking stiffness of foundations. It results in reducing the earthquake response of buildings in their upper stories.
5) Usually, horizontal motions of piles are controlled by the surrounding soils. However, large-diameter piles filter out the high frequency components of earthquake motions.

While the earthquake damage of pile foundations caused by liquefaction of surrounding soils are well documented, the damage to piles as a direct result of the ground vibrations set up by earthquakes are not so often found in the published data, as the State-of-the-Art report (2) describes. Chaturvedi (Paper 19) discusses the damage of pile foundations experienced in India, as caused by liquefaction of backfill of quay walls, slumping of highway fill, settlement by compaction of cohesionless soils and so on. But, damage analyses are not included.

IV. FINAL REMARKS by Prof. E. Nonveiller

In the closing remarks Nonveiller has analysed the proposed theoretical and empirical solutions for laterally loaded passive piles. Theoretical solutions based on simplified models of soil behaviour show remarkably different pile deformations than measurements on piles in the field. Therefore more sophisticated models in connection with complex F.E.M. program should be developed for realistic theoretical solutions. Establishing reliable parameters of soil behaviour and the cost of such computation may preclude practical application of this approach. At least parametric studies of some governing factors such as depth of weak strata, influence of soil anisotropy, stratification, pile stiffness, etc., on bending moments and displacement could improve the existing empirical approaches.

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