TEXAS TRANSPORTATION INSTITUTE

TEXAS HIGHWAY DEPARTMENT

COOPERATIVE RESEARCH

MODEL PILES
2-8-54-1

in cooperation with the
Department of Commerce
Bureau of Public Roads

BIBLIOGRAPHY (63-4)
SURVEY OF LIBRARY FACILITIES PROJECT

MODEL PILES

Compiled by
Texas Transportation Institute
October 1963

1. Model tests with transversally loaded rigid piles in sand, N. H. Christensen. Danish Geotechnical Institute (Copenhagen, Denmark), Bul. No. 12, pp 10-16, 1961. (In English)

   Twenty six model tests have been carried out on wooden piles in dry sand to determine their resistance against horizontal loads. The parameters varying from test to test were the pile depth, the height of the horizontal load, the density of the sand, and the way the pile was placed in the sand. The test results were used for drawing up load-deflection curves.

   Computations were carried out in accordance with the theory set forward in the preceding paper. These were, for each test, a determination of the friction angle that would, according to the theory, give the same ultimate load as found in the test. These friction angles are plotted against the void ratio of the sand as the main results of the present test series.

   It is seen that the "experimental" friction angle Φ is significantly influenced only by the void ratio of the sand. The values of Φ are only slightly greater (o degrees-2 degrees) than those found in active earth pressure tests, and their dependence on the void ratio conforms well to those earlier tests.

   The present model tests can therefore be regarded as a reasonable confirmation of the theory, indicating that it is usually a little on the safe side to use this theory, provided that Φ is taken as corresponding to a case of plane strain.

2. Experiments with model piles in groups, Thomas Whitaker. Geotechnique (Institute of Civil Engineers, Great George St., London, S.W. 1), 7: n 4, pp 147-167, December 1957.

   In piled foundations groups of piles are commonly used, and the piles in a group are seldom placed so far apart that they do not influence each other. Few data are available on the testing of groups in the field, because of the cost of such tests, and no satisfactory theory of group action has yet been derived.

   Experiments on model piles in groups in clay soil have been made to determine the influence of number, length, and spacing of piles on group-bearing capacity and settlement, and on the way in which a load is shared by piles in a model group.

   It was found that for square groups of given number and length of piles there was a value of pile spacing at which the mode of failure changed. For closer spacings failure was by the piles and soil enclosed within the perimeter of the group sinking as a block. For wider spacings failure was by local penetration of individual piles.

The experiments on the distribution of load showed that for a large range of loading the corner piles in a group take the largest and the center the smallest proportion of load, and that the proportion of load taken by any pile increases with its distance from the center of the group.

The results of the model tests are self-consistent, and where they touch on known or suspected properties of full-scale groups they show similarity in behavior to what occurs in practice.

3. Model study of a dynamically laterally loaded pile, Roy D. Gaul.
<u>ASCE--Proc.</u> 84: J of the Soil Mechanics and Foundations Div., paper 1535, 33pp., February 1958.
A dimensionally scaled model of a vertical pile in soft soil has been dynamically tested. Results indicate that a low frequency oscillatory lateral load induces pile bending moments which closely correspond to moments caused by the same load applied statically. Analytical computation of pile moments based on the assumption of a soil modulus constant with depth appears to agree well with dynamic test results.

4. The bearing capacity of friction pile groups in homogeneous clay from model studies, G. E. Sowers, C. B. Martin, Lyle L. Wilson and Marshall Fausold, Jr. 3B/24.
<u>Reprint, Proc., of 5th International Conference on Soil Mechanics and Foundation Engineering</u> (Paris), pp 155-158, July 1961.
Model studies have been made of friction piles in a homogeneous clay to determine the relation between the behavior of isolated single piles andsimilar piles closely spaced in groups. Tests were made using piles 0.5 in. and 1.25 in. in diameter, with embedments of 12, 24 and 36 diameters, in square groups of 2, 4, 9, and 16.

The results show that in all cases the average load per pile in a group is less than that of an isolated single pile. At close spacings the group fails as a unit, with the soil between acting as if it is a part of the piles; at larger spacings the piles individually punch into the soil. The minimum spacing to prevent group failure ranges from 1.75 diameters for a 2-pile group to 2.5 diameters for a 16-pile group. All piles of the group do not carry the same load, particularly at small spacings (when the group acts as a unit) and at loads less than failure. There is a readjustment and partial equalization of loads as failure is approached. The unequal loading of the piles and the inability of the group at large spacings to support the full load of the individual piles is caused by the unequal strains within the group and resulting progressive failure.

5. Model investigations concerned with driving piles by vibration, W. Eastwood.
<u>Civ Eng & Pub Works Rev</u> (England) 50: n 584, pp 189-191, February 1955.

This paper describes experiments on a model scale to find the factors which affect the natural frequency of vertical vibration ofpiles. These experiments may give some guidance as to the range of frequencies which will be most likely to give resonance in full-scale attempts at driving piles by vibration.

Although model test results cannot be extrapolated with the same confidence in investigations concerned with soils as in, say, experiments concerned with elastic materials or hydraulics, they can often serve as a guide to the course whichfull-scale trials should take.

The present tests were designed to furnish information concerning the factors which affect the natural frequency. It is, of course, important that the driving force should be applied at or near this natural frequency, since otherwise the size of the vibrator and the power required to maintain large vibrations is likely to be excessive.

The characteristics of the pile itself which may affect the natural frequency are: cross-section dimensions, weight of the pile, and depth of penetration. It was with these three variables that the present tests were concerned.

The effect of soil-type was not investigated, since it is likely that piles can only be driven by vibration in sandy soils.

The model piles were 1 inch,2 inches, and 4 inches square, up to 6 feet long, and made of timber. The sand was contained in a stiffened box 12 feet deep and 6 feet square. As it was intended to find the natural frequency of the piles with the sand inundated as well as merely damp, an arrangement was included for flooding the sand from below or draining it as required.

In order to make the density of the sand as uniform as possible throughout the box, it was placed by allowing it to settle under water. After each pile had been tested, it was withdrawn and the sand was flooded by injecting water at the bottom of the box under pressure. This had a scouring action, and when the water was turned off, the sand settled back to what appeared to be sensibly the same density each time. While the sand was still inundated, the next pile was driven to the appropriate depth and the natural frequency of vibration found. The drain at the bottom of the box was then opened for 24 hours to allow all except capillary water to drain out, and the natural frequency of vibration of thepile was again found with the sand in the damp condition.

The following is a summary of the principal findings: (1) The natural frequency of vibration appears to be approximately constant for a given pile, whatever the depth of penetration. (2) Increasing the total mass of a given pile reduced its natural frequency, but the reduction was not quite as great as would be expected if the frequency were inversely proportional to the square root of the weight of the pile. (3) Increasing the cross-sectional area of the pile decreases the natural frequency. (4) The effect of inundating the sand was to slightly decrease the natural frequency compared with that for damp sand.

6. Der Einfluss von Eigenspannungen auf das Knicken von Stahlstuetzen, B. Thuerlimann.
Schweizer Archiv 23: n 12, Dec 1957, p 388-404.
Influence of residual stresses on buckling of steel columns demonstrated on simple model; measurements of residual stresses on rolled shapes, welded and riveted members and results presented in graphs; two procedures explained for calculation of column buckling curves, including influence of residual stresses.

7. Experiments with model piles in groups, T. Whitaker.
Geotechnique 7: n 4, Dec 1957, p 147-67.
Experiments to determine influence of number, length, and spacing of piles on group bearing capacity and settlement, and on way in which load is shared by piles in model group; for square groups of given number and length of piles there was value of pile spacing at which mode of failure changed; for closer spacings failure was by piles and soil enclosed within perimeter of group sinking as block.

8. Laboratory study of breaking wave forces on piles.
U. S. Beach Erosion Board--Tech Memo n 106, Aug 1958, 24p.
Model studies to investigate forces of breaking waves on

piles located on sloping beach; suitable dynamometer developed and measurements made for number of different wave conditions on single beach slope (1:10) and for two different pile diameters; resulting maximum forces presented in dimensionless form.

9. Model study of dynamically laterally loaded pile, R. D. Gaul. ASCE Proc 84: (J Soil Mechanics & Foundations Div) n SM1 Feb 1958, Paper n 1535, 33p.
   Dimensionally scaled model of vertical pile in soft soil has been dynamically tested; results indicate that low frequency oscillatory lateral load induces pile bending moments which closely correspond to moments caused by same load applied statically.

10. Plastic yielding of I-beams, A. P. Green, B. B. Hundy. Engineering 184: n 4767, 4768, July 19, 1957, p 74-6, July 26 p 112-5.
   Theoretical relations reviewed which correct simple theory of pure bending by taking into account effect of shear force; experiments in which both loads and plastic deformation at yielding are investigated, using model mild steel I-beams; of existing formulas, those suggested by Heyman and Dutton are considered most useful; new experiments compared with those of other workers.

11. Resistance to overturning of single, short piles, E. Czerniak. Am Soc Civ Engrs--Proc 83: (J Structural Div) n ST2, Mar 1957, Paper n 1188, 25p.
   Practical aids for stress analysis and lateral force design of short piles that will effectively reduce labor required in their solution; foundation design in refineries and chemical plants, where short bored piles have been successfully used to transmit to ground all forces and couples acting on supports for elevated horizontal vessels, heat exchanger equipment, pipe supports and miscellaneous light structures.

12. Plastic deformations due to dynamic loading of beam with attached mass, T. J. Mentel. Can J Technology 33: n4, July 1955, p 237-55.
   Mathematical study of effect of attached mass on large plastic deformations of beam subjected to dynamic pressure loading; approximate solution based on simple one-dimensional model.

13. Model studies of scour around bridge piers and abutments--second progress report, Emmett M. Laursen and Arthur Toch. Nat'l Research Council--Highway Research Board Proc 31: 1952, p 82-87.

The Iowa Institute of Hydraulic Research is engaged in a laboratory investigation of four phases of scour at bridges: (1) geometry of piers and abutments, (2) hydraulic characteristics, (3) sediment characteristics, and (4) geometry of channel cross-section and alignment. A previous report, given at the 30th Annual Meeting of the Highway Research Board, presented reulsts of the first year's investigation on the effect of the geometry of representative Iowa designs of piers and abutments.

During the past year the more fundamental aspects of the problem have received special attention in an investigation of the effect of velocity and depth of flow on the depth of scour--the second phase of the program. Work on the first phase has been continued in a search for shapes and devices which would minimize scour. Although possible improvements are indicated by the latter study, their practicability is dependent upon the results of the other phases of the investigation and upon the structural requirements of pier design.

Study of Phase 2 indicates equilibrium depth of scour is primarily dependent on the depth of flow and that velocity has little influence on equilibrium conditions. The instantaneous rate of scour, however, is greatly influenced by the velocity, and scour depths in excess of the equilibrium condition can be attained under unsteady flow conditions. A flood, of course, is a state of unsteady flow, and an alluvial stream will have a tendency to degrade during the rising stage. The lowering of the bed results in a variable level to which the scour depth, as determined by these laboratory tests, must be referred. Further investigation is necessary, however, to determine whether the excess depth or the equilibrium depth of scour will obtain during the slowly varied flow of floods.

14. Bearing capacity of screw piles and screwcrete cylinders, G. Wilson.
Instn Civ Engrs--J 34: n 5, Mar 1950, p 4-73 (discussion), 74-93; see also discussion in Instn Civ Engrs--J supp to n 8, 1949-50, Oct 1950, p 374-86.

Model and full scale loading tests; observations on settlement of piles in actual structures; theory of bearing capacity; relationship between driving torque and bearing capacity of pile; formulation of design rules;

earth pressure at rest is critical factor in bearing capacity of structures founded in frictional medium; screwing cylinder with closed nose into dense sand increases bearing capacity.

15. Steel and timber pile tests--West Atchafelaya Floodway--New Orleans, Texas & Mexico Railway.
<u>Am Ry Eng Assn--Bul</u> 52: n 489, Sept-Oct 1950, p 149-202, Supp sheets.
Description and analysis of tests made on hollow steel and timber bearing piles in swamps of southern Louisiana; tests were made during driving of piles, and under static loading of piles, to shear failure in some cases, and in others to practical limit of loading; tables giving recorded static stresses.

16. Hydraulic model study of spur dikes for highway bridge openings, S. S. Karaki.
<u>Nat'l Research Council--Highway Research Board Abstracts</u> 29: n 4, April 1959, p 40.
The hydraulic model study of spur dikes for highway bridge openings is sponsored by the State Highway Departments of Mississippi and Alabama, in direct cooperation with the U. S. Bureau of Public Roads. The laboratory study is being conducted in a flume 16 ft wide and 84 ft long, with an erodible bed of fine sand to determine areas of severe scour. Various lengths, shapes and positions of spur dikes with respect to the bridge abutments have been tested under conditions of a fixed discharge of 4.8 cfs, 0.4 ft normal depth downstream of the contraction, and a fixed contraction of 50 percent in the flume. The spur dikes were made erodible by using a lean sand-cement-bentonite mixture to observe areas of erosion in the spur dike.

Various spur dike shapes have been tested for two principal lengths. The shapes have comprised straights and elliptical forms; the shape of the latter is described by the ratio of the length of major to minor axis. Results thus far have shown that elliptical dikes perform more satisfactorily than do straight dikes. In any event, dikes should not be offset from the bridge abutment along the highway embankment because scour will again prevail at the abutment, due to flow disturbance along the side of the dike. When spur dikes are used at the abutment of a bridge, the flow along the highway embankment is disrupted and redirected to make more effective use of the bridge opening. Under such conditions the scour hole, which usually forms at the bridge abutment, is reduced and a new scour hole is formed upstream in the vicinity of the nose of the spur dike where there is relatively little damage done to the bridge structure.

Additional studies are being conducted to determine the optimum shapes and lengths of dikes with different lengths of embankment. The research is being conducted by Colorado State University.

17. Model investigations concerned with driving piles by vibration, W. Eastwood.
<u>Civ Eng & Pub Works Rev</u> (England) 50: n 584, pp 189-191, February 1955.

This paper describes experiments on a model scale to find the factors which affect the natural frequency of vertical vibration ofpiles. These experiments may give some guidance as to the range of frequencies which will be most likely to give resonance in full-scale attempts at driving piles by vibration.

Although model test results cannot be extrapolated with the same confidence in investigations concerned with soils as in, say, experiments concerned with elastic materials or hydraulics, they can often serve as a guide to the course which full-scale trials should take.

The present tests were designed to furnish information concerning the factors which affect the natural frequency. It is, 6f course, important that the driving force should be applied at or near this natural frequency, since otherwise the size of the vibratory and the power required to maintain large vibrations is likely to be excessive.

The characteristics of the pile itself which may affect the natural frequency are: cross-section dimensions, weight of the pile, and depth of penetration. It was with these three variables that thepresent tests were concerned.

The effect of soil-type was not investigated, since it is likely that piles can only be driven by vibration in sandy soils.

The model piles were 1 inch, 2 inches, and 4 inches square, up to 6 feet long, and made of timber. The sand was contained in a stiffened box 12 feet deep and 6 feet square. As it was intended to find the natural frequency of the piles with the sand inundated as well as merely damp, an arrangement was included for flooding the sand from below or draining it as required,

In order to make the density of the sand as uniform as possible throughout the box, it was placed by allowing it to settle under water. After each pile had been tested, it was withdrawn and the sand was flooded by injecting water at the bottom of the box under pressure. This had a scouring action, and when the water was turned off, the sand settled back to what appeared to be sensibly the same density each time. While the sand was still inundated, the next pile was driven to the appropriate depth and the natural frequency of vibration found. The drain at the bottom of the box was then opened for 24 hours to allow all except capillary water to drain out, and the natural frequency of vibration of the pile was again found with the sand in the damp condition.

The following is a summary of the principal findings; (1) The natural frequency of vibration appears to be approximately constant for a given pile, whatever the depth of penetration. (2) Increasing the total mass of a given pile reduced its natural frequency, but the reduction was not quite as great as would be expected if the frequency were inversely proportional to the square root of the weight of the pile. (3) Increasing the cross-sectional area of the pile decreases the natural frequency. (4) The effect of inundating the sand was to slightly decrease the natural frequency compared with that for damp sand.

18. Soil failure during overturning of piles, T. E. H. Williams, Engineering 173: n 4488, pp 134-136, Feb 1, 1952, London.

Most investigators on this subject have recognized that, before the collapse of a pile, a body of sand of definite geometrical pattern is displaced by the embedded length. No general agreement has, however, been reached on the shape of this displaced wedge. It is now generally agfeed that when a vertically-embedded pole or pile is subjected to a horizontal force applied above ground level it begins to rotate at a point below the midpenetration depth. This center of rotation soon rises to the surface level of the ground as the magnitude of the applied force is increased. The existing methods for determining the resistance to overturning of piles are mainly based on the assumption that the center of rotation is initially below midpenetration depth. They also call for a series of overturning tests on trial piles in typical soils along the route of a proposed line in order to determine values for coefficients introduced into formulae.

The investigation which resulted in the production of this article was carried out with the object of solving three problems: (1) the determination of the position of the center of rotation when the maximum over-turning moment was effective, (2) the development of a method for determining the accurate form of the displaced body of sand, and (3) the derivation of a formula for the maximum resistance to overturning without the introduction of coefficients. The existing methods for determining the resistance of piles to overturning are based on the criterion of negligible movement. The passive pressure developed in the soil immediately surrounding the pile is assumed to be represented by parabolic or triangular diagrams.

The experimental program consisted of three test series. The first and second series were carried out with the object of noting the mechanism of soil failure; the third series produced numerical data on overturning moments.

The first of the test series proved that the maximum resistance to overturning is effective at the instant when the body of sand is fully developed: the center of rotation is at surface level when this occurs. Finally comes breakdown of the displaced sand body and collapse of the piles.

The second test series was carried out to determine the form of the displaced body of sand at various depths below surface level.

From measurement on the sections, the author concluded that the form of the displaced wedge of sand can be reproduced by drawing an inverted oblique cone with base of diameter equal to the depth of penetration of the pile. The tangents common to the cone and pile form the side planes of the completed wedge.

In the third series of tests, model piles were driven to predetermined depths in compacted dry sand which was contained in a large brick bin. For any defined depth of penetration the magnitude of the overturning moment recorded is the mean of ten results. The angle of internal friction ϕ of the sand was determined by means of the shear box. The bulk density of the compacted sand was also determined. By the use of many graphs, the consistency of the derived formulas for the stated soil conditions was demonstrated.

The assumption that the center of rotation is behind the pile in its undisturbed position is an error on the safe side, since when maximum resistance is encountered the pile has been titled away from the displaced soil wedge and the friction and weight moments will have longer lever-arms. Further research is being conducted to determine the amount of pile movement before maximum resistance is reached, in order that the true horizontal position of the center of rotation may be determined. The derived formulas make it possible to draw curves from which the maximum overturning moment can be obtained for a round-section pile of any diameter in a granular material of known frictional properties.

The three series of tests were repeated for square-section piles of face dimensions equal to the diameter of the circular-section piles. The form of the displaced soil wedge was similar to that for the circular piles and the center of rotation was found to be at surface level when the maximum resistance was effective. These tests proved that circular-section piles develop greater resistance than square-section piles.

The investigation which was started at the University College of Swansea, is being continued at King's College, University of Durham, to determine the effect of cohesion in moist material on the shape and proportions of the displaced soil wedge. The results, so far, suggest that there is no critical variation in either property.

19. New researchin soil mechanics, M. P. Jabib.
Annales de L'Institut Technique du Batiment et des Travaux Publics December 1951. Soils et Fondations, No. 5 (France).

The study of the relationships between compression and the resulting deformation in samples of sand has given interesting results where slight deformations are concerned distinguishing between reversible and permanent deformations, and on the role of intermediary stressing.

Tests on model piles have made possible the study of the distribution of skin friction and of point resistance when a pile is driven in dry or wet sand. The results obtained conform to the theory, provided different angles are admitted for the skin friction and for the point resistance.

Tests on small models in homogeneous grease permit the study of soils having zero internal friction, such as silts.

A supplementary note describes tests prompted by the conference. They deal with the influence of the mean principal stress in the case of sands submitted to triaxial compression.

20. A penetrometer study of the in situ strength of clays, Robert L. Kondner.
Materials Research and Standards 2: n 3, pp 193-195, March 1962.

Methods of dimensional analysis in conjunction with small-scale laboratory tests were used to develop graphic and analytic relations for the determination of the maximum unconfined compressive strength of cohesive soils by simple penetrometer methods.

Such techniques can be used in testing soils in a vertical or horizontal position, even at great depths, by advancing the penetrometer through a casing. Both a graphic relationship and an equation have been developed for the determination of the maximum unconfined compressive strength of a cohesive soil by penetrometer methods.

21. Measurement of stresses in rock, Karl Terzaghi.
Geotechnique 12: n 2, pp 105-124, June 1962.

The rational design of permanent supports for tunnels and caverns in rock requires information concerning the initial state of stress in the rock surrounding the excavated space. In order to provide such information, tests have been carried out during thepast three decades in a considerable number of tunnels and caverns for the purpose of determining the magnitude and orientation of the stresses which act in the rock adjacent to the cavity walls. However, even for a short length of tunnel, the scattering of individual values from the average is commonly so important that no reliable conclusions can be drawn concerning the initial state of stresses in the rock adjacent to the station where the measurements were made. An exception to this generalization is found in the work of Nils Hast (1958) who measured the stresses in rock located beyond the distance to which the rock was damaged by blasting. This article contains a brief review of the shortcomings of the data obtained from measurements on exposed surfaces, a description of Hast's procedures and a discussion of the benefits which can be derived from using his method of measurement in connection with the design of the permanent lining of rock tunnels and caverns.

22. Loading tests on large bored piles in clay, G. P. Manning.
Concrete & Constructional Eng LIX: n 1, January 1964, p 28.

All the results of loading tests on bored piles, which I have seen, appear to me to be incomplete. With a driven test-pile, the resistance encountered throughout the entire depth is recorded and this is a great help in interpreting any subsequent redriving or static test loading. The test loading of a bored pile, as normally carried out, is a comparatively blind operation and not very convincing. The traditional outlook on the bearing capacity of a bored pile is that it consists partly of end-bearing and partly of skin friction. This is obviously not the whole story, and more exhaustive testing and a wider outlook are needed if we are to have a clearer view of the problem.