COMMERCE
PUBLICATION

NOAA Technical Memorandum ERL MMTC-5

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

A Review of Literature on Anchor Blocks and Laterally Loaded Piles

GORDON R. KELLER
JAMES M. DUNCAN

Marine Minerals
Technology
Center
TIBURON,
CALIFORNIA
December 1972

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

VIRONMENTAL RESEARCH LABORATORIES

MARINE MINERALS TECHNOLOGY CENTER

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

IMPORTANT NOTICE

Technical Memoranda are used to insure prompt dissemination of special studies which, though of interest to the scientific community, may not be ready for formal publication. Since these papers may later be published in a modified form to include more recent information or research results, abstracting, citing, or reproducing this paper in the open literature is not encouraged. Contact the author for additional information on the subject matter discussed in this Memorandum.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

NOAA Technical Memorandum ERL MMTC-5

A REVIEW OF LITERATURE ON ANCHOR BLOCKS AND LATERALLY LOADED PILES

prepared by
Gordon R. Keller
and
James M. Duncan
Under Fellowship with the University of California, Berkeley

Final Report to the
Marine Minerals Technology Center
National Oceanic and Atmospheric Administration
U.S. Department of Commerce
Tiburon, California

June 1971

Marine Minerals Technology Center
Tiburon, California
December 1972

FOREWORD

This work was performed under the sponsorship of the NOAA, Marine Minerals Technology Center, Fundamental Technology Group. The technology of marine mining systems is as broad and diversified a subject as oceanography itself, but basically it refers to interactions between machines and earth materials. Thus, soil mechanics has been an important aspect of research at MMTC for a number of years, and this report in its application to the placement of objects on the bottom, whether they be anchors, platforms, or devices for mining, is a most relevant contribution.

The general objective of this report, which was begun in October 1970, was to review and summarize the literature on the passive resistance of objects embedded in soil in a form which would be useful for engineers engaged in research of practical problems. The literature review was performed by Gordon R. Keller, and the report was prepared by Gordon R. Keller and James M. Duncan.

TABLE OF CONTENTS

PURPOSE AND SCOPE

The purpose of this report is to summarize the literature concerned with the passive resistance of anchor blocks and laterally loaded piles. The information contained in each reference has been summarized on a single page using a consistent format so that those references containing information applicable to a particular problem may be identified quickly and efficiently. The report also includes a summary of the notations employed in subgrade reaction analyses and a bibliography of all of the references consulted.

The report is organized in five sections as follows:

Section I - contains summaries of 11 references on the ultimate load capacity for anchor blocks in sand and clay, subjected to horizontal or vertical loads. Much of the available information is presented in the Steel Sheet Piling Design Manual (U. S. Steel, 1970).

Section II - contains summaries of 17 references on analysis and design of laterally loaded piles, using both subgrade reaction and ultimate load theories. The references by Davisson (1960) and Davisson and Prakash (1963) contain comprehensive state-of-the-art reports on these subjects.

Section III - contains summaries of 16 references on pile-load tests and properties for analysis of laterally loaded piles. The most comprehensive consideration of the concept of subgrade reaction is contained in the reference by Terzaghi (1955).

Section IV - summarizes the notations used in subgrade reaction analyses and shows the relationships between the notations used by various authors.

Section V - lists all of the references consulted, including those summarized in Sections I, II, and III. Brief explanatory notes are given to indicate the types of information contained in some of the references not summarized in previous sections.

SECTION I

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Baker, W. H., and R. L. Kondner (1966). "Pullout Load Capacity of a Circular Earth Anchor Buried in Sand," Highway Research Board, Record No. 108, pp. 1-10.

TYPE OF ANCHOR OR OBJECT - A single circular plate, subjected to a vertical "pullout" load.

TYPE OF SOIL - Dense uniform sand.

TYPE OF TESTS CONDUCTED - Model tests on thin circular earth anchors of diameter varying from one to three inches, buried at varying depths, subject to vertical loads.

GRAPHS - Graphs of load vs. deflection and graphs of pullout capacity vs. anchor depth for various diameter anchors.

TYPE OF ANALYSIS - A dimensional analysis is used to develop empirical relationships among anchor size, depth of embedment, and pullout capacity of the plates. From test results, equations are developed for the pullout capacities of shallow and deep anchors.

CONCLUSIONS AND COMMENTS - Different modes of failure are seen for shallow and deep anchors and so require separate analysis.
- Comparison of results for a full-scale anchor shows that the calculated load capacity is slightly lower than the measured capacity.
- Scale effects have not been resolved.

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Balla, A. (1961). "The Resistance to Breaking Out of Mushroom Foundations for Pylons," Proc. 5th Int. Conf. Soil Mech., Vol. 1, pp. 569-576.

TYPE OF ANCHOR OR OBJECT - A single circular anchor (mushroom foundation pylon), subjected to a vertical "pullout" load.

TYPE OF SOIL - Dense uniform sand.

TYPE OF TESTS CONDUCTED- Model tests on circular earth anchors of varying diameter and varying depth of embedment, subject to vertical loads.

GRAPHS - Graphs of ultimate load capacity vs. anchor depth and ultimate load capacity vs. anchor diameter, and graphs of coefficients (for varying angles of ϕ) used to calculate the ultimate load capacity of anchors.

TYPE OF ANALYSIS - Based on model test results, a theoretical technique for calculating ultimate load capacity is developed using the dead weight of the pylon and soil within the failure cone and the shearing resistance of the soil along its failure surface.

CONCLUSIONS AND COMMENTS - A comparison of experimental (both model and full-scale tests) and theoretical results indicates satisfactory agreement.
- A comparison of ultimate load capacity values vs. anchor depth is presented for various available calculation methods.

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Hansen, J. Brinch (1966). "Resistance of a Rectangular Anchor Slab," Danish Geotechnical Inst. Bull. No. 21, Copenhagen, pp. 12-13.

TYPE OF ANCHOR OR OBJECT - Rectangular anchor slabs and rows of short or square anchor slabs, subjected to horizontal loads applied perpendicular to the axes of the slabs.

TYPE OF SOIL - Sand.

TYPE OF TESTS CONDUCTED -

GRAPHS -

TYPE OF ANALYSIS - Analysis procedures discussed are based on model tests by Ovesen (1964). Empirical equations are developed which may be used to calculate the ultimate load capacity of anchor blocks.

CONCLUSIONS AND COMMENTS - An equation is presented for the general case of an anchor slab of arbitrary shape.
- A comparison of results obtained using these equations with results obtained from model tests indicates satisfactory agreement.
- A complete design solution requires reference to the publication presented by Ovesen (1964) in D.G.I. Bull. No. 16.

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Leonards, G. A. (1962). Foundation Engineering, McGraw-Hill Book Co., Inc., N. Y., pp. 466-469.

TYPE OF ANCHOR OR OBJECT - Rectangular anchor slabs, subjected to horizontal loads.

TYPE OF SOIL - Sand and clay.

TYPE OF TESTS CONDUCTED -

GRAPHS - A graph of earth resistance coefficients vs. depth of embedment for determining the ultimate load capacity of continuous and square anchors in sand, and a graph of ultimate load capacity (as a function of cohesive strength) vs. depth of embedment for clay.

TYPE OF ANALYSIS - Analysis procedures discussed are based on experimental work done by other authors.

CONCLUSIONS AND COMMENTS - Methods presented involve solutions using classical earth pressure theory and model test results by Buchholtz (1930/1931), Hansen (1953), and Mackenzie (1955).

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Liu, C. L. (1969). "Ocean Sediment Holding Strength Against Breakout of Partially Embedded Objects," Proceedings of the Second ASCE Conference on Civil Engineering in the Oceans, Miami Beach, December 1969, pp. 105-116.

TYPE OF ANCHOR OR OBJECT - partially embedded objects of various sizes and shapes.

TYPE OF TESTS CONDUCTED - Vertical pullout tests on objects weighing from 0.6 lbs to 40,000 lbs.

GRAPHS - A graph of the undrained shear strength vs. depth at one of the test sites.

TYPE OF ANALYSIS - Analysis based on measured soil strength and curve fitting.

CONCLUSIONS - The ratio of the breakout force to the static soil resistance does not correlate well with the length of time required for breakout for the test data examined.

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Mackenzie, T. R. (1955). "Strength of Deadman Anchors in Clay," Master's Thesis, Princeton U., N. J., 63 p.

TYPE OF ANCHOR OR OBJECT - A single long rectangular anchor block, subjected to a horizontal load applied perpendicular to the axis of the block.

TYPE OF SOIL - Remoulded clay, mixed at a high water content.

TYPE OF TESTS CONDUCTED - Model tests on an anchor of dimensions 1"x1"x10", buried at varying depths in the clay, subject to a horizontal force applied at varying load rates.

GRAPHS - Graphs of load vs. displacement for each test, a graph of time vs. displacement for varying loads, and graphs of depth vs. anchor load capacity given both by test results and various theoretical results.

TYPE OF ANALYSIS - Based on model tests, the ultimate load capacity of "deadman" anchors is determined and presented in the form of empirical equations. Load capacity is seen to be principally a function of soil strength and depth of embedment. Test results are compared with load capacity values obtained using classical earth pressure theories and the "dowel" theory developed by Brinch Hansen (1953). End effects and tensile soil strength characteristics are examined.

CONCLUSIONS AND COMMENTS - It is considered that earth pressure wedge theory is valid only for anchor blocks which extend to the ground surface.

- For deep anchor blocks, ultimate load capacity values are observed to be lower than those given by the classical earth pressure or "dowel" theories.
- Tensile soil strength is observed to account for less than 10% of the anchor strength.
- Diagrams of observed failure patterns in the soil are presented.

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Muga, B. J. (1967). "Bottom Breakout Forces," Proceedings of the ASCE Conference on Civil Engineering in the Oceans, San Francisco, September 1967, pp. 569-600.

TYPE OF ANCHOR OR OBJECT - partially embedded objects of various shapes, subjected to vertical pullout forces.

TYPE OF SOIL - San Francisco Bay mud.

TYPE OF TESTS CONDUCTED - Vertical pullout tests on objects weighing as much as 46,000 lbs.

GRAPHS - Graphs of movements vs. time for several pullout tests, and graphs of pullout time vs. applied force.

TYPE OF ANALYSIS - Curve fitting to determine an empirical equation which would represent the test results.

CONCLUSIONS AND COMMENTS - An empirical equation is presented which may be used to estimate the breakout force as a function of the size of the object and the time the force is applied for objects partially embedded in San Francisco Bay mud.

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Ovesen, N. K. (1964). "Anchor Slabs, Calculation Methods and Model Tests," Danish Geotechnical Inst. Bull. No. 16, Copenhagen, 39 p.

TYPE OF ANCHOR OR OBJECT - Rectangular anchor slabs and rows of short slabs, subjected to horizontal loads applied perpendicular to the axes of the slabs, and rectangular slabs with horizontal loads applied parallel to their axes.

TYPE OF SOIL - Loose and dense sand.

TYPE OF TESTS CONDUCTED - Model load tests on anchor slabs of varying length, depth of embedment, and slab spacing in both loose and dense sand.

GRAPHS - Graphs of earth pressure coefficients (for various angles of ϕ) for calculating earth pressure in front of an anchor slab of continuous length and extending to the ground surface (basic case), graphs for determining the location of the point of resultant earth pressure on the slab, graphs of load vs. deflection for various tests conducted, and graphs of anchor resistance factors for the various anchor systems tested.

TYPE OF ANALYSIS - the ultimate load capacity of an anchor slab is found by first calculating a resistance factor for a continuous anchor extending to the ground surface (basic case), using a modified earth pressure theory. This resistance factor is then modified for the actual anchor dimensions under consideration and used as a factor in the equation for ultimate load capacity. The location of the line of action of the resultant forces is found in a similar manner.

CONCLUSIONS AND COMMENTS - A method for estimating the horizontal movement of a slab under an actual load is given.

- The results of scale effects from large and small models tested are discussed.
- A design solution is outlined and numerical examples are presented. A portion of the design solution can be simplified by methods presented by Hansen (1966) in D.G.I. Bull. No. 21.

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Steel Sheet Piling Design Manual (1970). U. S. Steel Corp., AD USS 25-3848-02, pp. 44-55.

TYPE OF ANCHOR OR OBJECT - Rectangular anchor slabs and rows of short anchor slabs, subjected to horizontal loads applied perpendicular to the axis of the slabs.

TYPE OF SOIL - Sand and clay.

TYPE OF TESTS CONDUCTED -

GRAPHS - A graph of earth pressure coefficients for earth pressures in front of an anchor slab, graphs of resistance factors for slabs of various spacings and depths of embedment for sand, and a graph of ultimate load capacity vs. depth of embedment for clay.

TYPE OF ANALYSIS - The results of model tests and analyses conducted by Ovesen (1964) and Mackenzie (1955) are presented, along with the analysis developed by Teng (1962).

CONCLUSIONS AND COMMENTS - This reference includes much of the basic design criteria available today for earth anchors.

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Teng, W. C. (1962). Foundation Design, Prentice-Hall, New Jersey, pp. 375-377.

TYPE OF ANCHOR OR OBJECT - Single rectangular anchor slabs, subjected to horizontal loads.

TYPE OF SOIL - Sand and clay.

TYPE OF TESTS CONDUCTED -

GRAPHS -

TYPE OF ANALYSIS - The ultimate load capacity of a "deadman" anchor is determined using classical earth pressure theory, plus the additional load capacity gained from end effects for an anchor of short length.

CONCLUSIONS AND COMMENTS - For deadman anchors at great depths, the ultimate load capacity is considered to be approximately equal to the bearing capacity of a deep footing whose base is located at a depth corresponding to the midheight of the anchor, as presented by Terzaghi (1943).

REFERENCES ON PASSIVE RESISTANCE OF ANCHOR BLOCKS AND BREAKOUT RESISTANCE OF EMBEDDED OBJECTS

REFERENCE - Vesić, A. S. (1969). "Breakout Resistance of Objects Embedded in Ocean Bottom," Proceedings of the Second ASCE Conference on Civil Engineering in the Oceans, Miami Beach, December 1969, pp. 137-165.

TYPE OF ANCHOR OR OBJECT - A single circular plate and a general 3-dimensional object, subjected to a vertical or inclined load.

TYPE OF SOIL - Sand and clay.

TYPE OF TESTS CONDUCTED - Results of various model anchor pullout capacity tests conducted by other authors are presented.

GRAPHS - Graphs of breakout factors vs. relative depth of embedment for anchor plates of varying diameter tested in sands and clays.

TYPE OF ANALYSIS - The breakout resistance is found to be the sum of the following forces: effective weight of the anchor, effective weight of the soil above the anchor, shearing resistance of the overburden soil along its failure plane, adhesion between the object and soil, and the soil suction force.

CONCLUSIONS AND COMMENTS - The breakout factors and equations presented may be used to determine breakout resistances of anchors.

- Comparison of experimental and theoretical results indicates satisfactory agreement.
- A literature review of the topic is presented.

SECTION II

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Bowles, J. (1968). Foundation Analysis and Design, McGraw-Hill, 1st ed., pp. 503-513.

TYPE OF PILE SYSTEM - Flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head.

TYPE OF ANALYSES - Subgrade reaction.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR -

B. SOIL STRENGTH CHARACTERISTICS -

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Constant and increasing linearly with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Linear.

SOLUTION PROCEDURE - Digital computer solution (FORTRAN program included).

GRAPHS AND TABLES - Table of representative values of modulus of subgrade reaction for various soil types and soil densities.
- Table of safe lateral loads for various pile types and soils, allowing 1/4-inch deflection at ground surface.

CONCLUSIONS AND COMMENTS - A concise development of a finite difference analysis is presented.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Broms, B. B. (1964). "Lateral Resistance of Piles in Cohesive Soils," ASCE, J. Soil Mech. & Found. Div., Vol. 90, No. SM2, pp. 27-63.

TYPE OF PILE SYSTEM - Rigid and flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head and fixed head.

TYPE OF ANALYSES - Subgrade reaction and ultimate resistance (separation).

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR - Ultimate lateral resistance is considered to be nine times the undrained strength (S_u) of the soil.

B. SOIL STRENGTH CHARACTERISTICS - $\phi = 0$, $S_u = c$, constant with depth.

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Constant.

B. LINEAR OR NONLINEAR ANALYSIS - Linear.

SOLUTION PROCEDURE - Hand calculations using graphs.

GRAPHS AND TABLES - Nondimensional graphs of deflection vs. embedded length, ultimate lateral resistance vs. embedded length, and ultimate lateral resistance vs. yield moment.

CONCLUSIONS AND COMMENTS - Available test data on lateral deflection, ultimate lateral resistance, and maximum bending moment for laterally loaded piles are included.
- Data are compared with calculated deflection and maximum bending moment values.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Broms, B. B. (1964). "Lateral Resistance of Piles in Cohesionless Soils," ASCE, J. Soil Mech. & Found. Div., Vol. 90, No. SM3, pp. 123-156.

TYPE OF PILE SYSTEM - Rigid and flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head and fixed head.

TYPE OF ANALYSES - Subgrade reaction and ultimate resistance (separately).

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR - Ultimate lateral resistance is considered to be three times the passive Rankine earth pressure.

B. SOIL STRENGTH CHARACTERISTICS - $c = 0$, $\phi > 0$, constant with depth.

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Increasing linearly with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Linear.

SOLUTION PROCEDURE - Hand calculations using graphs and tables.

GRAPHS AND TABLES - Nondimensional graphs of deflection vs. embedded length, ultimate lateral resistance vs. embedded length, and ultimate lateral resistance vs. yield moment.
- Tables of subgrade reaction coefficients for soils of varying relative densities.

CONCLUSIONS AND COMMENTS - Available test data on lateral deflection, ultimate lateral resistance, and maximum bending moment for laterally loaded piles are included.
- Data are compared with calculated deflection and ultimate lateral resistance values.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Broms, B. B. (1965). "Design of Laterally Loaded Piles," ASCE, J. Soil Mech. & Found. Eng., Vol. 91, No. SM3, pp. 79-99.

TYPE OF PILE SYSTEM - Rigid and flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head and fixed head.

TYPE OF ANALYSES - Subgrade reaction and ultimate resistance (separately).

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR - For short piles, ultimate resistance is considered to be governed by the passive lateral resistance of the soil around it.
 - For long piles, ultimate resistance is considered to be governed by the ultimate (yield) resistance of the pile section.

B. SOIL STRENGTH CHARACTERISTICS - Either $\phi = 0$, $S_u > 0$, or $c = 0$, $\phi > 0$, both constant with depth.

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Constant and increasing linearly with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Linear.

SOLUTION PROCEDURE - Hand calculations using graphs (example problem included).

GRAPHS AND TABLES - Nondimensional graphs of ultimate lateral resistance vs. embedded length, ultimate lateral resistance vs. yield moment, and lateral deflection of the ground surface vs. length.

CONCLUSIONS AND COMMENTS - The use of factors of safety in design calculations is discussed.
 - For short piles, deflections of "working loads" are mainly a function of penetration depth and deformation properties of the soil.
 - For long piles, deflections at "working loads" are dependent on the stiffness of the pile section.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Davisson, M. T. (1960). "Behavior of Flexible Vertical Piles Subjected to Moment, Shear, and Axial Loads," Ph.D. Thesis, Univ. of Illinois, Urbana, 141 p.

TYPE OF PILE SYSTEM - Flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head, pinned head, and fixed head.

TYPE OF ANALYSES - Subgrade reaction and ultimate resistance (separately).

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR - Near the ground surface, ultimate resistance is considered to be slightly higher than conventional two-dimensional passive resistance.
- At depths greater than several pile diameters, ultimate resistance is considered to be equal to the bearing capacity of a deep foundation.

B. SOIL STRENGTH CHARACTERISTICS - $\phi = 0$, $S_u = c$, increasing linearly with depth, or $c = 0$, $\phi > 0$, constant with depth.

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Constant and increasing linearly with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Nonlinear.

SOLUTION PROCEDURE - Hand calculations using graphs.

GRAPHS AND TABLES - Nondimensional graphs of moment, deflection, and soil reaction vs. depth.

CONCLUSIONS AND COMMENTS - An excellent literature review is presented on theory and test results on laterally loaded pile systems; also a summary of values of coefficients of subgrade reaction is determined for various soil types.
- The effects of degree of consolidation on the variation of the soil modulus are discussed.
- Author concludes that plastic resistance is usually developed near the ground surface; elastic soil behavior is observed at some depth.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Davisson, M. T., and H. L. Gill (1963). "Laterally Loaded Piles in a Layered Soil System," ASCE, J. Soil Mech. & Found. Div., Vol. 89, No. SM3, pp. 63-94.

TYPE OF PILE SYSTEM - Flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head and fixed head.

TYPE OF ANALYSES - Subgrade reaction.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR -

B. SOIL STRENGTH CHARACTERISTICS -

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Constant (within each layer of a two-layer system).

B. LINEAR OR NONLINEAR ANALYSIS - Linear.

SOLUTION PROCEDURE - Hand calculations using graphs (example problem included).

GRAPHS AND TABLES - Nondimensional graphs of moment and deflection vs. depth, layer thickness, and layer coefficients.

CONCLUSIONS AND COMMENTS - Characteristics of the surface layer are considered to be most important in determining pile behavior.
- Use of a subgrade modulus constant with depth may lead to underestimating moments and deflections by as much as a factor of two.

REFERENCE - Francis, A. J. (1964). "Analysis of Pile Groups with Flexural Resistance," ASCE, J. Soil Mech. & Found. Div., Vol. 90, No. SM3, pp. 1-32.

TYPE OF PILE SYSTEM - Groups of flexible piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Piles pinned at both head and tip, and fixed head.

TYPE OF ANALYSES - Subgrade reaction.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR -

B. SOIL STRENGTH CHARACTERISTICS -

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Constant and increasing linearly with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Linear.

SOLUTION PROCEDURE - Hand calculations using tables (example problem included).

GRAPHS AND TABLES - Tables of coefficients and factors developed to solve shear, moment, and displacement equations.

CONCLUSIONS AND COMMENTS - The importance of the region of soil near the ground surface in determining the flexural stiffness of the soil-pile system is emphasized.
- Stability of partially embedded piles and loads required for buckling is examined.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Gill, H. L. (1968). "Soil Behavior Around Laterally Loaded Piles," NCEL Tech. Rpt. R-571, Port Hueneme, Calif., 55 p. (AD 667833)

TYPE OF PILE SYSTEM - Flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head.

TYPE OF ANALYSES - Subgrade reaction and ultimate resistance (combined).

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR - In clay, ultimate resistance is considered to be function of S_u, pile depth, and pile width.
- In sand, ultimate resistance is considered to be a function of ϕ, γ, pile depth, and pile width.

B. SOIL STRENGTH CHARACTERISTICS - $\phi = 0$, $S_u = c$, increasing linearly with depth, and $c = 0$, $\phi > 0$, constant with depth.

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Increasing nonlinearly with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Nonlinear.

SOLUTION PROCEDURE - Digital computer solution (program included).

GRAPHS AND TABLES -

CONCLUSIONS AND COMMENTS - Load-displacement characteristics of soil deposits are evaluated in terms of shear strength, depth, pile width, and compressibility characteristics of the soil.
- Results are shown for tests conducted in a bay mud, with and without a dessicated crust.
- A hyperbolic variation of the soil modulus with depth is employed in the analyses.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Gill, H. L., and K. R. Demars (1970). "Displacement of Laterally Loaded Structures in Nonlinearly Responsive Soil," NCEL Tech. Rpt. R-670, Port Hueneme, Calif., 59 p.

TYPE OF PILE SYSTEM - Flexible single piles.

LOADING CONDITIONS - Constant and cyclic shear and moment.

BOUNDARY CONDITIONS - Free head.

TYPE OF ANALYSES - Subgrade reaction and ultimate resistance (combined).

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR - In clay, ultimate resistance is considered to be a function of S_u, pile depth, and pile width.
- In sand, ultimate resistance is considered to be a function of ϕ, γ, pile depth, and pile width.

B. SOIL STRENGTH CHARACTERISTICS - $\phi = 0$, $S_u = c$, increasing linearly with depth, or $c = 0$, $\phi > 0$, constant with depth.

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Increasing nonlinearly with depth (through layered soils).

B. LINEAR OR NONLINEAR ANALYSIS - Nonlinear.

SOLUTION PROCEDURE - Hand calculations in a tabular form, using design charts from NAVDOCKS DM-7 Design Manual (example problem included) and a digital computer solution (program included).

GRAPHS AND TABLES -

CONCLUSIONS AND COMMENTS - The nonlinear response of the soil is accounted for by an iterative finite difference solution.
- For cyclic loading, authors suggest that computed displacements should be increased by 50% and that soil pressures should remain unchanged.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Hansen, J. B. (1961). "The Ultimate Resistance of Rigid Poles Against Transversal Forces," Danish Geotechnical Inst. Bull. No. 12, Copenhagen, Denmark, pp. 5-9.

TYPE OF PILE SYSTEM - Rigid single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head.

TYPE OF ANALYSES - Ultimate resistance.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR - Strength is based on the earth pressures developed around a pile, as a function of ϕ, c, γ, pile depth, and pile width.

B. SOIL STRENGTH CHARACTERISTICS - $\phi = 0$, $S_u = c$, or $c = 0$, $\phi > 0$, or $c > 0$, $\phi > 0$, all constant with depth.

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH -

B. LINEAR OR NONLINEAR ANALYSIS -

SOLUTION PROCEDURE - Hand calculations using earth pressure equations and graphs of earth pressure coefficients (example problem included).

GRAPHS AND TABLES - Graphs of earth pressure coefficients for cohesion and overburden pressure, as functions of ϕ and a ratio of pile depth to pile width.

CONCLUSIONS AND COMMENTS - Long-term (drained) and short-term (undrained) loading conditions are examined.

REFERENCE - Matlock, H., and L. C. Reese (1960). "Generalized Solutions for Laterally Loaded Piles," ASCE, J. Soil Mech. & Found Div., Vol. 86, No. SM5, pp. 63-91.

TYPE OF PILE SYSTEM - Rigid and flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head.

TYPE OF ANALYSES - Subgrade reaction.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR -

B. SOIL STRENGTH CHARACTERISTICS -

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Increasing nonlinearly (as a power function and as a polynomial function of depth).

B. LINEAR OR NONLINEAR ANALYSIS - Nonlinear.

SOLUTION PROCEDURE - Hand calculations using graphs.

GRAPHS AND TABLES - Nondimensional graphs of moment and deflection vs. pile length.

CONCLUSIONS AND COMMENTS - A comparison is made of rigid-pile and linear elastic-pile theory.
- An outline of the finite difference method of analysis for elastic-pile theory is presented.
- The nonlinear solution requires a trial-and-error adjustment of the constants in the soil modulus function, and perhaps in the form of the function, until compatibility is achieved between the behavior of the pile and the supporting soil.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Matlock, H., and L. C. Reese (1961). "Foundation Analysis of Offshore Pile Supported Structures," Proc. 5th Int. Conf. Soil Mech., Paris, 2, pp. 91-97.

TYPE OF PILE SYSTEM - Flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head.

TYPE OF ANALYSES - Subgrade reaction.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR -

B. SOIL STRENGTH CHARACTERISTICS -

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Increasing linearly with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Nonlinear.

SOLUTION PROCEDURE - Hand calculations using graphs and tables (example problem included).

GRAPHS AND TABLES - Nondimensional graphs of deflection vs. depth.
- Tables of coefficients for slope, deflection, moment, shear, and soil reaction.

CONCLUSIONS AND COMMENTS - A detailed example of a hand solution is presented for an offshore pile-supported structure.
- A comparison is made between the results of the hand solution and results obtained from a computer solution.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Patterson, D. (1957). Pole Building Design, American Wood Preservers Institute, 6th ed., Washington, D. C., 48 p.

TYPE OF PILE SYSTEM - Flexible single poles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head.

TYPE OF ANALYSES - Based on subgrade reaction concept employing correlations with ultimate strength characteristics.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR - Allowable lateral soil pressure (stress) is determined from direct measurements with an Auger Indicator Test or by correlation with soil description.

B. SOIL STRENGTH CHARACTERISTICS - Lateral soil pressure values increasing linearly with depth (an average allowable pressure value is used for design purposes).

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH -

B. LINEAR OR NONLINEAR ANALYSIS -

SOLUTION PROCEDURE - Hand calculations using a nomograph (example problems included).

GRAPHS AND TABLES - A nomograph relating allowable soil pressure, pole dimensions, and loads to determine the required depth of embedment for stability of the pile.
- Charts for determining soil stresses and locations of the soil reaction resultants for given percentages of the maximum load.
- Tables of allowable lateral soil pressures.

CONCLUSIONS AND COMMENTS - A design method is presented for attaining lateral stability of a pole in the soil with a minimum depth of embedment of the pole. A factor of safety of approximately five is incorporated in this design procedure; results are based on an allowable ground line deflection of 1/2 inch.
- This reference also contains useful information on properties of wood poles and on typical design considerations in structures utilizing poles.
- The design nomograph can also be found in a discussion presented by J. O. Osterberg, ASTM Special Technical Publication No. 154-A (1954).

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Prakash, S. (1962). "Behavior of Pile Groups Subjected to Lateral Loads," Ph.D. Thesis, Univ. of Illinois, Urbana, 245 p.

TYPE OF PILE SYSTEM - Groups of flexible piles.

LOADING CONDITIONS - Shear.

BOUNDARY CONDITIONS - Free head (piles are connected with a pile cap).

TYPE OF ANALYSES - Subgrade reaction.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR -

B. SOIL STRENGTH CHARACTERISTICS -

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Increasing linearly with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Linear.

SOLUTION PROCEDURE - Hand calculations using graphs and tables (example problem included).

GRAPHS AND TABLES - Nondimensional graphs for comparison of shear, deflection, and relative stiffness of single piles and piles in a pile group.
- Tables for distribution of shears and moments in pile groups.

CONCLUSIONS AND COMMENTS - A review of literature on pile groups is presented.
- Effects of cyclic loading, pile driving, sand density, and variations in pile spacing within a group are examined.
- Behavior of pile groups is shown to be predictable from tests made on single piles.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Reddy, A. S., and A. J. Valsangkar (1968). "An Analytical Solution for Laterally Loaded Piles in Layered Soils," Sols Soils No. 21, pp. 23-28.

TYPE OF PILE SYSTEM - Flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head.

TYPE OF ANALYSES - Subgrade reaction.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR -

B. SOIL STRENGTH CHARACTERISTICS -

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Constant and increasing linearly with depth (within each layer of a two-layer system).

B. LINEAR OR NONLINEAR ANALYSIS - Linear.

SOLUTION PROCEDURE - Hand calculations using graphs.

GRAPHS AND TABLES - Nondimensional graphs of moment and deflection vs. depth for varying ratios of the soil modulus values of the two layers and for varying layer thicknesses.

CONCLUSIONS AND COMMENTS - An analytical solution of the laterally loaded pile problem is presented in the form of a power series.
- The importance of the soil properties of the uppermost soil layer is emphasized.
- Theory is developed for solutions in soils with the soil modulus varying as a second-order polynomial function of depth.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Reese, L. C., and H. Matlock (1956). "Non-Dimensional Solutions for Laterally Loaded Piles with Soil Modulus Assumed to be Proportional to Depth," Proc. 8th Texas Conf. Soil Mech. & Found. Engr., Special Publ. No. 29, Bureau of Engr. Res., Univ. of Texas, Austin.

TYPE OF PILE SYSTEM - Flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head and fixed head.

TYPE OF ANALYSES - Subgrade reaction.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR -

B. SOIL STRENGTH CHARACTERISTICS -

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Increasing linearly with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Linear.

SOLUTION PROCEDURE - Hand calculations using graphs (example problem included).

GRAPHS AND TABLES - Nondimensional graphs of deflection, slope, moment, shear, and soil resistance vs. depth (for applied shear and moment).

CONCLUSIONS AND COMMENTS - Coefficients are developed for a soil modulus assumed proportional to depth ($E_s = kx$). Limitations of this assumption are discussed.

- A nonlinear solution is suggested, by multiple adjustments of k, to achieve more accurate design solutions.

REFERENCES ON ANALYSIS AND DESIGN OF LATERALLY LOADED PILES

REFERENCE - Reese, L. C., and H. Matlock (1960). "Numerical Analysis of Laterally Loaded Piles," Proc. ASCE 2nd Structural Div. Conf. on Electronic Computation, Pittsburgh, pp. 657-668.

TYPE OF PILE SYSTEM - Flexible single piles.

LOADING CONDITIONS - Shear and moment.

BOUNDARY CONDITIONS - Free head.

TYPE OF ANALYSES - Subgrade reaction.

FOR ULTIMATE RESISTANCE ANALYSES
A. METHOD OF CHARACTERIZING SYSTEM BEHAVIOR -

B. SOIL STRENGTH CHARACTERISTICS -

FOR HORIZONTAL SUBGRADE REACTION ANALYSES
A. VARIATION OF SOIL MODULUS WITH DEPTH - Increasing nonlinear with depth.

B. LINEAR OR NONLINEAR ANALYSIS - Nonlinear.

SOLUTION PROCEDURE - Digital computer solution (program not included) (example problem included).

GRAPHS AND TABLES -

CONCLUSIONS AND COMMENTS - A flow chart of a computer program for laterally loaded piles is presented.
- Advantages of a digital computer solution of the nonlinear differential equation are shown.

SECTION III

REFERENCES ON PILE-LOAD TESTS AND PROPERTIES FOR ANALYSIS OF LATERALLY LOADED PILES

REFERENCE - Alizadeh, M. (1969). "Lateral Load Tests on Instrumented Timber Piles," Performance of Deep Foundations, ASTM, STP 444, pp. 379-394.

TYPE OF INVESTIGATION - From measured slopes, moments are found along the pile length in full-scale lateral-loaded pile tests and compared with calculated moment values, assuming the soil modulus to be (1) constant with depth and (2) increasing linearly with depth.

TYPE OF PILE SYSTEM - Flexible single timber piles.

TYPE OF SOIL - Layered clay, silt, sand, and gravel.

LOADING CONDITIONS - Constant and cyclic shear.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED - Lateral load tests on full-scale instrumented piles.

TEST DATA PRESENTED - Graphs of load vs. groundline deflection and groundline deflection vs. load cycle.

BASIS FOR DETERMINING SOIL PROPERTIES - Analysis of data obtained from tests on laterally loaded piles.

SOIL PROPERTY VALUES - A graph of values for the soil modulus vs. groundline deflection, and values for the constant of subgrade reaction vs. groundline deflection.

CONCLUSIONS AND COMMENTS - Comparison of measured and computed slopes indicates that a linear variation of the soil modulus with depth is a reasonable approximation.

- The constant of subgrade reaction is seen to be dependent on deflection.
- Total deflection is found to increase with increasing load and to increase with repeated loading at any constant load value.

RELATED REFERENCES -

REFERENCE - Alizadeh, M., and M. T. Davisson (1970). "Lateral Load Tests on Piles - Arkansas River Project," ASCE, J. Soil Mech. & Found. Div., Vol. 96, No. SM5, pp. 1583-1604.

TYPE OF INVESTIGATION - Lateral load tests are conducted on full-scale piles and pile groups to determine the load-deflection characteristics of the individual piles, both single and in a group, effects of repetitive loading, and effects of different pile-driving techniques on the pile behavior.

TYPE OF PILE SYSTEM - Flexible single vertical and batter piles, and groups of flexible piles.

TYPE OF SOIL - Silty sand.

LOADING CONDITIONS - Constant and cyclic shear.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED - Lateral load tests on single piles and on selected individual piles within the pile groups. Test piles are instrumented with strain gages.

TEST DATA PRESENTED - Graphs of load vs. groundline deflection for all tests conducted, groundline deflection vs. load cycle, and theoretical and measured bending moment vs. depth for the single piles tested. Tables of properties of the piles tested.

BASIS FOR DETERMINING SOIL PROPERTIES - Values of coefficients of subgrade reaction are computed based on equations relating load-deflection data and pile stiffness. Moment values are determined theoretically and computed directly from the pile strain data.

SOIL PROPERTY VALUES - Graphs of coefficients of subgrade reaction vs. groundline deflection for all tests conducted.
- Diagrams of standard penetration test values vs. depth at each test location.
- Tables of coefficients of subgrade reaction corresponding to pile head deflections of 1/2 and 1/4 inch for each pile tested.

CONCLUSIONS AND COMMENTS - Pile types tested are timber, steel pipe, prestressed concrete, and steel H-type piles.
- Effects of jetting and prejetting, and densifying of the foundation material on the behavior of the piles under lateral loads are examined.

RELATED REFERENCES - Mansur, C., A. Hunter, and M. T. Davisson (1964). "Pile Driving and Loading Tests, Lock and Dam No. 4, Arkansas River and Tributaries, Arkansas and Oklahoma."

REFERENCE - Davisson, M. T. (1960). "Behavior of Flexible Vertical Piles Subjected to Moment, Shear, and Axial Load," Ph.D. Thesis, Univ. of Illinois, Urbana, 141 p.

TYPE OF INVESTIGATION - A review of available literature on laterally loaded piles is presented. Pile behavior is examined and a flexural analysis of a laterally loaded pile conducted. Several variations of soil modulus with depth are examined.

TYPE OF PILE SYSTEM - Flexible single piles, with comments concerning the behavior of pile groups.

TYPE OF SOIL - Sand, silt, and clay.

LOADING CONDITIONS - Constant and cyclic shear, moment, and axial loads.

TYPE OF ANALYSIS - Review of theory for subgrade reaction analysis.

TYPE OF TESTS CONDUCTED - A review of significant available test results on scale model and field test piles.

TEST DATA PRESENTED - Soil parameters, observed deflections for given loads, and related information on other specific test conditions and pile behavior presented in text form.

BASIS FOR DETERMINING SOIL PROPERTIES - Soil modulus values and variations with depth are determined by examining the effects of factors, such as effective confining pressure and shear strength, and by examining pile soil reaction-deflection curves.
- A method of establishing approximate soil reaction-deflection curves from assumed tangent modulus and ultimate load values is presented.

SOIL PROPERTY VALUES - A summary of values of the coefficient of subgrade reaction and constant of horizontal subgrade reaction for various soil conditions.

CONCLUSIONS AND COMMENTS - The following factors affecting the soil modulus are discussed: soil strength, soil stiffness, remoulding, cyclic loading, vibration, degree of consolidation, creep, size of loaded area, mode of deformation of the soil, and effective confining pressure.
- In many cases, piles should be analyzed considering both elastic and plastic soil resistance.

RELATED REFERENCES -

REFERENCE - Davisson, M. T., and S. Prakash (1963). "A Review of Soil-Pole Behavior," Highway Research Board, Record No. 39, pp. 25-48.

TYPE OF INVESTIGATION - A review of soil-pole behavior is conducted; the concepts of subgrade reaction and ultimate resistance are presented, along with factors affecting pole behavior. Analytical studies, theoretical developments, and experimental results are presented and their applications discussed.

TYPE OF PILE SYSTEM - Rigid single poles.

TYPE OF SOIL - Sand and clay.

LOADING CONDITIONS - Constant and cyclic shear and moment.

TYPE OF ANALYSIS - Subgrade reaction and ultimate soil resistance.

TYPE OF TESTS CONDUCTED - Available test results from literature are analyzed. Tables of noteworthy events in experimental and theoretical research are presented.

TEST DATA PRESENTED - Typical graphs of moment vs. depth from laterally loaded pole tests.

BASIS FOR DETERMINING SOIL PROPERTIES - Studies by various authors are presented.

SOIL PROPERTY VALUES - Graphs of bearing capacity factors vs. depth for determining ultimate soil resistance, and variations of the soil modulus with depth.
- Charts and equations for determining the points of zero and maximum soil reaction.
- Tables of recommended values of the soil modulus for various ranges of soil strength (in clays), and values of the constant of subgrade reaction for sands.

CONCLUSIONS AND COMMENTS - A linear soil modulus variation with depth is assumed for sand and normally consolidated clay, and a nearly constant variation is assumed for preconsolidated clay.
- Factors affecting soil-pole behavior discussed are: cyclic loading, seasonal variations in soil properties, compaction methods, soil strength properties, and variations of soil modulus with depth.

RELATED REFERENCES -

REFERENCE - Davisson, M. T., and J. R. Salley (1970). "Model Study of Laterally Loaded Piles," ASCE, J. Soil Mech. & Found. Div., Vol. 96, No. SM5, pp. 1605-1627.

TYPE OF INVESTIGATION - Scale model pile tests are conducted in connection with the Arkansas River Project to develop information on the relationship between the lateral load-deflection behavior of single piles, a small group of piles, and large groups of piles subject to constant and repeated loads.

TYPE OF PILE SYSTEM - Flexible single piles and groups of as many as 150 flexible vertical and batter piles.

TYPE OF SOIL - Silty sand.

LOADING CONDITIONS - Constant and cyclic shear, with an applied axial load.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED - Model tests including lateral load tests on a single pile, a group of 6 piles containing both vertical and batter piles, and monoliths containing approximately 100-150 piles, some of which are batter piles. Several piles of each test group are instrumented with strain gages.

TEST DATA PRESENTED - Graphs for bending moment vs. depth for the single pile and individual piles in the pile groups (including theoretical and experimentally derived curves). Also graphs of load per pile vs. groundline deflection in the pile groups.

BASIS FOR DETERMINING SOIL PROPERTIES - Assuming a linearly increasing variation of the soil modulus with depth, values of the constant of subgrade reaction are found using groundline load-deflection data.

SOIL PROPERTY VALUES -

CONCLUSIONS AND COMMENTS - Group loading is seen to decrease the effective value of the coefficient of subgrade reaction compared to that of a single pile.
- Deflections observed in pile groups, as well as single piles, are seen to almost double under load cycles beyond the initial load.
- A Hrennikoff-type analysis for determining deflections of the pile cap is presented for groups containing batter piles.

RELATED REFERENCES - Prakash, S. (1962). "Behavior of Pile Groups Subjected to Lateral Loads."
- Alizadeh, M., and M. T. Davisson (1970). "Lateral Load Tests on Piles--Arkansas River Project."

REFERENCE - Gill, H. L. (1964). "Lateral-Plate and Rigid-Pile Tests on Beach Sand," U.S. NCEL Tech. Rpt. R-310, Port Hueneme, Calif. (AD444370)

TYPE OF INVESTIGATION - Lateral load tests on piles and bearing plates in sand are used to determine variations of soil modulus with depth, which are compared with variations of shear strength with depth.

TYPE OF PILE SYSTEM - Rigid single piles.

TYPE OF SOIL - Saturated sand.

LOADING CONDITIONS - Shear.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED - Rigid pile load-deflection tests and lateral plate-bearing tests. Also vane shear and standard penetration tests on the in-situ soil.

TEST DATA PRESENTED - Graphs of load vs. plate deflection, and pile deflection vs. depth for various loads and pile diameters.
- A graph of average vane shear strength vs. depth.

BASIS FOR DETERMINING SOIL PROPERTIES -

SOIL PROPERTY VALUES -

CONCLUSIONS AND COMMENTS - The lateral-bearing capacity and the coefficient of horizontal subgrade reaction at any depth are found to be nearly directly proportional to the shear strength of the soil at that depth.
- At shallow depths, the coefficient of subgrade reaction is assumed to increase linearly with depth.

RELATED REFERENCES - Gill, H. L., and T. J. Garcia (1965). "Lateral-Plate Tests with Plate Diameter Varied."

REFERENCE - Gill, H. L. (1968). "Soil Behavior Around Laterally Loaded Piles," U.S. NCEL Tech. Rpt. R-571, Port Hueneme, Calif., 55 p. (AD667833)

TYPE OF INVESTIGATION - Based on results from segmental pile tests, theoretical information, and soil property data, a rectangular hyperbolic relationship between lateral load and deflection is used to predict the variation of soil modulus with deflection.

TYPE OF PILE SYSTEM - Flexible single piles.

TYPE OF SOIL - Silty clay with a dessicated crust, saturated silty clay, and sand.

LOADING CONDITIONS - Shear and moment.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED - Full-scale laterally loaded pile tests in each soil and segmental pile tests in the saturated bay mud. Also vane shear tests in each soil and unconfined compression tests on bay mud samples.

TEST DATA PRESENTED - Graphs of load vs. displacement for segmental piles at various depths and load vs. groundline deflection for full-scale piles of varying diameter and depth of embedment. Also a graph of the ratio of lateral load to vane resistance vs. normalized displacement for segmental pile tests.

BASIS FOR DETERMINING SOIL PROPERTIES -

SOIL PROPERTY VALUES -

CONCLUSIONS AND COMMENTS - Comparison of experimental data and theoretical predictions substantiate the validity of the assumed hyperbolic function.
- Width and shape of the loaded area are accounted for in analyzing the segmental and full-scale pile data.
- A brief discussion of an attempt to relate the soil modulus to the compressibility of the bay mud is included.

RELATED REFERENCES - Gill, H. L., and K. R. Demars (1970). "Displacement of Laterally Loaded Structures in Nonlinearly Responsive Soil."
- Gill, H. L., and T. R. Kretschmer (1965). "Horizontal Load Tests with a Segmental Pile."

REFERENCE - Kondner, R. L., and J. A. Cunningham (1963). "Lateral Stability of Rigid Poles Partially Embedded in Sand," Highway Research Board, Record No. 39, pp. 49-67.

TYPE OF INVESTIGATION - Model test results are used, employing dimensional analysis techniques, to develop a functional relationship for the load-deflection characteristics of a soil-pole system. This relationship is represented by a two-constant hyperbolic equation.

TYPE OF PILE SYSTEM - Rigid single pole.

TYPE OF SOIL - Sand.

LOADING CONDITIONS - Shear and moment.

TYPE OF ANALYSIS -

TYPE OF TESTS CONDUCTED - Lateral load tests on model aluminum and steel poles.

TEST DATA PRESENTED - Nondimensional graphs of moment-strength vs. deflection for varying pole shapes and embedment depths.

BASIS FOR DETERMINING SOIL PROPERTIES -

SOIL PROPERTY VALUES -

CONCLUSIONS AND COMMENTS - Soil parameters considered are relative density, angle of internal friction, and dry density.
- Variables considered include deflection, depth of embedment, pole geometry, and applied forces.
- The hyperbolic relationship presented here is applied in subsequent work by H. L. Gill.

RELATED REFERENCES - Kondner, R. L., and G. E. Green (1962). "Lateral Stability of Rigid Poles Subjected to a Ground Line Thrust."
- Kondner, R. L. (1963). "Hyperbolic Stress-Strain Response: Cohesive Soils."
- Gill, H. L. (1968). "Soil Behavior Around Laterally Loaded Piles."

REFERENCE - Matlock, H., and E. A. Ripperger (1958). "Measurement of Soil Pressure on a Laterally Loaded Pile," Proc., ASTM, Vol. 58, pp. 1245-1259.

TYPE OF INVESTIGATION - A discussion of pile instrumentation techniques with strain gages is presented. From strain measurements, bending moment curves can be developed and subsequently soil reaction-deflection curves.

TYPE OF PILE SYSTEM - Flexible piles.

TYPE OF SOIL - Clay.

LOADING CONDITIONS - Shear and/or moment.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED - Instrumented lateral load tests on a pile.

TEST DATA PRESENTED -

BASIS FOR DETERMINING SOIL PROPERTIES -

SOIL PROPERTY VALUES -

CONCLUSIONS AND COMMENTS - An analysis of the precision required in measuring strains to produce useful bending moment curves is presented.
- Instrumentation techniques, such as selection of strain gages, waterproofing, and circuitry are discussed.

RELATED REFERENCES -

REFERENCE - McClelland, B., and J. A. Focht, Jr. (1958). "Soil Modulus for Laterally Loaded Piles," Trans., ASCE, Vol. 123, pp. 1049-1086.

TYPE OF INVESTIGATION - The soil modulus for transient load conditions is estimated by correlating laboratory triaxial test stress-strain curves with pile test soil reaction -deflection curves.

TYPE OF PILE SYSTEM - Flexible single piles.

TYPE OF SOIL - Clay.

LOADING CONDITIONS - Transient shear and moment.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED - Lateral load tests on full-scale piles, and Atterberg Limit tests, unconfined compression tests, and C-U triaxial tests on samples of the clay.

TEST DATA PRESENTED - Graphs of moment, shear, soil reaction, and deflection vs. depth from pile tests, and stress-strain curves from triaxial tests.

BASIS FOR DETERMINING SOIL PROPERTIES - Laboratory triaxial stress-strain curves are used as a basis for establishing soil reaction-deflection curves. The soil modulus is then determined by successive approximations of these pile deflection curves.

SOIL PROPERTY VALUES - Graphs of soil modulus values vs. depth.

CONCLUSIONS AND COMMENTS - The correlations presented are considered valid only for transient loads.

RELATED REFERENCES -

REFERENCE - McCorkle, B. L. (1969). "Side-Bearing Pier Foundations," Civil Engineering - ASCE, Vol. 39, No. 5, pp. 65-66.

TYPE OF INVESTIGATION - Useful soil properties are tabulated. Two equations are presented (derivations not included) whereby pile dimensions, external forces, and soil parameters are related and from which corresponding lateral deflections can be calculated.

TYPE OF PILE SYSTEM - Rigid single piers, with a length-to-width ratio not exceeding 10.

TYPE OF SOIL - Sand and clay.

LOADING CONDITIONS - Shear and moment.

TYPE OF ANALYSIS - Subgrade reaction and passive earth-pressure considerations.

TYPE OF TESTS CONDUCTED -

TEST DATA PRESENTED -

BASIS FOR DETERMINING SOIL PROPERTIES - Standard soil tests (sources of soil property values presented are not mentioned).

SOIL PROPERTY VALUES - A table with ranges of values for passive earth pressures and coefficients of subgrade reaction, corresponding to Standard Penetration Test "N" values (blows/feet) for clays varying from very soft to hard and for sand of varying relative density from loose to very dense.

CONCLUSIONS AND COMMENTS - For design criteria, it is suggested that deflections at the ground surface be limited to 1/4 inch for important structures and 1/2 inch for less significant structures.

RELATED REFERENCES -

REFERENCE - Prakash, S. (1962). "Behavior of Pile Groups Subjected to Lateral Loads," Ph.D. Thesis, Univ. of Illinois, Urbana, 245 p.

TYPE OF INVESTIGATION - A review of literature on experimental and theoretical aspects of pile group behavior is presented. Laboratory model tests are conducted and evaluated to establish the behavior of the pile groups subjected to lateral loads and to compare the behavior of the pile group to a similarly tested single pile.

TYPE OF PILE SYSTEM - Groups of 4 and 9 flexible piles, with information included on single piles.

TYPE OF SOIL - Sand.

LOADING CONDITIONS - Constant shear, with mention of cyclic loading effects.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED - Lateral load tests on single piles and on pile groups, with strain measurements taken along the embedded length of the piles.

TEST DATA PRESENTED - Graphs of soil reaction, shear, moment, pile rotation, and deflection vs. depth for pile groups, and moment vs. depth for a single pile. Effects of pile spacing within a group and cyclic loads on a group are also presented.

BASIS FOR DETERMINING SOIL PROPERTIES -

SOIL PROPERTY VALUES -

CONCLUSIONS AND COMMENTS - Analytical techniques used on single piles are seen to be applicable to pile groups.
- The effects of pile spacing and soil density variation on group behavior are examined.

RELATED REFERENCES -

REFERENCE - Prakash, S., and D. Saran (1967). "Behavior of Laterally Loaded Piles in Cohesive Soil," Proc., 3rd Asian Reg. Conf. Soil Mech. and Found. Engrs., Haifa, pp. 235-238.

TYPE OF INVESTIGATION - The behavior of groups of piles subject to lateral loads is predicted using the observed behavior of a single pile.

TYPE OF PILE SYSTEM - Flexible single piles and groups of 4 and 9 flexible piles held together with pile caps.

TYPE OF SOIL - Clay.

LOADING CONDITIONS - Shear.

TYPE OF ANALYSIS - Comparison of test results for single piles and groups of piles.

TYPE OF TESTS CONDUCTED - Load-deflection tests on model piles, with deflections measured at the groundline.

TEST DATA PRESENTED - Graphs of time vs. deflection for loads on single piles, load vs. deflection for single piles, load vs. pile spacing for varying deflections of pile groups, and load vs. deflection and rotation for varying pile spacing within a group.

BASIS FOR DETERMINING SOIL PROPERTIES -

SOIL PROPERTY VALUES -

CONCLUSIONS AND COMMENTS - Interference in pile groups is seen to decrease with increasing pile spacing and essentially to be negligible for spacing exceeding 6-pile diameters.
- Increasing interference from groups with decreasing pile spacing is seen to cause increasing deflections in the group for a given load and decreasing load-carrying capacity for a given deflection.

RELATED REFERENCES -

REFERENCE - Reese, L. C., H. Matlock, R. L. Tucker, R. E. Smith, and W. B. Ingram (1962). "Review of Data from Lateral Thrust Loadings on Piles," Final Report to the U.S. Naval Civil Engineering Laboratory, Port Hueneme, Structural Mechanics Research Laboratory, Univ. of Texas, Austin, 98 pp.

TYPE OF INVESTIGATION - An extensive test program on laterally loaded piles and lateral-bearing plates is summarized and the test results analyzed to develop the soil reaction-deflection curves.

TYPE OF PILE SYSTEM - Flexible single piles with free and fixed heads.

TYPE OF SOIL - Sand and clay.

LOADING CONDITIONS - Cyclic, short-term, and sustained shear and moment.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED - Laterally loaded pile and lateral plate-bearing tests in both soils. Also Atterberg limits, vane shear, triaxial compression, and standard penetration tests on the clay.

TEST DATA PRESENTED - Graphs of load vs. deflection for varying depths along the pile length, and soil pressure vs. deflection of laterally loaded plates.

BASIS FOR DETERMINING SOIL PROPERTIES - Soil reaction values are obtained from pressure cell measurements. Deflection values are found by actual measurement, interpolation between points, and integration procedures. Thus various forms of the p-y curve are plotted.

SOIL PROPERTY VALUES - Graphs of soil reaction vs. deflection for different loads and at different depths, showing the effects of sustained and cyclic loading.
- A graph of soil modulus values vs. depth from lateral plate-bearing tests in sands of varying density.
- Graphs of water content, shear strength, and penetration resistance vs. depth in the clay.

CONCLUSIONS AND COMMENTS - Behavior of the soil-pile system in the first 10 feet of depth is considered most significant.

RELATED REFERENCES -

REFERENCE - Reese, L. C., and W. R. Cox (1969). "Soil Behavior from Analysis of Tests of Uninstrumented Piles Under Lateral Loading," Performance of Deep Foundations, ASTM, STP 444, pp. 160-176.

TYPE OF INVESTIGATION - A method is presented to establish the soil reaction-deflection curve for a laterally loaded pile, using only soil and pile properties, and data obtained from pile tests measured above the ground surface. Full pile instrumentation can be eliminated.

TYPE OF PILE SYSTEM - Flexible single piles.

TYPE OF SOIL - Sand or clay.

LOADING CONDITIONS - Shear and moment.

TYPE OF ANALYSIS - A nondimensional analysis based on the concept of subgrade reaction.

TYPE OF TESTS CONDUCTED -

TEST DATA PRESENTED -

BASIS FOR DETERMINING SOIL PROPERTIES - An analytic solution is developed relating pile properties, magnitude and location of loads, and deflection and rotation of the pile top to produce an estimated soil reaction-deflection curve for the soil-pile system.

SOIL PROPERTY VALUES - A graph of the soil reaction vs. deflection for various depths along the embedded length of the test piles.

CONCLUSIONS AND COMMENTS - By comparing computed and experimentally determined load-deflection and load-slope curves (at the ground surface), the method of developing the p-y curve presented appears sufficiently accurate for soil-pile interaction.

RELATED REFERENCES -

REFERENCE - Terzaghi, K. (1955). "Evaluation of Coefficients of Subgrade Reaction," Geotechnique, Vol. 5, No. 4, pp. 297-326.

TYPE OF INVESTIGATION - The basic theory and concepts of vertical and horizontal subgrade reaction are presented. Factors which determine the values of the coefficients of subgrade reaction for sands and clays are discussed and the concept applied to the analysis of laterally loaded piles and other structures.

TYPE OF PILE SYSTEM - Rigid single pile.

TYPE OF SOIL - Sand and clay.

LOADING CONDITIONS - Shear.

TYPE OF ANALYSIS - Subgrade reaction.

TYPE OF TESTS CONDUCTED -

TEST DATA PRESENTED -

BASIS FOR DETERMINING SOIL PROPERTIES - The coefficient of horizontal subgrade reaction is found (1) experimentally by measurement of rotation and horizontal deflection of a rigid pile subject to a horizontal load, or (2) by computational procedures based on the theory of elasticity relating contact pressure to corresponding lateral deflection.

SOIL PROPERTY VALUES - A table of values of the constant of horizontal subgrade reaction for a pile of unit width embedden in saturated or unsaturated sand of varying density.
- A table of values of the coefficient of subgrade reaction for a pile of unit width embedded in clay of varying stiffness. Values are related to unconfined compressive strength values.

CONCLUSIONS AND COMMENTS - Methods for calculating values of the coefficients and constants of subgrade reaction are presented.
- Analysis techniques for horizontal beams, anchored bulkheads, and rigid footings and mats are presented as well as laterally loaded piles.

RELATED REFERENCES -

SECTION IV

- SUMMARY OF NOTATIONS EMPLOYED IN SUBGRADE REACTION ANALYSIS

- LIST OF SYMBOLS

SUMMARY OF NOTATIONS EMPLOYED IN SUBGRADE REACTION ANALYSIS

Parameter and Units	This report	Bowles, J.	Broms, B. B.	Davisson, M. T.	Gill, H. L.	Matlock, H.	NAVDOCKS DM-7	Prakash, S.	Reese, L. C.	Sowers & Sowers	Teng, W. C.	Terzaghi, K.
Soil Modulus (Modulus of Subgrade Reaction) = product of the Coefficient of Subgrade Reaction multiplied by the width (B) of the pile or beam. (F/L^2)	E_s	k'	K_h	k	K	E_s	E_s	k	E_s	E	E_{av}	E_s
Coefficient of Horizontal Subgrade Reaction = ratio of horizontal contact pressure to deflection. (F/L^3)	k_h	k_h	k_h							k	k	k_h
Coefficient of Vertical Subgrade Reaction = ratio of vertical contact pressure to deflection. (F/L^3)	k	k_s					K			k_s	k	k_s
Constant of Horizontal Subgrade Reaction = rate of change of the Soil Modulus with depth. (F/L^3)	n_h	n_h	n_h	n_h	n_h	k	f	n_h	k	k'	k_1	n_h
Constant = rate of change of the Coefficient of Subgrade Reaction with depth. (F/L^4)												m_h
Constant of Vertical Subgrade Reaction = rate of change of the Soil Modulus with depth. (F/L^3)		C									k'	
Coefficient of Horizontal Subgrade Reaction for a one-foot wide pile. (F/L^3)				k_{h1}							k_1	k_{h1}
Coefficient of Vertical Subgrade Reaction for a one-foot wide beam. (F/L^3)				k_{s1}							k_1	k_{s1}
Coefficient of Subgrade Reaction for a one-foot square plate. (F/L^3)		k					K_{v1}				k_1	$\overline{k}_{s1}$
Coefficient of Subgrade Reaction for a square plate or footing of width B. (F/L^3)							K_v				k_s	
Coefficient relating Soil Modulus to depth by means of an equation of the form $E_s = kx^n$. (F/L^{2+n})						k			k			
Exponent relating Soil Modulus to depth in an equation of the form $E_s = kx^n$. (dimensionless)						n			n			

Notes Concerning Units

1. The term "modulus" as used here has units of F/L^2, and the term "coefficient" has units of F/L^3.

2. Terzaghi and other authors have employed the following equations to relate the Coefficient of Subgrade Reaction for a beam of width B (k_s) to the Coefficient of Subgrade Reaction for a beam one foot wide (k_{s1}):

$$k_s = k_{s1}\left(\frac{B+1}{2B}\right)^2 \quad \text{for sand} \qquad k_s = k_{s1}\,\frac{1}{B} \quad \text{for clay}$$

Confusion over units can be avoided if it is considered that both the widths (B) and the values of (1) in these equations have dimensions of feet, as follows:

$$k_s = k_{s1}\left(\frac{B(\text{ft.}) + 1(\text{ft.})}{2B(\text{ft.})}\right)^2 \quad \text{for sand} \qquad k_s = k_{s1}\left(\frac{1(\text{ft.})}{B(\text{ft.})}\right) \quad \text{for clay}$$

Similar equations may be developed for use when the widths are expressed in other units:

$$k_s = k_{s1}\left(\frac{B(\text{in.}) + 12(\text{in.})}{2B(\text{in.})}\right) \quad \text{for sand} \qquad k_s = k_{s1}\left(\frac{12(\text{in.})}{B(\text{in.})}\right) \quad \text{for clay}$$

LIST OF SYMBOLS

Symbol	Term	Units
B	Width of pile or beam	L
c	Cohesion intercept	F/L^2
E_s	Soil Modulus (Modulus of Subgrade Reaction)	F/L^2
k	Coefficient of Subgrade Reaction	F/L^3
k_h	Coefficient of Horizontal Subgrade Reaction	F/L^3
n_h	Constant of Horizontal Subgrade Reaction	F/L^3
n	Exponent	
N	Standard penetration resistance of soil	blows/foot
p	Soil reaction per unit length of pile	F/L
S_u	Undrained shear strength	F/L^2
x	Depth below ground surface	L
y	Deflection	L
ϕ	Angle of internal friction	degrees
γ	Unit weight of soil	F/L^3

SECTION V

ANNOTATED BIBLIOGRAPHY

1. Alizadeh, M. (1969) "Lateral Load Tests on Instrumented Timber Piles," Performance of Deep Foundations, ASTM, STP 444, pp. 379-394. (Section III)

2. Alizadeh, M., & M. T. Davisson (1970) "Lateral Load Tests on Piles--Arkansas River Project," ASCE, J. Soil Mech. and Found. Div., Vol. 96, No. SM5, pp. 1583-1604. (Section III)

3. Baker, W. H., & R. L. Kondner (1966) "Pullout Load Capacity of a Circular Earth Anchor Buried in Sand," Highway Research Board, Record No. 108, pp. 1-10. (Section I)

4. Balla, A. (1961) "The Resistance to Breaking Out of Mushroom Foundations for Pylons," Proc. 5th Int. Conf. on Soil Mech., Vol. 1, pp. 569-576. (Section I)

5. Bomben, S. M., & E. H. Kalajian (1969) "Vertical Holding Capacity of Marine Anchors in Sand," Proceedings of the Second ASCE Conference on Civil Engineering in the Oceans, Miami Beach, December 1969, pp. 117-136.

   The holding capacities of marine anchors with embedding flukes are examined for various depths of fluke embedment, size of fluke, and method of embedment in sand. Significant anchor movement is required to mobilize full soil resistance.

6. Bowles, J. (1968) Foundation Analysis and Design, McGraw-Hill, 1st ed., pp. 503-513. (Section II)

7. Broms, B. B. (1964) "Lateral Resistance of Piles in Cohesive Soils," ASCE, J. Soil Mech. and Found. Div., Vol. 90, No. SM2, pp. 27-63. (Section II)

8. Broms, B. B. (1964) "Lateral Resistance of Piles in Cohesionless Soils," ASCE, J. Soil Mech. and Found. Div., Vol. 90, No. SM3, pp. 123-156. (Section II)

9. Broms, B. B. (1965) "Design of Laterally Loaded Piles," ASCE, J. Soil Mech. and Found. Div., Vol. 91, No. SM3, pp. 79-99. (Section II)

10. Buchholtz (1930/1931) "Erdwiderstand auf Ankerplatten," Jahrb. Hafenbautechn. Ges., Vol. 12.

    Printed in German, this reference contains model test results on anchor blocks buried in sand. Coefficients for calculating ultimate resistances of square and continuous blocks are presented.

11. Chellis, R. D. (1961) Pile Foundations, McGraw-Hill, 2nd ed., 704 p.

12. Christensen, N. H. (1961) "Model Tests with Transversally Loaded Rigid Piles in Sand," Danish Geotechnical Inst. Bull. No. 12, Copenhagen, pp. 12-13.

A series of lateral load tests on model piles is conducted to determine their ultimate lateral resistance and investigate the validity of the theory of J. Brinch Hansen (DGI Bull. No. 12). The results confirm the validity of the theory. Test parameters varied are pile depth, height of load application, sand density, and methods of placing the piles.

13. Davisson, M. T. (1960) "Behavior of Flexible Vertical Piles Subjected to Moment, Shear, and Axial Loads," Ph.D. Thesis, Univ. of Illinois, Urbana, 141 p. (Sections II and III)

14. Davisson, M. T., & H. L. Gill (1963) "Laterally Loaded Piles in a Layered Soil System," ASCE, J. Soil Mech. and Found. Div., Vol. 89, No. SM3, pp. 63-94. (Section II)

15. Davisson, M. T., & S. Prakash (1963) "A Review of Soil-Pole Behavior," Highway Research Board, Record No. 39, pp. 25-48. (Section III)

16. Davisson, M. T., & J. R. Salley (1970) "Model Study of Laterally Loaded Piles," ASCE, J. Soil Mech. and Found. Div., Vol. 96, No. SM5, pp. 1605-1627. (Section III)

17. Francis, A. J. (1964) "Analysis of Pile Groups with Flexural Resistance," ASCE, J. Soil Mech. and Found. Div., Vol. 90, No. SM3, pp. 1-32. (Section II)

18. Gill, H. L. (1964) "Lateral-Plate and Rigid-Pile Tests on Beach Sand," U. S. NCEL Tech. Rpt. R-310, Port Hueneme, Calif. (AD 444370) (Section III)

19. Gill, H. L., & T. J. Garcia (1965) "Lateral-Plate Tests with Plate Diameter Varied," U. S. NCEL Tech. Rpt. R-374, Port Hueneme, Calif.

20. Gill, H. L., & T. R. Kretschmer (1965) "Horizontal Load Tests with a Segmental Pile," U. S. NCEL Tech. Rpt. R-386, Port Hueneme, Calif. (AD 617916)

Tests on 4", 8", and 12" pile segments are conducted in sand to investigate the interaction of horizontally loaded piles and the surrounding soil. Results are correlated with vane shear-strength values.

21. Gill, H. L. (1968) "Soil Behavior Around Laterally Loaded Piles," U. S. NCEL Tech. Rpt. R-571, Port Hueneme, Calif., 55 p. (AD 667833) (Sections II and III)

22. Gill, H.L., & K. R. Demars (1970) "Displacement of Laterally Loaded Structures in Nonlinearly Responsive Soil," U. S. NCEL Tech. Rpt. R-670, Port Hueneme, Calif., 59 p. (Section II)

23. Hansen, J. Brinch (1953) "The Stabilizing Effect of Piles in Clay," Christiani & Nielsen Post.

The concept of stabilizing slopes with piles driven to a depth greater than the shearing surface of the critical circle is examined. The resistance of each pile is a function of pile dimensions and soil shear strength.

24. Hansen, J. B. (1961) "The Ultimate Resistance of Rigid Poles Against Transversal Forces," Danish Geotechnical Inst. Bull. 12, Copenhagen, Denmark, pp. 5-9. (Section II)

25. Hansen, J. Brinch (1966) "Resistance of a Rectangular Anchor Slab," Danish Geotech. Inst. Bull. 21, Copenhagen, pp. 12- 13. (Section I)

26. Hetenyi, M. (1946) Beams on Elastic Foundation, University of Michigan Press, Ann Arbor, and Oxford University Press, London, pp. 108-112.

27. Hrennikoff, A. (1950) "Analysis of Pile Foundations with Batter Piles," Trans., ASCE, Vol. 115, pp. 351-374.

A method of analyzing pile groups with nonparallel batter piles, subject to vertical and horizontal loads, is presented. A simple approximate method of solution is given. Lateral pile resistance and horizontal displacements are considered.

28. Kerisel, J. L. (1965) "Vertical and Horizontal Bearing Capacity of Deep Foundations in Clay," Proc., Symp. on Bearing Capacity and Settlement of Foundations, Duke Univ., pp. 45-51.

Bearing capacity of horizontally and vertically loaded piles are included; shear, moment, soil reaction and deflection distributions with depth, and the maximum passive earth pressures are given in terms of soil shear-strength parameters. Pile group behavior is examined.

29. Kondner, R. L., & Green, G. E. (1962) "Lateral Stability of Rigid Poles Subjected to a Ground Line Thrust," Highway Research Board, Bull. No. 342, pp. 124-151.

Nondimensional techniques are used, based on model tests in a dense sand, to develop pole load-deflection characteristics. Variables considered are groundline deflection, depth of embedment, pole geometry, and soil parameters. A failure criterion relating ultimate groundline thrust to pole geometry is given.

30. Kondner, R. L. (1963) "Hyperbolic Stress-Strain Response: Cohesive Soils," ASCE, J. Soil Mech. and Found. Div., Vol. 89, No. SM2, pp. 115-143.

A two-constant hyperbolic stress-strain relationship is developed in which the ultimate shear strength is contained within the general formula in the limits of the stress value. Variables contained in this relationship include lateral pressure, rebound stress, pre-consolidation pressure, strains, and rate of strain.

31. Kondner, R. L., & J. A. Cunningham (1963) "Lateral Stability of Rigid Poles Partially Embedded in Sand," Highway Research Board, Record No. 39, pp. 49-67. (Section III)

32. Kondner, R. L., P. Pfister, and J. S. Zelasko (1966) "Void Ratio Effects on Lateral Stability of Rigid Poles Partially Embedded in Sand," Highway Research Board, Record No. 108, pp. 42-53.

The effects of void ratio, in terms of relative density, on the lateral resistance of rigid poles are examined. Nondimensional techniques, together with small-scale model studies, are used to determine the interrelationships among physical quantities such as pole dimensions, density of soil, loading. A response equation is given which may be used to estimate the load deflection characteristics of the pole.

33. Kozlov, S. M. (1967) "Investigation of the Behavior of Anchorages Acted on by Horizontal Loads," Soil Mechanics and Found. Engr. (Translated from Russian), No. 6, Nov.-Dec., pp. 410-414.

Thin horizontal anchors embedded in sand and subjected to horizontal loads are tested. Bearing capacity of the anchors and movements are found to depend on anchor length, size of vertical projection, and anchor surface roughness.

34. Kubo, K. (1965) "Experimental Study of the Behavior of Laterally Loaded Piles," Proc., 6th Int. Conf. Soil Mech., Montreal, 2, pp. 275-279.

Laterally loaded model pile tests are conducted. A linear variation of the soil modulus with depth is established. A relationship between the coefficient of subgrade reaction and the standard penetration value "N" is developed for sand and clay soils. Basic references are in Japanese.

35. Leonards, G. A. (1962) Foundation Engineering, McGraw-Hill Book Co., Inc., N. Y., pp. 466-469. (Section I)

36. Liu, C. L. (1969) "Ocean Sediment Holding Strength Against Breakout of Partially Embedded Objects," Proceedings, Second ASCE Conference on Civil Engineering in the Oceans, Miami Beach, December 1969, pp. 105-116. (Section I)

37. Mackenzie, T. R. (1955) "Strength of Deadman Anchors in Clay," Master's Thesis, Princeton Univ., N. J., 63 p. (Section I)

38. Mansur, C., A. Hunter, & M. T. Davisson (1964) "Pile Driving and Loading Tests, Lock and Dam No. 4, Arkansas River and Tributaries, Arkansas and Oklahoma," U. S. Army Engineer District, Little Rock.

The pile test program for the Arkansas River Project and design procedures for vertically and laterally loaded piles are presented in this report.

39. Matlock, H., & E. A. Ripperger (1958) "Measurement of Soil Pressure on a Laterally Loaded Pile," Proc., ASTM, Vol. 58, pp. 1245-1259. (Section III)

40. Matlock, H., & L. C. Reese (1960) "Generalized Solutions for Laterally Loaded Piles," ASCE, J. Soil Mech. and Found. Div., Vol. 86, No. SM5, pp. 63-91. (Section II)

41. Matlock, H., & L. C. Reese (1961) "Foundation Analysis of Offshore Pile Supported Structures," Proc. 5th Int. Conf. of Soil Mech., Paris, 2, pp. 91-97. (Section II)

42. McClelland, B., & J. A. Focht, Jr. (1958) "Soil Modulus for Laterally Loaded Piles," Trans., ASCE, Vol. 123, pp. 1049-1086. (Section III)

43. McCorkle, B. L. (1969) "Side-Bearing Pier Foundations," Civil Engineering - ASCE, Vol. 39, No. 5, May 1969, pp. 65-66. (Section III)

44. Menard, L. (1962) "Behavior of Deep Foundation Subjected to Lateral Loads," Sols Soils No. 3, pp. 9-27.

Simple equations are presented which relate the ultimate resistance of piles to lateral loads to the pile dimensions and the soil strength properties. (In French)

45. Muga, B. J. (1967) "Bottom Breakout Forces," Proceedings, ASCE Conference on Civil Engineering in the Oceans, San Francisco, September 1967, pp. 569-600. (Section I)

46. NAVDOCKS DM-7 Design Manual, Soil Mechanics, Foundations and Earth Structures, Dept. of the Navy, Bureau of Yards and Docks, Washington, D. C.

47. Osterberg, J. O. (1954) "Discussion, Supplement to Symposium on Lateral Load Tests on Piles," ASTM Special Tech. Publ. No. 154-A, pp. 33-37.

Test procedures for obtaining load-deflection data on laterally loaded piles and the use of the difference equation to determine pressure, deflection, moment, and shear along the length of a pile are discussed. Typical curves of the required factors are given, along with a design curve developed by Rutledge and used by Patterson (1957) in Pole Building Design. A discussion on the concept of "Soil Modulus" is also presented.

48. Ovesen, N. K. (1964) "Anchor Slabs, Calculation Methods and Model Tests," Danish Geotech. Inst. Bull. No. 16, Copenhagen, 39 p. (Section I)

49. Palmer, L. A., & J. B. Thompson (1948) "Earth Pressure and Deflection Along the Embedded Lengths of Piles Subjected to Lateral Thrusts," Proc., 2nd Int. Conf. on Soil Mech., Rotterdam, Vol. 5, pp. 156-161.

Pressures, deflections, shear, and moments along a vertical pile or row of sheet piles are determined by solution of 13 simultaneous difference equations. The Soil Modulus is assumed to be an exponential function of depth.

50. Patterson, D. (1957) Pole Building Design, American Wood Preservers Institute, 6th ed., Washington, D. C., 48 p. (Section II)

51. Prakash, S. (1962) "Behavior of Pile Groups Subjected to Lateral Loads," Ph.D. Thesis, Univ. of Illinois, Urbana, 245 p. (Sections II and III)

52. Prakash, S., & D. Saran (1967) "Behavior of Laterally Loaded Piles in Cohesive Soil," Proc., 3rd Asian Reg. Conf. Soil Mech. & Found. Engrs., Haifa, pp. 235-238. (Section III)

53. Reddy, A. S., & A. J. Valsangkar (1968) "An Analytical Solution for Laterally Loaded Piles in Layered Soils," Sols Soils No. 21, pp. 23-28. (Section II)

54. Reese, L. C., & H. Matlock (1956) "Non-Dimensional Solutions for Laterally Loaded Piles with Soil Modulus Assumed to be Proportional to Depth," Proc., 8th Texas Conf. on Soil Mech. and Found. Eng., Special Publ. No. 29, Bureau of Engr. Res., Univ. of Texas, Austin. (Section II)

55. Reese, L. C., & A. S. Ginzbarg (1960) "Difference Equation Method for Laterally Loaded Piles with Abrupt Changes in Flexural Rigidity," Shell Devpt. Co., Publ. No. 221, Exploration and Production Research Division.

56. Reese, L. C., & H. Matlock (1960) "Numerical Analysis of Laterally Loaded Piles," Proc., ASCE 2nd Struct. Div. Conf. on Electronic Computation, Pittsburgh, pp. 657-668. (Section II)

57. Reese, L. C., H. Matlock, R. L. Tucker, R. E. Smith, & W. B. Ingram (1962) "Review of Data from Lateral Thrust Loadings on Piles," Final Report to U. S. Naval Civil Engineering Laboratory, Port Hueneme, Structural Mechanics Research Laboratory, Univ. of Texas, Austin, 98 p. (Section III)

58. Reese, L. C., & M. W. O'Neill (1967) "The Analysis of Three-Dimensional Pile Foundations Subjected to Inclined and Eccentric Loads," Proc., ASCE Conference on Civil Engineering in the Oceans, San Francisco, September 1967, pp. 245-276.

A rational procedure, providing compatibility between pile deflections and reactions and complete structural equilibrium, is developed for analyzing pile foundations of three-dimensional offshore structures and other batter-pile foundations. Equations are formulated as matrices for solutions on a digital computer.

59. Reese, L. C., & Cox. W. R. (1969) "Soil Behavior from Analysis of Tests of Uninstrumented Piles Under Lateral Loading," Performance of Deep Foundations, ASTM, STP 444, pp. 160-176. (Section III)

60. Rowe, P. W. (1956) "The Single Pile Subject to Horizontal Force," Geotechnique, Vol. 6, No. 2, pp. 70-85.

The value of the Coefficient of Horizontal Subgrade Reaction is seen to be dependent on the pile geometry and stiffness. A procedure is developed for estimating the relationship between the soil modulus for a pile of width "B" and the soil modulus for a continuous wall. A procedure for estimating the load-deflection curve for a pile is proposed and compared with available test results.

61. Shiraishi, S. (1960) "The Horizontal Reactions on a Pneumatic Caisson," Japanese Soc. of Soil Mech. and Found. Engr., Vol. 1, No. 1, pp. 20-34.

The results of a full-scale lateral load test on a caisson in a sand and clay-layered soil are compared with theoretical estimates. Actual test results indicated soil reaction values greater than those obtained theoretically.

62. Snitko, N. K., & A. N. Snitko (1967) "Calculation of Rigid Flexible Supports Embedded in the Ground Under the Simultaneous Action of Horizontal and Vertical Forces," Soil Mechanics and Found. Engr. (Translated from Russian), No. 3, pp. 153-156.

Moment, shear, deflection, and soil reaction values vs. depth are determined for a pile subject to vertical and horizontal loads, using a subgrade reaction analysis, with the soil modulus increasing linearly with depth. References cited are in Russian.

63. Spillers, W. R., & R. D. Stoll (1964) "Lateral Response of Piles," ASCE, J. Soil Mech. and Found. Div., Vol. 90, No. 4, pp. 1-9.

A theory of pile response to lateral thrusts is presented in which the soil is considered as a continuous elastic medium with nonlinear behavior. The theory assumes progressive zones of yielding in an elastic halfspace. Computer solutions have been developed.

64. Steel Sheet Piling Design Manual (1970) U. S. Steel Corp., AD USS 25-3848-02, pp. 44-55. (Section I)

65. Teng, W. C. (1962) Foundation Design, Prentice-Hall, Inc., N.J., 466 p. (Section I)

66. Terzaghi, K. (1943) Theoretical Soil Mechanics, 9th ed., John Wiley and Sons, Inc., New York, pp. 229-234.

67. Terzaghi, K. (1955) "Evaluation of Coefficients of Subgrade Reaction," Geotechnique, Vol. 5, No. 4, pp. 297-326. (Section III)

68. Tucker, R. L. (1964) "Lateral Analysis of Piles with Dynamic Behavior," Proc., Conf. on Deep Foundations, Mexico, pp. 157-171.

A computer solution is used to analyze laterally loaded piles subjected to dynamic loading. The method allows for discontinuous variations of load, flexural stiffness, and elastic restrains along the length of the pile. It is applicable to impact loading on a fixed-head pile and forced vibrations of a free-head pile.

69. Vesić, A. S. (1969) "Breakout Resistance of Objects Embedded in Ocean Bottom," Proc., Second ASCE Conference on Civil Engineering in the Oceans, Miami Beach, December 1969, pp. 137-165. (Section I)