

## Design of Laterally Loaded Single Piles by Using P-Y Curves and the Cone Penetration Test (CPT) in Sandy Soils

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### ABSTRACT

The aim of this paper is to present a simple method of construction of the load-transfer P-Y curves for the design of laterally loaded piles in sand based on the cone penetration test (CPT). The proposed method was developed on the basis of interpretation of 5 field tests on single instrumented piles conducted in sandy sites in France and shows a simple relationship linking the P-Y curve parameters, the cone penetration resistance and the lateral pile/soil stiffness ratio.

The validation process was carried out by direct comparison of the predicted load-deflection curves based on the proposed method to those obtained from a worldwide case history of field lateral loading tests on piles and showed a very good quality of the prediction using the proposed method.

**KEYWORDS:** Piles, Lateral load, Sand, Full-scale loading, P-Y curves, CPT test.

### INTRODUCTION

The accumulation of case histories of field lateral loading tests on piles carried out worldwide shows that the load-deflection behaviour is governed by a multitude of parameters involved in such an interaction. The theoretical modeling of laterally loaded piles is a difficult task due to the 3D response of the pile/soil system. In engineering practice, pile/soil interaction analysis is usually undertaken within the framework of a serviceability limit state (SLS) design, the pile deflection being either measured from a full-scale loading test or computed based on a variety of methods, such as elasticity-based methods (Banerjee & Davis, 1978; Budhu & Davies, 1987; Randolph, 1981; Poulos & Hull, 1992), numerical methods (Hacouari & Bouafia, 2019; Khedija et al, 2020) and the P-Y curve methods (Matlock & Reese, 1960; Ménard et al., 1969; Baguelin et al, 1978; Reese & van Impe, 2001; Briaud, 2013).

In some particular pile/soil configurations (offshore

structures, monopiles of wind turbines, ... etc.) working under severe lateral loading conditions, an ultimate limit state (ULS) design should be carried out involving the lateral soil resistance (Ménard, 1969; Reese et al., 1974; Reese & van Impe, 2001).

It is nowadays recognized in engineering practice that the methods based on P-Y curves' concept offer a powerful framework to the analysis of the pile response under lateral load, with the advantage to account for the non-homogeneous distribution of the soil properties and the non-linear response of the pile/soil system. According to the P-Y curves' theory, a series of non-linear springs along the pile is used to model the pile/soil interface, where a spring subjected to the soil reaction  $P$ , at a given depth, exhibits a lateral displacement  $Y$ . A typical P-Y curve is depicted in Figure 1, where the main parameters are the initial reaction modulus  $E_{pi}$  and the lateral soil resistance  $P_u$ . According to the experience of full-scale lateral loading tests of piles, the shape of such a curve is usually non-linear and characterized by an initial linear portion corresponding to small pile deflections, as well as by a non-linear portion followed by a horizontal segment BC describing the soil failure around the pile.

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# Design Of Laterally Loaded Piles In Clays Based On Cone

**Hsai-Yang Fang**



## **Design Of Laterally Loaded Piles In Clays Based On Cone:**

**Analysis of Pile Foundations Subject to Static and Dynamic Loading** Amir M. Kaynia, 2021-08-30 This book presents computational tools and design principles for piles used in a wide range of applications and for different loading conditions. The chapters provide a mixture of basic engineering solutions and latest research findings in a balanced manner. The chapters are written by world renowned experts in the field. The materials are presented in a unified manner based on both simplified and rigorous numerical methods. The first four chapters present the basic elements and steps in analysis of piles under static and cyclic loading together with clear references to the appropriate design regulations in Eurocode 7 when relevant. The analysis techniques cover conventional code based methods, solutions based on pile soil interaction springs and advanced 3D finite element methods. The applications range from conventional piles to large circular steel piles used as anchors or monopiles in offshore applications. Chapters 5 to 10 are devoted to dynamic and earthquake analyses and design. These chapters cover a range of solutions from dynamic pile soil springs to elasto dynamic solutions of large pile groups. Both linear and nonlinear soil behaviours are considered along with response due to dynamic loads and earthquake shaking including possible liquefaction. The book is unique in its unified treatment of the solutions used for static and dynamic analysis of piles with practical examples of application. The book is considered a valuable tool for practicing engineers, graduate students and researchers. *Géotechnique*, 2009 *Proceedings of GeoShanghai 2018 International Conference: Multi-physics Processes in Soil Mechanics and Advances in Geotechnical Testing* Liangbo Hu, Xiaoqiang Gu, Junliang Tao, Annan Zhou, 2018-05-03 This book is the second volume of the proceedings of the 4th GeoShanghai International Conference that was held on May 27-30, 2018. This conference showcased the recent advances and technology in geotechnical engineering, geoenvironmental engineering and transportation engineering. This volume entitled *Multi physics Processes in Soil Mechanics and Advances in Geotechnical Testing* covers a wide range of topics in soil mechanics focusing on the behaviours of partially saturated soils, combined effects of multi physics processes in geological materials and systems and emerging methods and techniques in geotechnical in situ testing and monitoring. This book may benefit researchers and scientists from the academic fields of soil and rock mechanics, geotechnical engineering, geoenvironmental engineering, transportation engineering, geology, mining and energy as well as practical engineers from the industry. Each of the papers included in this book received at least two positive peer reviews. The editors would like to express their sincerest appreciation to all of the anonymous reviewers all over the world for their diligent work. **Advanced Design of Pile Foundations Under Lateral Loading** Wei Dong Guo, 2023-12-15 This book presents models that capture the nonlinear response of piles subjected to lateral forces. Utilising a consistent approach encompassing new mathematical models, it offers solutions presented as closed form expressions and underpinned by the same set of 3-5 measurable soil input parameters. These focus on nonlinear response of mono piles, anchored piles, pile groups and torsional piles as well as passive piles subjected to soil

movement induced in shearing sliding slopes or excavation and earthquake shaking The models can also be used for pipelines and similar beam structures Solutions are provided in the form of design charts with each parameter obtained using available test data and illustrated with real world cases The models reveal for the first time the mysterious mechanisms of amplification resulting from back rotation which have incurred the collapse of structures such as the Showa Bridge and Nicoll Highway as well as the distortion of piles during earthquakes Advanced Design of Pile Foundations Under Lateral Loading is ideal for practicing foundation engineers and students at graduate level Wei Dong Guo is co founder of Hans Innovation Group and former Associate Professor at the University of Wollongong Australia He is a Chartered Professional Engineer and is a Fellow of Engineers Australia by whom he was awarded the 2012 Warren Medal

**Cone Penetration Testing 2022** Guido Gottardi, Laura Tonni, 2022-11-11 This abstracts volume including full keynote and invited papers contains the proceedings of the 5th International Symposium on Cone Penetration Testing CPT 22 held in Bologna Italy 8 10 June 2022 More than 500 authors academics researchers practitioners and manufacturers contributed to the peer reviewed papers included in this book which includes three keynote lectures four invited lectures and 169 technical papers The contributions provide a full picture of the current knowledge and major trends in CPT research and development with respect to innovations in instrumentation latest advances in data interpretation and emerging fields of CPT application The paper topics encompass three well established topic categories typically addressed in CPT events Equipment and Procedures Data Interpretation Applications Emphasis is placed on the use of statistical approaches and innovative numerical strategies for CPT data interpretation liquefaction studies application of CPT to offshore engineering comparative studies between CPT and other in situ tests Cone Penetration Testing 2022 contains a wealth of information that could be useful for researchers practitioners and all those working in the broad and dynamic field of cone penetration testing

**Piezocone and Cone Penetration Test (CPTu and CPT) Applications in Foundation Engineering** Abolfazl Eslami, Sara Moshfeghi, Hossein MolaAbasi, Mohammad M. Eslami, 2019-11-23 Piezocone and cone penetration tests CPTu and CPT applications in foundation engineering includes different approaches for determining the bearing capacity of shallow foundations along with methods for determining pile bearing capacity and settlement concepts The use of soft computing GMDH neural networks related to CPT records and Geotechnical parameters are also discussed In addition different cases regarding the behavior of foundation performance using case records such as shallow foundation deep soil improvement soil behavior classification SBC and bearing capacity are also included Provides the latest on CPT and CPTu performance in geotechnical engineering i e bearing capacity settlement liquefaction soil classification and shear strength prediction Introduces soft computing methods for processing soil properties and pile bearing capacity via CPT and CPTu Explains CPT and CPTu testing methods which allows for the continuous or virtually continuous record of ground conditions

**Single Piles and Pile Groups Under Lateral Loading** Lymon C. Reese, William F. Van Impe, 2010-12-15 The complexities of designing piles for lateral loads are manifold as

there are many forces that are critical to the design of big structures such as bridges offshore and waterfront structures and retaining walls The loads on structures should be supported either horizontally or laterally or in both directions and most structures have in common that they are founded on piles To create solid foundations the pile designer is driven towards finding the critical load on a certain structure either by causing overload or by causing too much lateral deflection This second edition of Reese and Van Impe's course book explores and explains lateral load design and procedures for designing piles and pile groups accounting for the soil resistance as related to the lateral deflection of the pile It addresses the analysis of piles of varying stiffness installed into soils with a variety of characteristics accounting for the axial load at the top of the pile and for the rotational restraint of the pile head The presented method using load transfer functions is currently applied in practice by thousands of engineering offices in the world Moreover various experimental case design examples including the design of an offshore platform pile foundation are given to complement theory The rich list of relevant publications will serve the user into further reading Designed as a textbook for senior undergraduate graduate student courses in pile engineering foundation engineering and related subjects this set of book and CD ROM will also benefit professionals in civil and mining engineering and in the applied earth sciences

**ICE Manual of Geotechnical Engineering Volume 1** Hilary Skinner, D G Toll, Kelvin Higgins, Mike Brown, John Burland, 2023-11-17 ICE Manual of Geotechnical Engineering Second edition brings together an exceptional breadth of material to provide a definitive reference on geotechnical engineering solutions Written and edited by leading specialists each chapter provides contemporary guidance and best practice knowledge for civil and structural engineers in the field

**Soil Mechanics in Engineering Practice** Karl Terzaghi, Ralph B. Peck, Gholamreza Mesri, 1996-02-07 This book is one of the best known and most respected books in geotechnical engineering In its third edition it presents both theoretical and practical knowledge of soil mechanics in engineering It features expanded coverage of vibration problems mechanics of drainage passive earth pressure and consolidation

**Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering** The Organizing Committee of the 16th ICSMGE, 2005-09-12 The 16th ICSMGE responds to the needs of the engineering and construction community promoting dialog and exchange between academia and practice in various aspects of soil mechanics and geotechnical engineering This is reflected in the central theme of the conference Geotechnology in Harmony with the Global Environment The proceedings of the conference are of great interest for geo engineers and researchers in soil mechanics and geotechnical engineering Volume 1 contains 5 plenary session lectures the Terzaghi Oration Heritage Lecture and 3 papers presented in the major project session Volumes 2 3 and 4 contain papers with the following topics Soil mechanics in general Infrastructure and mobility Environmental issues of geotechnical engineering Enhancing natural disaster reduction systems Professional practice and education Volume 5 contains the report of practitioner academic forum 20 general reports a summary of the sessions and workshops held during the conference

*Geotechnical and*

*Geoenvironmental Engineering Handbook* R. Kerry Rowe, 2012-12-06 Preface Dedication List of Figures List of Tables List of Contributors Basic Behavior and Site Characterization 1 Introduction R K Rowe 2 Basic Soil Mechanics P V Lade 3 Engineering Properties of Soils and Typical Correlations P V Lade 4 Site Characterization D E Becker 5 Unsaturated Soil Mechanics and Property Assessment D G Fredlund et al 6 Basic Rocks Mechanics and Testing K Y Lo A M Hefny 7 Geosynthetics Characteristics and Testing R M Koerner Y G Hsuan 8 Seepage Drainage and Dewatering R W Loughney Foundations and Pavements 9 Shallo

*Theory and Practice of Pile Foundations* Wei Dong Guo, 2012-11-14 Pile Foundations are an essential basis for many structures It is vital that they be designed with the utmost reliability because the cost of failure is potentially huge Covering a whole range of design issues relating to pile design this book presents economical and efficient design solutions and demonstrates them using real world examples Coverage includes nonlinear response of single piles to vertical or torsional loading and to cyclic lateral loading as well as prediction of nonlinear response of lateral pile groups vertically loaded pile groups and the design of slope stabilising piles Most solutions are provided as closed form expressions Theory and Practice of Pile Foundations is illustrated with case studies accompanied by practical applications in Excel and MathCad the first book to incorporate nonlinear interaction into pile design A valuable resource for students of geotechnical engineering taking courses in foundations and a vital tool for engineers designing pile foundations

**Offshore Geotechnical Engineering** Mark Randolph, Susan Gourvenec, 2017-07-12 Design practice in offshore geotechnical engineering has grown out of onshore practice but the two application areas have tended to diverge over the last thirty years driven partly by the scale of the foundation and anchoring elements used offshore and partly by fundamental differences in construction and installation techniques As a consequence offshore geotechnical engineering has grown as a speciality The structure of Offshore Geotechnical Engineering follows a pattern that mimics the flow of a typical offshore project In the early chapters it provides a brief overview of the marine environment offshore site investigation techniques and interpretation of soil behaviour It proceeds to cover geotechnical design of piled foundations shallow foundations and anchoring systems Three topics are then covered which require a more multi disciplinary approach the design of mobile drilling rigs pipelines and geohazards This book serves as a framework for undergraduate and postgraduate courses and will appeal to professional engineers specialising in the offshore industry

**Structural Engineering and Geomechanics - Volume 1** Sashi K. Kunnath, 2020-06-22 An understanding of dynamic effects on structures is critical to minimize losses from earthquakes and other hazards These three books provide an overview of essential topics in structural and geotechnical engineering with an additional focus on related topics in earthquake engineering to enable readers gain such an understanding One of the ultimate objectives of these books is to provide readers with insights into seismic analysis and design However in order to accomplish that objective background material on structural and geotechnical engineering is necessary Hence the first two sections of the book provide this background material followed by selected topics in

earthquake engineering The material is organized into three major parts The first section covers topics in structural engineering Beginning with fundamental mechanics of materials the book includes chapters on linear and nonlinear analysis as well as topics on modeling of structures from different perspectives In addition to traditional design of structural systems introductions to important concepts in structural reliability and structural stability are discussed Also covered are subjects of recent interest viz blast and impact effects on structures as well as the use of fiber reinforced polymer composites in structural applications Given the growing interest in urban renewal an interesting chapter on restoration of historic cities is also included The second part of the book covers topics in geotechnical engineering covering both shallow and deep foundations and issues and procedures for geotechnical modeling The final part of the book focuses on earthquake engineering with emphasis on both structures and foundations Here again the material covered includes both traditional seismic design and innovative seismic protection And more importantly concepts in modeling for seismic analysis are highlighted

*Foundation Engineering Handbook* Hsai-Yang Fang, 2013-06-29 More than ten years have passed since the first edition was published During that period there have been a substantial number of changes in geotechnical engineering especially in the applications of foundation engineering As the world population increases more land is needed and many soil deposits previously deemed unsuitable for residential housing or other construction projects are now being used Such areas include problematic soil regions mining subsidence areas and sanitary landfills To overcome the problems associated with these natural or man made soil deposits new and improved methods of analysis design and implementation are needed in foundation construction As society develops and living standards rise tall buildings transportation facilities and industrial complexes are increasingly being built Because of the heavy design loads and the complicated environments the traditional design concepts construction materials methods and equipment also need improvement Further recent energy and material shortages have caused additional burdens on the engineering profession and brought about the need to seek alternative or cost saving methods for foundation design and construction

### **Design of Foundations for Offshore Wind Turbines**

Subhamoy Bhattacharya, 2019-03-01 Comprehensive reference covering the design of foundations for offshore wind turbines As the demand for green energy increases the offshore wind power industry is expanding at a rapid pace around the world Design of Foundations for Offshore Wind Turbines is a comprehensive reference which covers the design of foundations for offshore wind turbines and includes examples and case studies It provides an overview of a wind farm and a wind turbine structure and examines the different types of loads on the offshore wind turbine structure Foundation design considerations and the necessary calculations are also covered The geotechnical site investigation and soil behavior soil structure interaction are discussed and the final chapter takes a case study of a wind turbine and demonstrates how to carry out step by step calculations Key features New important subject to the industry Includes calculations and case studies Accompanied by a website hosting software and data files Design of Foundations for Offshore Wind Turbines is a must have reference for

engineers within the renewable energy industry and is also a useful guide for graduate students in this area *Méthodes Numériques de Calcul Des Pieux Pour Les Ouvrages en Mer* Institut Français du Pétrole. Rueil-Malmaison, Laboratoire central des ponts et chaussées, 1986 Electrical Measuring Instruments and Measurements S.C. Bhargava, 2012-12-27 This book written for the benefit of engineering students and practicing engineers alike is the culmination of the author's four decades of experience related to the subject of electrical measurements comprising nearly 30 years of experimental research and more than 15 years of teaching at several engineering institutions The unique feature of this book apart from covering the syllabi of various universities is the style of presentation of all important aspects and features of electrical measurements with neatly and clearly drawn figures diagrams and colour and b/w photos that illustrate details of instruments among other things making the text easy to follow and comprehend Enhancing the chapters are interspersed explanatory comments and where necessary footnotes to help better understanding of the chapter contents Also each chapter begins with a recall to link the subject matter with the related science or phenomenon and fundamental background The first few chapters of the book comprise Units Dimensions and Standards Electricity Magnetism and Electromagnetism and Network Analysis These topics form the basics of electrical measurements and provide a better understanding of the main topics discussed in later chapters The last two chapters represent valuable assets of the book and relate to a Magnetic Measurements describing many unique features not easily available elsewhere a good study of which is essential for the design and development of most electric equipment from motors to transformers and alternators and b Measurement of Non electrical Quantities dealing extensively with the measuring techniques of a number of variables that constitute an important requirement of engineering measurement practices The book is supplemented by ten appendices covering various aspects dealing with the art and science of electrical measurement and of relevance to some of the topics in main chapters Other useful features of the book include an elaborate chapter by chapter list of symbols worked examples exercises and quiz questions at the end of each chapter and extensive authors and subject index This book will be of interest to all students taking courses in electrical measurements as a part of a B Tech in electrical engineering Professionals in the field of electrical engineering will also find the book of use *Calibration of Deterministic Parameters: Reassessment of Offshore Platforms in the Arabian Gulf* Hassan Zaghloul, 2011-04-18 The Arabian Gulf oil and gas production reserves have made it one of the world's strategic producers since the early 1960s with many of the existing platforms stretched beyond their original design life Advances in drilling technology and reservoir assessments have extended the requirement for the service life of those existing platforms even further Extension of the life span of an existing platform requires satisfactory reassessment of its various structural components including piled foundations The American Petroleum Institute Recommended Practice 2A API RP2A is commonly used in the Arabian Gulf for reassessment of existing platforms The API guidelines have been developed for conditions in the Gulf of Mexico the waters off Alaska and the Pacific and Atlantic seabords of the USA However the Arabian Gulf conditions



are fundamentally different to those encountered in US waters Hence there is a need to develop guidelines for reassessment of existing offshore structures to account for the specific conditions of the Arabian Gulf This thesis performs statistical analyses on databases collected during this research from existing platforms to calibrate relevant load and resistance factors for the required guidelines The developed guidelines are based on established approaches used in developing international codes and standards such as API RP2A LRFD The outcome of this research revolves around the following three main issues 1 Calibration of resistance factors for axial capacity of piles driven in the carbonate soils 2 Development of open area live loads OALL on offshore platforms 3 Effect of extreme storm conditions on the reliability of existing platforms in the Arabian Gulf The outcomes of this research are expected to have a profound influence on reassessment of existing platforms in the Arabian Gulf

*Cone Penetration Testing 2018* Michael A. Hicks, Federico Pisanò, Joek Peuchen, 2018-06-13 Cone Penetration Testing 2018 contains the proceedings of the 4th International Symposium on Cone Penetration Testing CPT 18 Delft The Netherlands 21 22 June 2018 and presents the latest developments relating to the use of cone penetration testing in geotechnical engineering It focuses on the solution of geotechnical challenges using the cone penetration test CPT CPT add on measurements and companion in situ penetration tools such as full flow and free fall penetrometers with an emphasis on practical experience and application of research findings The peer reviewed papers have been authored by academics researchers and practitioners from many countries worldwide and cover numerous important aspects ranging from the development of innovative theoretical and numerical methods of interpretation to real field applications This is an Open Access ebook and can be found on [www.taylorfrancis.com](http://www.taylorfrancis.com)

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## **Table of Contents Design Of Laterally Loaded Piles In Clays Based On Cone**

1. Understanding the eBook Design Of Laterally Loaded Piles In Clays Based On Cone
  - The Rise of Digital Reading Design Of Laterally Loaded Piles In Clays Based On Cone
  - Advantages of eBooks Over Traditional Books
2. Identifying Design Of Laterally Loaded Piles In Clays Based On Cone
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Design Of Laterally Loaded Piles In Clays Based On Cone
  - User-Friendly Interface
4. Exploring eBook Recommendations from Design Of Laterally Loaded Piles In Clays Based On Cone
  - Personalized Recommendations
  - Design Of Laterally Loaded Piles In Clays Based On Cone User Reviews and Ratings

- Design Of Laterally Loaded Piles In Clays Based On Cone and Bestseller Lists
- 5. Accessing Design Of Laterally Loaded Piles In Clays Based On Cone Free and Paid eBooks
  - Design Of Laterally Loaded Piles In Clays Based On Cone Public Domain eBooks
  - Design Of Laterally Loaded Piles In Clays Based On Cone eBook Subscription Services
  - Design Of Laterally Loaded Piles In Clays Based On Cone Budget-Friendly Options
- 6. Navigating Design Of Laterally Loaded Piles In Clays Based On Cone eBook Formats
  - ePub, PDF, MOBI, and More
  - Design Of Laterally Loaded Piles In Clays Based On Cone Compatibility with Devices
  - Design Of Laterally Loaded Piles In Clays Based On Cone Enhanced eBook Features
- 7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Design Of Laterally Loaded Piles In Clays Based On Cone
  - Highlighting and Note-Taking Design Of Laterally Loaded Piles In Clays Based On Cone
  - Interactive Elements Design Of Laterally Loaded Piles In Clays Based On Cone
- 8. Staying Engaged with Design Of Laterally Loaded Piles In Clays Based On Cone
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Design Of Laterally Loaded Piles In Clays Based On Cone
- 9. Balancing eBooks and Physical Books Design Of Laterally Loaded Piles In Clays Based On Cone
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Design Of Laterally Loaded Piles In Clays Based On Cone
- 10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
- 11. Cultivating a Reading Routine Design Of Laterally Loaded Piles In Clays Based On Cone
  - Setting Reading Goals Design Of Laterally Loaded Piles In Clays Based On Cone
  - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Design Of Laterally Loaded Piles In Clays Based On Cone
  - Fact-Checking eBook Content of Design Of Laterally Loaded Piles In Clays Based On Cone
  - Distinguishing Credible Sources

13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends
  - Integration of Multimedia Elements
  - Interactive and Gamified eBooks

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