NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **89**

GEOTECHNICAL INSTRUMENTATION FOR MONITORING FIELD PERFORMANCE

JOHN DUNNICLIFF

Geotechnical Instrumentation Consultant
Lexington, Massachusetts

Topic Panel

MICHAEL BOZOZUK, *National Research Council of Canada*
ROGER D. GOUGHNOUR, *Federal Highway Administration*
JOHN W. GUINNEE, *Transportation Research Board*
JOSEPH B. HANNON, *California Department of Transportation*
VERNE C. MCGUFFEY, *New York State Department of Transportation*
ERNEST T. SELIG, *University of Massachusetts*

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. APRIL 1982

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP SYNTHESIS 89

Project 20-5 FY 1979 (Topic 11-06)
ISSN 0547-5570
ISBN 0-309-03414-0
Library of Congress Catalog Card No. 82-60121

Price: $6.80

Subject Areas
Soil Exploration and Classification
Soil Foundations
Soil and Rock Mechanics

Modes
Highway Transportation
Rail Transportation

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council, acting in behalf of the National Academy of Sciences. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the National Academy of Sciences, or the program sponsors.

Each report is reviewed and processed according to procedures established and monitored by the Report Review Committee of the National Academy of Sciences. Distribution of the report is approved by the President of the Academy upon satisfactory completion of the review process.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the Federal Government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their servives to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

The Transportation Research Board evolved from the 54-year-old Highway Research Board. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America.

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of special interest to geotechnical engineers and others seeking information on instrumentation for monitoring performance in subsurface construction. Guidance is provided on acquisition and application of instruments for measuring soil conditions.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this cndcavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Geotechnical engineers are making greater use of instrumentation to monitor indicators of field performance such as pore pressure, earth pressure, deformation, load, and strain. This report of the Transportation Research Board provides guidance on selection and use of the necessary geotechnical instrumentation.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

This synthesis was completed by the Transportation Research Board under the supervision of Paul E. Irick, Assistant Director for Special Technical Activities Division. The Principal Investigators responsible for conduct of the synthesis were Thomas L. Copas and Herbert A. Pennock, Special Projects Engineers. This synthesis was edited by Nancy A. Ackerman.

Special appreciation is expressed to John Dunnicliff, Geotechnical Instrumentation Consultant, Lexington, Massachusetts, who was responsible for the collection of data and the preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Michael Bozozuk, Senior Research Officer, Division of Building Research, National Research Council of Canada; Roger D. Goughnour, Chief, Experimental Construction and Applications Branch, Federal Highway Administration; Joseph B. Hannon, Senior Materials and Research Engineer, Transportation Laboratory, California Department of Transportation; Verne C. McGuffey, Associate Soils Engineer, Soil Mechanics Bureau, New York State Department of Transportation; and Ernest T. Selig, Professor of Civil Engineering, University of Massachusetts.

The following contributions to this synthesis are acknowledged: extensive assistance by J. Barrie Sellers, President, Geokon Inc., West Lebanon, New Hampshire, in the preparation of the sections in Chapter 5 on measurement of deformation using borehole extensometers and on measurement of load and strain in structural members, and also in the preparation of Chapter 6; and permission by Elmo DiBiagio and Frank Myrvoll of the Norwegian Geotechnical Institute to reproduce the material presented in the appendix.

John W. Guinnee, Engineer of Soils, Geology, and Foundations, Transportation Research Board, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway agencies. Their cooperation and assistance were most helpful.

GEOTECHNICAL INSTRUMENTATION FOR MONITORING FIELD PERFORMANCE

SUMMARY

Geotechnical instrumentation for monitoring field performance rather than for investigating and determining in situ properties for design is examined in this synthesis. Field performance monitoring commonly includes measurement of pore pressure, earth pressure, deformation, load, and strain. This report addresses key issues that need to be considered when planning and implementing an instrumentation program. The purpose is to provide guidance that will lead to improved cost effectiveness of instrumentation programs.

Measurements with geotechnical instruments are used as input to the initial design of a facility or remedial treatment, and to ensure safety, reduce construction costs, or control construction procedures. Measurements can also be used to ensure long-term satisfactory performance, to provide legal protection to an owner responsible for construction, and to advance the state of the art of geotechnical engineering.

The use of instrumentation is not merely the selection of instruments, but is a comprehensive step-by-step engineering process beginning with defining the objective and ending with implementation of the data. The various steps, each of which is critical to the success or failure of the instrumentation program, are outlined in this synthesis.

The purchase of instruments should not be considered as a routine construction procurement item because, if valid measurements are to be made, careful attention must be given to quality and detail. Various methods of procurement are described, and recommendations given for the methods most likely to result in high-quality products. Careful attention must also be given to the selection of personnel responsible for field instrument installation and data collection and interpretation, because successful measurements require extreme dedication to detail throughout all phases of the work. Several possible contractual arrangements for selecting specialty field personnel are outlined and recommendations given for the arrangements most likely to result in high-quality data.

Various instruments used to measure pore pressure, earth pressure, deformation, load, and strain are described. The principle of operation is explained and comparative information is presented to assist with selection. General guidelines are presented on instrument calibration and installation and on data collection, processing, and interpretation.

Examples of instrumentation applications are given for braced excavations, embankments, tunnels, excavated slopes, tie-back anchors, driven piles, cast-in-place piles, and slurry trench excavations.

Past experience and available information on each topic are synthesized in this report. The document should be of particular value both to individuals in decision-making roles and to engineers directly responsible for planning and implementing geotechnical instrumentation programs. For the former, the question "why instrumentation?" is answered, indicating that a properly planned and specified instrumentation program can make a large contribution toward increasing safety, reducing cost or environmental impact of construction, and reducing potential litigation. For the latter, the question "how instrumentation?" is answered with a description of the details of program planning and measurement methods.

CHAPTER ONE

INTRODUCTION

The responsibility for planning and implementing a geotechnical instrumentation program in a transportation agency may rest in different sections or offices. It is, therefore, not uncommon for personnel assigned to Materials, Roadway Design, Bridge Design, Construction, Research, and perhaps Maintenance sections of an agency to use, on occasion, similar types of instrumentation. The importance of geotechnical instrumentation has been magnified by increasingly complex design techniques, recent technical developments, and program modifications within the transportation industry. For example:

- Urban mass transit projects have substantially increased the quantity of tunneling work performed in the United States.
- The Federal Highway Administration's Bridge Replacement Program will require a substantial quantity of foundation improvement work.
- Remaining sections of the Interstate Program are primarily located in urban areas. This implies a large number of retaining structures, difficult foundation conditions, and extreme right-of-way restrictions on most projects.
- New construction methods and technologies are being developed at an increasing pace to meet the needs of a rapidly changing transportation program. These products will require field verification before widespread implementation can be recommended.
- Unusual and specialized projects are being planned more frequently.

The constraints and requirements placed on these projects make it difficult and often impossible to apply past experience from similar situations.

During the past two decades, instrumentation manufacturers have developed a large assortment of valuable and versatile products for the monitoring of geotechnically related parameters. Those unfamiliar with instrumentation might believe that obtaining needed information entails nothing more than pulling an instrument from a shelf, installing it, and taking readings. Although successful utilization may at first appear simple and straightforward, considerable engineering and planning are required to obtain the desired end results. An instrumentation program involves a series of steps, each of which is critical to the success or failure of the entire program.

At present, few state transportation agencies design instrumentation programs on a rational basis. A typical instrumentation program is based primarily on knowledge obtained through previous use of the particular instrument or blind trial use. Instrumentation is often included during construction when no valid reason exists for its use, except, perhaps, because instrumentation is popular and "everybody is doing it" (*1*). Clearly, instrumentation should not be used unless the designer has a valid reason that can be defended. The importance of the instrumentation results makes them entirely too valuable for a cut-and-try approach.

Geotechnical instrumentation is used for monitoring the behavior of soil or rock. The term "geotechnical construction" denotes construction requiring consideration of the engineering properties of soil or rock. In the design of a surface facility, the ability of the ground to support the construction must be considered. In the design of a subsurface facility, consideration must also be given to the ability of the ground to support itself or be supported by other means. In both cases the engineering properties of the soil or rock are the factors of interest. These properties include strength, compressibility, and permeability, none of which can be defined accurately.

The significance of these statements on geotechnical construction can be demonstrated by comparison with steel construction. A designer of a steel structure works with manufactured materials. The materials are specified, their manufacture is controlled, and exact numerical values of engineering properties are available for design. An accurate analysis can be made and design plans and specifications prepared. Then, provided construction is in accordance with those plans, the structure will perform as designed. There will generally be no need to monitor performance. In contrast, a designer of geotechnical construction works with naturally occurring materials, which may be altered to make them more suitable, but exact numerical values of their engineering properties cannot be assigned. Laboratory or field tests may be performed on selected samples to obtain values for certain properties; however, these tests will only provide a range of possible values for engineering properties. The design will be based on judgment in selecting the most probable values within those ranges. As construction progresses and geotechnical conditions are observed or behavior monitored, the design judgments can be evaluated and, if necessary, updated. Hence, engineering observations during geotechnical construction are often an integral part of the design process, and instrumentation is a tool to assist with these observations.

PURPOSE OF SYNTHESIS

This synthesis addresses the key issues that need to be considered when planning and implementing an instrumentation program. The purpose is to provide guidance that will lead to improved cost effectiveness of instrumentation programs. The planning process for instrumentation is outlined in Chapter 2; the specification methods for procuring instruments are defined in Chapter 3; and contractual arrangements for field instrumentation services are discussed in Chapter 4. Devices for measuring pore pressure, earth pressure, deformation, and structural load and strain are described in Chapter 5. Chapter 6 presents general guidelines on instrument calibration, installation, and maintenance and on data collection, processing, and interpretation. Examples of instrumentation applications are presented in the appendix.

Emphasis is on typical state transportation work; i.e. embankments and surcharges, excavations, earth and rock cut slopes, braced and tied-back excavations, bridge foundations, and tunnels. The last section of this chapter and Chapters 2–4 should be of particular value to persons in decision-making roles, as a properly planned and specified instrumentation program can make a large contribution toward increasing safety, reducing cost or environmental impact of construction, and reducing potential litigation. Chapters 2, 5, and 6 should be of value to engineers directly responsible for planning and implementing geotechnical instrumentation programs.

A large part of the text of this synthesis is based on Dunnicliff and Sellers (*2*) and Dunnicliff (*3*).

REASONS FOR USING GEOTECHNICAL INSTRUMENTATION ON TRANSPORTATION FACILITIES

There are ample reasons for using geotechnical instrumentation on transportation facilities. If an instrumentation program is performed for the right reasons, planned properly, and executed by diligent people, it can make a large contribution toward increasing safety, reducing cost or environmental impact of construction, and reducing potential litigation. The reasons for using instrumentation can be grouped into the categories described in the following sections. Examples of instrumentation applications, abstracted from DiBiagio and Myrvoll (*4*), are presented in the appendix. These include braced excavations, embankments, tunnels, excavated slopes, tie-back anchors, driven piles, cast-in-piles, and slurry trench excavations. A more complete discussion of the reasons for instrumenting tunnels is given in Dunnicliff et al. (*5*).

Design Purposes

Instrumentation is used to provide input to the initial design of a facility or for the design of remedial treatment. Examples of the use of instrumentation include:

1. For designing tunnels and depressed highways, groundwater-level fluctuations must be determined.
2. If an adverse event occurs, it must be defined in order that remedial measures can be planned and put into practice. Instrumentation can play a role in defining the problem. For example, measurements of water-table fluctuation and failure plane depth are needed to define the nature of a landslide.
3. Because of the uncertainties inherent in a design, specifications for geotechnical construction may require that the contractor conduct one or more proof tests to verify adequacy of design. Ideally proof tests are performed as part of the design phase so that construction specifications reflect test results, but time constraints or contractural restrictions often make this impossible. A proof test will always include observations, which may include instrumentation. For example, specifications for pile-supported bridge foundations usually call for one or more pile load tests before production pile driving, entailing the use of deformation gages and a load cell. Similar instrumentation is required for proof testing of tie-backs.

Construction Purposes

Instrumentation is used to ensure safety, reduce construction costs, and control construction procedures or schedules.

1. Safety, both during and after construction, is an essential consideration in all construction projects. Instrumentation programs can provide the needed safeguards, while permitting a lower factor of safety or more rapid construction. Continued safety in service can be evaluated through long-term monitoring.

   There is often a need to monitor the effect of construction on adjacent structures, such as the measurement of deformation in and around a tied-back excavation as a means of ensuring safety of the lateral support. If instrumentation is used for safety-monitoring purposes, the designer should have a preconceived recourse in the event construction is shown to be unsafe.
2. Construction is becoming increasingly expensive, nullifying the justification for overconservative designs. Construction costs can be reduced by the use of instrumentation, for example, to disclose when underpinning of adjacent buildings is not needed, or when spacing of tunnel supports can be increased.
3. Uncertainties in engineering properties during the design phase may affect construction procedures or schedules. The designer may therefore specify a program to monitor actual behavior during construction so that procedures or schedules can be determined in accordance with actual behavior. This use of instrumentation is normally referred to as "construction control," even though it also plays a role in ensuring safety and reducing construction costs. For example, in the construction of a highway embankment on a soft clay deposit using staged construction procedures, instrumentation will normally be used to determine when the clay can support the next stage of fill. Similarly, instrumentation is useful to monitor the progress of consolidation beneath surcharge fills.

Verifying Long-Term Satisfactory Performance

Engineers have an obligation to build safe structures, particularly if loss of life would result from lack of safety. Performance monitoring over the life of a structure, using observations and instrumentation, may be the expedient way to ensure long-term safety. For example: (a) If permanent tie-backs are used to support an excavation for a depressed highway, surface and subsurface ground deformations may be measured, and perhaps load in representative tie-backs. (b) Where rock bolts have been used to stabilize a rock cut alongside a highway, extensometers may be installed to provide a permanent means of monitoring rock movements to indicate long-term rock-bolt performance. (c) If drainage arrangements have been provided to increase the stability of a slope or retaining wall, observation wells may be installed to check the performance.

Legal Reasons

Where geotechnical construction may affect neighboring property, instrumentation is useful in determining if there is a relationship between construction and the changing conditions of that property. For example, if a depressed highway is to be constructed in a city, the highway designer or a building owner may use instrumentation to provide a bank of data concerning performance of adjacent structures during excavation for possible use in the event of litigation. Also monitoring of vibration due to pile driving or blasting may be needed to determine responsibility for any expected damage. Instrumentation for legal reasons will be used to a greater extent if the construction procedure is relatively new, for example, ground freezing; or if there is a possible direct link between the construction procedure and damage to property off the right-of-way, such as dewatering.

Advancing the State of the Art

Many advances in geotechnical engineering have resulted from field measurements. Often these measurements have been made for one of the project-specific reasons described above, and the general advance of knowledge has been a by-product. However, several notable practical research tests have been, and are being, made to check and extend existing theories for soil and rock behavior, and hence provide a basis for extending the state of the art for design of geotechnical construction. These research-oriented investigations, which usually require much more extensive field instrumentation than is required for construction control, include full-scale tests of deformation around and loading on slurry wall panels, measurement of earth pressures on culverts beneath highway embankments, full-scale tests on individual piles or a pile group to determine load transfer relationships, measurement of tunnel support load and ground deformation as input to improved support design procedures, and measurement of the effectiveness of various types of sand or wick drains.

Enhancing Public Relations

Instrumentation programs, which indicate that the construction is being carefully watched, can give reassurance to the public, and thus can expedite the approval of the project. Dunnicliff et al. (*5*) describe a project for which the owner specified extensive instrumentation, more than was needed for technical reasons, to reassure the public that safety would be enhanced and damage potential or adverse problems would be minimized. This resulted in more rapid approval of the project and removed many of the political obstacles. Because the effects of inflation and other costs of delays were reduced, the higher-than-normal instrumentation cost still resulted in a cost saving.

General Considerations

When the need for instrumentation is properly and correctly established, and when the program is properly planned, cost savings may directly result, as indicated by previous examples. However, instrumentation does not have to reduce costs to be justified. In some cases, instrumentation has been valuable proving that the design is correct. In other cases, instrumentation might show that the design is inadequate, which may result in increased construction costs. However, the value of added safety and the avoidance of failure (and saving the cost of repairs) will make the instrumentation program cost effective.

CHAPTER TWO

SYSTEMATIC APPROACH TO PLANNING MONITORING PROGRAMS USING GEOTECHNICAL INSTRUMENTATION

Planning a monitoring program using geotechnical instrumentation is similar to other engineering design efforts, which begin with a definition of purpose and proceed through a series of logical steps to preparation of plans and specifications. However, an engineer responsible for planning a monitoring program all too often proceeds in an illogical manner. Unfortunately, there is a tendency among some engineers to select an instrument, make some measurements, and then wonder what to do with the data obtained. The use of instrumentation is not merely the selection of instruments, but is a comprehensive engineering process that begins with defining the objective and ends with implementation of the data. Planning should proceed through the steps listed below.

DEFINE PROJECT CONDITIONS

Project conditions include subsurface stratigraphy and engineering properties, groundwater conditions, status of nearby structures, and planned construction method.

DEFINE PURPOSE OF INSTRUMENTATION

Instrumentation should not be used unless the designer has a valid reason that can be defended. (The reasons for using instrumentation are discussed in Chapter 1.)

SELECT VARIABLES TO BE MONITORED

Variables to be monitored include groundwater level, pore water pressure, earth pressure, vertical and horizontal deformation, tilt, load, and strain.

MAKE PREDICTIONS OF BEHAVIOR

Predictions are necessary so that required instrument ranges and accuracies can be selected. Predictions also provide input to locating and orienting instruments used to measure pressure and deformations. If measurements are for purposes of construction control, numerical values should be determined for the parameters, which, if attained, will require remedial action to be taken.

DEVISE SOLUTIONS TO PROBLEMS THAT MAY BE DISCLOSED BY OBSERVATIONS

Inherent in the use of instrumentation is the absolute necessity for deciding, in advance, a positive means for solving any problem that may be disclosed by the results of the observations. If the observations should demonstrate that the least favorable conditions compatible with the results of the subsurface studies actually do prevail, the corresponding problems must be met with appropriate, previously anticipated solutions (*6*).

ASSIGN TASKS

A list of instrumentation tasks for which responsibility must be assigned is given in Chapter 4. Completion of this list will identify any gaps in the assignment of responsibilities; if personnel are not available to complete these tasks, this may influence the direction of the entire monitoring program. The tasks assigned to the instrumentation specialist should be under the supervision of one individual. Tasks assignments should clearly indicate who has overall responsibility for implementing the results of the observations.

SELECT INSTRUMENTS

The preceding six steps should be completed before instruments are selected. In the selection of instruments, the overriding desirable feature is reliability. Inherent in reliability is maximum simplicity (*7*), maximum durability in the installed environment, minimum sensitivity to climatic conditions; and a good past performance record. With certain instruments, if a reading can be obtained, that reading is necessarily correct (*8*); clearly these instruments are preferable. Components that will not be damaged by construction equipment, vandalism, water, dust, heat, or subsurface chemistry and that will survive deformation of the materials in which they are installed (*8*) should be selected. Sensor, readout, and linkage between sensor and readout should be considered separately, as different criteria may apply to each.

The least expensive instrument may not result in minimum total cost. In evaluating the economics of alternative instruments, the total costs of procuring, calibration, installation, maintenance, monitoring, and data processing should be compared.

PLAN RECORDING OF FACTORS THAT MAY INFLUENCE MEASURED DATA

Measurements by themselves are rarely sufficient to provide useful conclusions (*7*). The use of instrumentation entails relating measurements to causes, and therefore complete records must be maintained of all factors that might cause changes in the measured variables. Construction details, visual observations of behavior, temperature, snow and rainfall, and installation details of each instrument should be recorded.

ESTABLISH PROCEDURES FOR ENSURING READING CORRECTNESS

Personnel responsible for instrumentation should be able to answer the question: Is the instrument functioning correctly? Among the procedures for addressing this question are a simple visual means of checking for gross errors, a backup system, and periodic calibration and maintenance (see discussion in Chapter 6). Certain instruments are equipped with self-verification features (*8*) whereby a reading can be verified in place; this feature is desirable.

SELECT INSTRUMENT LOCATIONS

The selection of instrument locations should reflect predicted behavior. Locations should be selected so that data can be obtained as early as possible in the construction process. Flexibility should be maintained so that location plans can be changed as new information becomes available during construction. Recognizing the inherent variability of soil and rock, it is often worthwhile to instrument a few locations fully, and to use inexpensive "index" devices at these and many other locations to address the question: Are the fully instrumented locations representative of behavior? If the answer is no, it may be necessary to install additional instruments to define behavior adequately.

LIST SPECIFIC PURPOSE OF EACH INSTRUMENT

Each instrument indicated on the plans should be numbered and its purpose listed. If no viable specific purpose can be found for a planned instrument, it should be deleted.

WRITE INSTRUMENT PROCUREMENT SPECIFICATIONS

Attempts by users to design and manufacture instruments usually have not been successful. Therefore procurement specifications are needed. Advantages and limitations of various instrument procurement specifications are described in Chapter 3.

WRITE CONTRACTUAL ARRANGEMENTS FOR FIELD INSTRUMENTATION SERVICES

Contractual arrangements for the selection of personnel responsible for field instrument installation and data collection and interpretation may govern success or failure of a monitoring program. Advantages and limitations of various contractual arrangements for field instrumentation services are described in Chapter 4.

PLAN INSTALLATION

Installation procedures should be planned well in advance of scheduled installation dates. Written step-by-step procedures should be prepared, making use of the manufacturer's instruction manual and the designer's knowledge of specific site needs. The written procedures should include a detailed listing of required materials and tools and should provide for alternative methods in the event that problems arise in the field, such as inability to maintain an open borehole with drilling fluid or unanticipated subsurface stratigraphy. The fact that the owner's personnel will install the instruments does not eliminate the need for written procedures. Installation record sheets should be prepared (see discussion in Chapter 6). Plans should be coordinated with the contractor and arrangements made to protect installed instruments from damage caused by construction and vandalism.

PLAN PROCEDURES SUBSEQUENT TO INSTALLATION

General guidelines for instrument calibration and maintenance and for data collection, processing, and interpretation are given in Chapter 6. Data sheets should be prepared at this stage. All parties should be forewarned of the planned means of solving any problems that may be disclosed as a result of the observations.

CHAPTER THREE

SPECIFICATIONS FOR PROCUREMENT OF INSTRUMENTS

Procurement of sophisticated geotechnical instruments should not be considered as a routine construction procurement item because, if valid measurements are to be made, extreme attention must be paid to quality and details. Simple devices, such as settlement platforms and observation wells, however, may be procured as routine construction items. The following factors should be considered in preparing a procurement specification:

- Specification method,
- Party responsible for procurement, and
- Method for determining price.

In selecting the combination of these variables for a project, the designer should remember that the primary needs are high quality and reliability.

SPECIFICATION METHODS

Three methods of specifying instruments are described below. Advantages and limitations of these methods are given in Table 1. There is no preferred method; the selection depends on factors specific to each project.

Method Specification, with Model Number

The designer will select the measurement method, including preferred instrument model. The selection may be based on the designer's previous experience, on the experience of others, on the reputation of a particular manufacturer, or on the lack of awareness of an alternative method. Depending on public agency regulations, the designer may be required to add an "or equal" provision to the model number. In this case, the designer will indicate who will approve the substitution and who will specify conformance with various criteria, such as instrument type, physical size limitations, operating environment, readout requirements, material, power supplies, auxiliary equipment, and calibration test requirements (*9*).

Method Specification, without Model Number

The designer will select the measurement method and write a generic specification to define the required characteristics of the system and components. For example, a specification may call for pneumatic piezometers, with certain size, range, mechanical, electrical, and other requirements. On

TABLE 1

ADVANTAGES AND LIMITATIONS OF VARIOUS SPECIFICATION METHODS FOR PROCUREMENT OF INSTRUMENTS

METHOD	ADVANTAGES	LIMITATIONS
Method specification, with model number	Least effort required to write specifications. Most direct way of obtaining preferred device if sole source procurement is permitted without "or equal" provision.	May be difficult for owner to document rejection of a substitution, even when it is believed to be undesirable. Designer may have to accept responsibility if specified model number does not perform adequately.
Method specification, without model number	No bias toward particular model.	Designer's preconceived requirements may limit innovation on part of manufacturer. Assumes owner has necessary skill to write specification. Designer may have to accept responsibility if device does not perform adequately.
Performance specification	Allows maximum innovation on part of manufacturer. Manufacturer has contractual commitment to ensure that device performs adequately. No bias toward particular model.	Assumes manufacturer will understand design criteria dictated by the specific geotechnical environment. Can be difficult for designer to evaluate if manufacturer's proposed instrument will perform as needed. Difficult to use when instrumentation is a small part of a major construction contract.

occasion the generic specification may be so limiting that the requirements can be satisfied only by one commercial model.

Performance Specification

To apply this method the designer specifies the end result required. For example, the specification might state that piezometers shall have a certain range and accuracy and must operate for a certain period in the geotechnical environment described in the specifications. The designer will need to determine in advance how to evaluate if the manufacturer's proposed instrument will perform as required.

PROCUREMENT BY OWNER OR CONTRACTOR

Instruments can be procured either directly by the owner (or by the design consultant on behalf of the owner) or by the contractor. Advantages and limitations of the two approaches are given in Table 2. Procurement by the owner is generally preferable.

METHOD FOR DETERMINING PRICE

If instruments are procured directly by the owner, price can be determined either by bidding or by negotiation. If instruments are procured by the contractor, the bid method will normally be used unless an allowance item (see Chapter 4) for furnishing instruments has been included in the general contract bid schedule.

Negotiation can be conducted with more than one possible source, but will usually be with a preferred sole source. Advantages and limitations of the two methods, applicable both to direct procurement by the owner and to procurement by the contractor, are indicated in Table 3. Negotiation is generally preferable.

TABLE 2
ADVANTAGES AND LIMITATIONS OF OWNER OR CONTRACTOR PROCUREMENT

PROCUREMENT BY	ADVANTAGES	LIMITATIONS
Owner or design consultant	Least costly (because no markup by contractor). Owner has direct control over inspection during manufacture and over acceptability on receipt. Owner has direct control over acceptance of substitution. Can select between competitive bid method or (if permitted by public agency regulations) negotiation with preferred sole source. More flexible to accommodate changes.	Usually cannot be financed by construction funds. Contractor has no liability for performance.
Contractor	Financed by construction funds. Contractor's liability is clear.	May be difficult for owner to document rejection of a substitution, even when it is believed to be undesirable. Negotiated price from preferred source not possible unless by use of allowance item (see Chapter 4) in general contract bid schedule.

TABLE 3
ADVANTAGES AND LIMITATIONS OF METHODS FOR DETERMINING PRICE

METHOD	ADVANTAGES	LIMITATIONS
Bid	Will tend to be least costly.	Requires preparation of bid specification and associated documents. Lowest cost runs risk of lowest quality and invalid measurement data.
Negotiation	Purchaser has direct control over quality. Can use preferred sources. More flexible to accommodate changes.	Not permitted under some public agency regulations.

SPECIFICATIONS FOR BID PROCUREMENT OF INSTRUMENTS

Despite the recommendation to negotiate prices, it is recognized that some public agencies require the bid method. If instrument procurement is bid, a comprehensive specification is essential and will often be combined with a specification for field services following the recommendations given in Chapter 4. The procurement part of the specification should address the following topics (*5*):

- Division of responsibilities among owner, designer, resident engineer, instrumentation specialist, and contractor for procuring and calibrating instruments
- Procedure for approval of instruments
- Specifications for instruments (see previous discussion on specification methods)
- Quality control
- Factory calibration and preshipment tests
- Step-by-step acceptance test procedure to be accomplished by the user on receipt to ensure correct functioning
- Spare parts
- Warranty
- Instruction manual requirements
- Repair and replacement
- Responsibility for work stoppage if instruments malfunction

- Delivery schedule
- Method of shipment
- Disposition of instruments at end of job
- Measurement and payment

Cording et al. (*9*) provide more detailed guidelines. If instruments are procured by negotiation instead of by bidding, most of the topics in the above list should also be addressed.

INSTRUCTION MANUAL

The procurement specification should indicate instruction manual requirements, including a description of theory of operation and procedures for installation, reading or operation, data calculation and presentation, calibration, and maintenance. Sample wording for these requirements is given by Schmidt and Dunnicliff (*10*).

CHAPTER FOUR

CONTRACTUAL ARRANGEMENTS FOR FIELD INSTRUMENTATION SERVICES

Contractual arrangements for the selection of personnel responsible for field instrument installation and data collection and interpretation may govern the success or failure of a monitoring program. Even if the program has been planned in a complete and systematic way and appropriate instrumentation devices have been procured, measured data may not be reliable unless contractual arrangements ensure that field personnel perform high-quality work. Geotechnical instrumentation field work should not be considered a routine construction item, because successful measurements require extreme dedication to detail throughout all phases of the work.

DIVISION OF RESPONSIBILITIES

The various tasks involved in accomplishing a monitoring program, together with alternative choices of the parties available for performing them, are listed in Figure 1. It is useful to complete this type of list during the planning stage by indicating the responsible person for each item. Obviously, several of the tasks involve the participation of more than one party. The instrumentation specialist, when needed, will be an employee of the owner or the designer or a consultant with special expertise in geotechnical instrumentation.

GOALS OF CONTRACTUAL ARRANGEMENTS

The goals of contractural arrangements for field instrumentation services are (a) to ensure quality work at minimum cost to the owner; (b) to create a cooperative working relationship between specialty instrumentation personnel and the contractor; and (c) to permit flexibility to accommodate changes as the work proceeds, which is necessary because unforeseen factors are often revealed during construction that change the basis for selecting instrument types and locations.

DEFINITION OF TERMS

Definitions of terms used in the discussion on contractual arrangements are given below:

Support Work Tasks that are within the capability of the average general contractor.

Biddable Support Work Support work of a production nature (e.g., production drilling) and support work that can be bid by the hour (e.g., drill rig and crew to assist during instrument installation).

Nonbiddable Support Work Support work that will be controlled by the owner's instrumentation schedules or procedures (e.g., access for reading). Support work that is not defined at the time of bid (e.g., revised instrumentation due to geologic conditions revealed during construction). Contractor's assistance that will be needed on an "as required" basis (e.g., assistance of tradesmen).

Specialist Work All instrumentation tasks outside the capability of the average general contractor.

Force Account A method of payment to the general contractor whereby reimbursement is on a cost-plus basis.

Allowance Item An item included in the general contract bid schedule for work not defined precisely at the time of bid or for work over which the owner will exercise direct control. For instrumentation services, the item description will be: "Provide services of specialty instrumentation personnel." The designer includes a cost estimate in the bid schedule and specifies that, after contract award, the contractor will be instructed to enter into a subcontract with an organization selected by the owner. Price is determined by the owner, and payment made via the contractor under the allowance item.

CONTRACTUAL ARRANGEMENTS FOR INSTRUMENT INSTALLATION

Five basic types of contractual arrangements for achieving an instrument installation are described below.

1. Installation by Owner's Personnel

The owner's personnel perform all specialist work, sometimes using their own equipment such as drill rigs. Biddable support work is performed by the contractor. Nonbiddable support work is paid for by force account. The prime contract bid specifications need to be sufficiently detailed to define support and specialist work and to convey how the monitoring program will affect the contractor's work. The contractor is then able to bid a fair price for the support work and include sufficient costs for performing an adequate role in the monitoring program. Special attention must be paid to specifying cooperation between the contractor and owner.

2. Bid Items in Prime Contract, with No Prequalification

All instrument installation work is included in the prime contract, usually specified as "furnish and install," and bid on a unit or lump-sum basis. No qualification requirements for specialist personnel are included. Details of installation procedures are usually specified; they should be as detailed as possible, but not unreasonably restrictive. The wording "installation procedures shall be in accordance with the manufacturer's recommendations" is applicable *only* if the manufacturer's procedures are first reviewed, in order to ensure that they are complete and applicable to the specific site geotechnical conditions. Contents of the specifications should be as discussed later in this chapter, except that personnel qualification requirements are not indicated. If the work is specified as "furnish and install," the specification should include the topics listed in Chapter 3.

3. Bid Items in Prime Contract, with Prequalification

Contractual arrangements are similar to the preceding method, but include qualification requirements for specialist personnel, as described later in this chapter.

4. Instrumentation Specialist Contracting with Owner

The instrumentation specialist contracts with the owner, the owner's design consultant, the construction manager, or the resident engineer. The owner or the design consultant selects an instrumentation specialist, following the qualification guidelines presented later in this chapter and described in *ASCE Manual 45* (*11*), negotiates a time and materials payment method for performing specialist work; and enters into a contract with the instrumentation specialist. Biddable support work is bid on a unit-price basis in the prime contract. Nonbiddable support work is paid for by force account. Specification detail is as described for method 1.

	RESPONSIBLE PARTY			
TASK	OWNER	DESIGNER	INSTRUMENTATION SPECIALIST	CONTRACTOR
Determine requirements				
Prepare prime contract plans and specifications				
Make detailed instrument designs				
Procure instruments				
Calibrate instruments				
Install instruments				
Maintain instruments				
Establish and update reading schedule				
Collect data				
Process data				
Interpret data				
Decide on implementation of results				

FIGURE 1 Chart used to list responsibilities in accomplishing a monitoring program.

TABLE 4

ADVANTAGES AND LIMITATIONS OF VARIOUS CONTRACTUAL ARRANGEMENTS FOR INSTRUMENTATION INSTALLATION

METHOD	ADVANTAGES	LIMITATIONS
1. Installation by owner's personnel	Owner has direct control over cost and quality. Flexible to accommodate changes.	Potential problems with contractor cooperation if instrumentation work interferes with other work. Owner must plan for work load well in advance. Assumes owner has necessary in-house skills. Cannot always be financed by construction funds.
2. Bid items in prime contract, with no prequalification	Initial cost will tend to be least. Least effort required to write specifications. Financed by construction funds.	Generally contractor will shop for lowest price subcontractor, with risk of lowest quality and invalid measurement data. Requires strong and experienced supervision by owner's representative. Not flexible to accommodate changes.
3. Bid items in prime contract, with prequalification	Initial cost will tend to be low. Excludes inexperienced instrumentation subcontractors. Small specification writing effort. Financed by construction funds.	Generally contractor will shop for lowest price "qualified" subcontractor with risk of sub-contract having inadequate price, cutting corners, and thus invalid measurement data. Often difficult to substantiate desire to reject questionably qualified subcontractor. Usually requires strong and experienced supervision by owner's representative. Not flexible to accommodate changes.
4. Instrumentation specialist contracting with owner	Owner has direct control over cost and quality. Flexible to accommodate changes. Instrumentation specialist can, if retained early enough, assist with design of monitoring program.	Potential problems with contractor cooperation if instrumentation work interferes with other work. Cannot always be financed by construction funds.
5. Instrumentation specialist contracting with contractor	In selecting the specialist, owner has some control over cost and quality. Facilitates cooperation and scheduling with contractor. Flexible to accommodate changes. Financed by construction funds.	Assumes "professionalism" on part of instrumentation specialist, who has negotiated with the owner but contracted with the contractor. Not permitted under some public agency regulations.

5. Instrumentation Specialist Contracting with Contractor

The instrumentation specialist works as a subcontractor to the general contractor. The contractor is advised, in the bid specifications, that the owner will select an acceptable instrumentation specialist and that payment will be made under an allowance item. After the contract is awarded, the owner and contractor mutually select an instrumentation specialist in the following manner. The owner supplies a list of suitable instrumentation specialists to the contractor. From this list the contractor selects and submits the names of three specialists (which can include specialists not on the owner's original list). The owner finally selects an instrumentation specialist from this short list, following the qualification guidelines given later in this chapter and the selection procedures described in *ASCE Manual 45* (*11*); negotiates a time and materials payment method for performing specialist work; and instructs the contractor to enter into a subcontract with the instrumentation specialist under the negotiated terms. Biddable and nonbiddable support work are as described for method 4. Specification detail is as described for method 1, except that there is no need to specify cooperation between contractor and instrumentation specialist.

Advantages and Limitations of Various Contractual Arrangements for Instrument Installation

The major advantages and limitations of the five methods of contractual arrangements for instrument installation are given in Table 4. Unless the installation is simple and can be considered as a normal construction item, methods 1, 4, and 5 are more likely to result in valid measurement data than are methods 2 and 3. If method 2 or 3 is used, comprehensive specification wording is necessary, as outlined later in this chapter. Whichever method is used, cooperation is an essential ingredient for success. Guidelines for cooperation between the contractor and specialist field personnel are given at the end of this chapter.

CONTRACTUAL ARRANGEMENTS FOR DATA COLLECTION AND INTERPRETATION

Contractual arrangements for data collection should preferably follow method 1, 4, or 5. If method 2 or 3 is used, the bid item unit should be "data set" or "man-hour" with clear definition of procedures and personnel qualifications. Data interpretation must be the direct responsibility of the owner or his representative; therefore, methods 2 and 3 are not suitable.

BID SPECIFICATION FOR FIELD INSTRUMENTATION SERVICES

Despite the above recommendation favoring methods 1, 4, and 5, it is recognized that some public agencies require use of bid methods. If instrumentation field services are bid, a comprehensive specification is essential and will often be combined with a specification for instrument procurement following the recommendations given in Chapter 3. The field services specification should address the following topics (*5*) [see Cording et al. (*9*) for more detailed guidelines]:

- Purpose of the instrumentation program
- Division of responsibilities among owner, designer, resident engineer, instrumentation specialist, and contractor for installing and maintaining instruments; establishing and updating reading schedules; and collecting, processing, and interpreting data
- Qualifications of specialist field personnel
- Need for submittal of technical information (including proposed procedures) to the owner or designer by personnel responsible for field services
- Availability of data to owner and contractor
- Contractor cooperation and support services
- Locations of instruments
- Installation schedule and procedures
- Delay to construction caused by instrumentation field work
- Access for installation
- Protection and maintenance of instruments
- Responsibility for damage to instruments and instrument malfunction
- Data collection, processing, and interpretation
- Who acts (and how) when unforeseen events occur
- Disposition of instruments at end of job
- Ground surface restoration
- Measurement and payment

QUALIFICATIONS OF SPECIALIST FIELD INSTRUMENTATION PERSONNEL

Successful operation of an instrumentation program requires a special effort; thus motivated field personnel are essential. In specifying or selecting personnel to perform or supervise field installation work, consulting firms and manufacturers with special expertise in the installation of geotechnical instrumentation should be considered. Geotechnical consulting firms are listed in various professional magazines, in the *ACEC Directory* (*12*), and in the *ASFE Membership List* (*13*). Many instrumentation manufacturers do not maintain a staff of experienced geotechnical engineers and technicians; therefore caution should be exercised in specifying that "installation of the instruments shall be supervised by a representative of the manufacturer." If instrument installation entails combining a knowledge of an instrumentation device with a knowledge of appropriate geotechnical conditions, it will usually be necessary to involve a geotechnical engineer having comprehensive experience with the selected instruments.

Qualifications can either be defined by reference to the names of qualified firms "or equal" or by specifying that specialist personnel who will be directly performing the field work must demonstrate the specific previous experience.

COOPERATION BETWEEN CONTRACTOR AND SPECIALIST FIELD INSTRUMENTATION PERSONNEL

A cooperative working relationship between the construction contractor and the personnel responsible for field instrumentation work is essential. The best way of establishing such a relationship is for instrumentation personnel to initiate thorough communication with all levels of the contractor's personnel several weeks or months before anything has to be accomplished physically in the field. The instrumentation personnel should meet with the contractor's engineers, superintendents, and foremen to explain what will be done, why it must be done, and what will be required of the contractor. They should prepare sketches to forewarn the contractor of the impact on normal construction work, provide lists of materials that will be required for support work, and be willing to adjust their own plans to create minimum interference to the contractor's work. In short, mutual respect can usually be established by thorough communication, dispelling the "adversary relationship" problem that often arises when professional engineers work with construction contractors. Having established this prefield work respect, instrumentation personnel should maintain the contractor's respect by performing top-quality work, be responsive to the effects of the program on the contractor, and work *with* the contractor to minimize any adverse effects.

CHAPTER FIVE

DETAILS OF INSTRUMENTS

The instruments discussed in this chapter are used to measure pore pressure, earth pressure, deformation, load, and strain. The various devices are described briefly, comparative information is presented to assist with selection, and some guidelines on installation are included. Examples of applications are given in the appendix.

MEASUREMENT OF PORE PRESSURE

There are two general categories of pore pressure instruments: (a) observation wells for measuring groundwater levels and (b) piezometers for measuring pore water pressures. The five types of piezometers are: open standpipe, twin-tube hydraulic, pneumatic, vibrating-wire strain gage, and bonded resistance strain gage. These instruments are described by Bozozuk (*14*), Cording et al. (*9*), Corps of Engineers (*15*), Dunnicliff and Sellers (*2*), Dunnicliff (*3*), Hanna (*16*), U.S. Bureau of Reclamation (USBR) (*17*), and Wilson and Mikkelson (*18*).

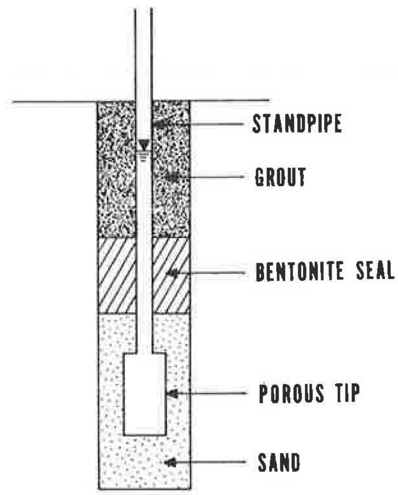


FIGURE 3 Open standpipe piezometer.

Observation Wells

As shown in Figure 2, an observation well consists of a perforated section of pipe or wellpoint attached to a riser pipe, installed in a sand-filled borehole. The elevation of the water surface in the well is determined by sounding with a probe.

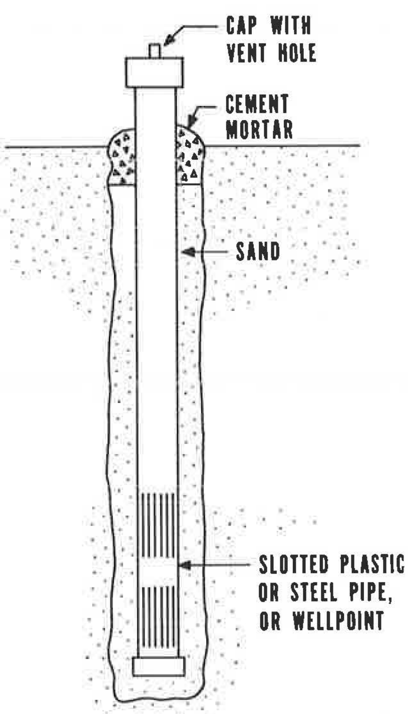


FIGURE 2 Observation well.

Open Standpipe Piezometers

An open standpipe piezometer (Figure 3) consists of sealing off a porous tip in a borehole or fill to isolate it from pore pressures at other elevations. The water level in the standpipe, which represents the pressure head at the tip, is determined by lowering a probe until water is encountered, thereby completing an electric circuit. When the piezometric level rises above the frost line, the upper portion of water in the standpipe can be replaced with an antifreeze mixture. Corrections must be made if the specific gravity of the mixture is not equal to unity.

Some piezometers can be installed by pushing directly into the ground on the end of a pipe or drill rod and can be recovered later from soft clays. However, this installation method should be used with caution, as it relies on adequate sealing between the soil and the outside of the pipe or rod.

Twin-Tube Hydraulic Piezometers

The twin-tube hydraulic piezometer (Figure 4), sometimes referred to as a closed hydraulic piezometer, consists of a porous tip connected to two standpipes with a pressure gage on the upper end of one standpipe. The second standpipe is used for periodic flushing of gas that may enter the piezo-

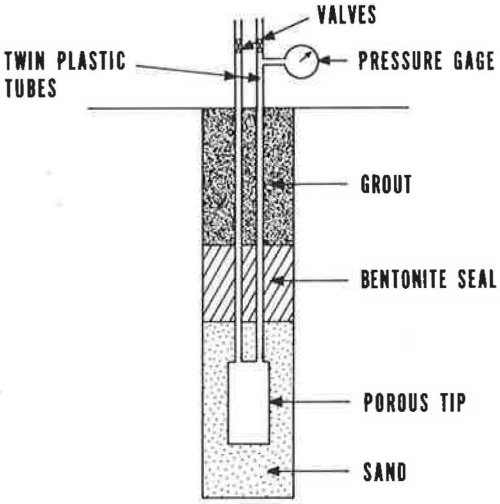


FIGURE 4 Twin-tube hydraulic piezometer with local readout.

meter tip. The standpipes can be extended horizontally at grade, locating the pressure gage outside the immediate work area; problems associated with extending standpipes through subsequent construction are overcome. However, great care must be taken to exclude air bubbles by using de-aired water prepared in a high-quality de-airing device (*19*). This piezometer can be used where the piezometric level is above the top of the standpipe.

Pneumatic Piezometers

A pneumatic piezometer consists of a sensitive check valve and a diaphragm separating the pore water from the measuring system. In a two-tube version (Figure 5), pressurized gas applied to the inlet tube causes the check valve to open and vent from the outlet tube when the applied gas pressure equals the pore water pressure. The pressure is read at the pressure gage on the inlet tube. Similar piezometers (usually termed hydraulic piezometers), in which oil is used instead of gas, are available; however, they do not appear to offer any advantages over pneumatic piezometers.

Vibrating-Wire Strain Gage Piezometers

The vibrating-wire strain gage piezometer has a metallic disc diaphragm separating the pore water from the measuring system. As shown in Figure 6, a prestressed wire is attached to the midpoint of the diaphragm such that diaphragm deflections cause changes in wire tension. Consequently, a change in pore pressure deflects the diaphragm and changes the tension in the wire. The tension is measured by plucking the wire, using an electric coil, and measuring the frequency of its vibration. The wire vibrates in the magnetic field of a permanent magnet causing an alternating voltage to be induced inside the plucking coil. The frequency of the output voltage is identical to the frequency of the wire vibration and is transmitted to a frequency-counting device. A calibration

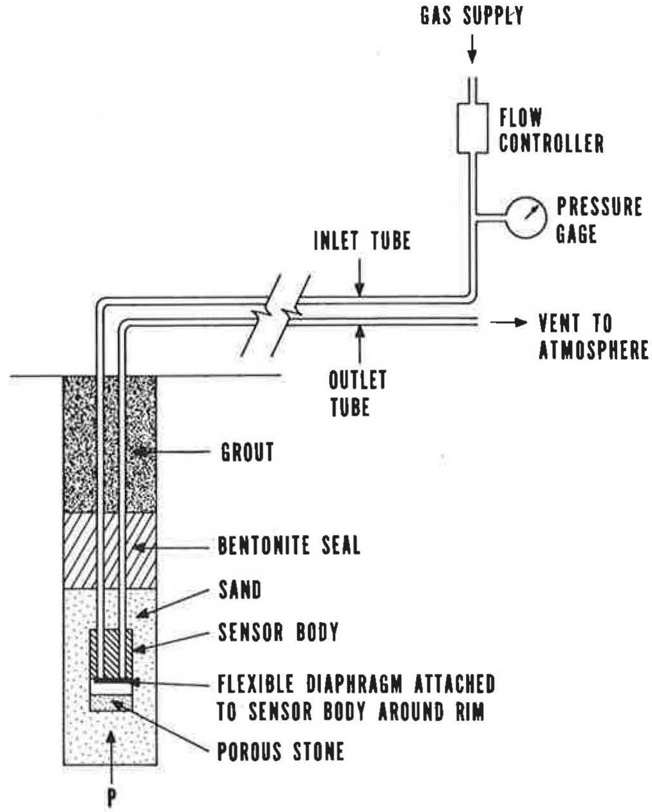


FIGURE 5 Typical pneumatic piezometer.

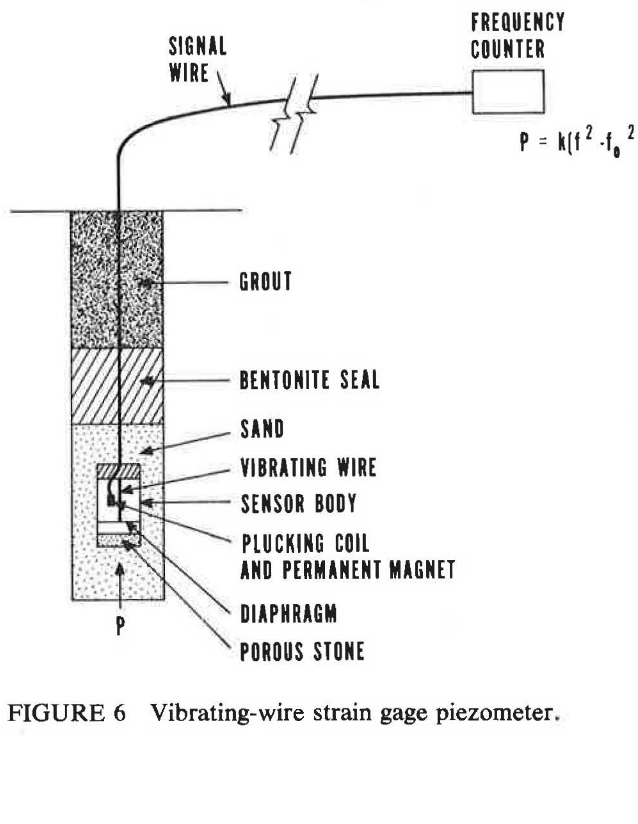


FIGURE 6 Vibrating-wire strain gage piezometer.

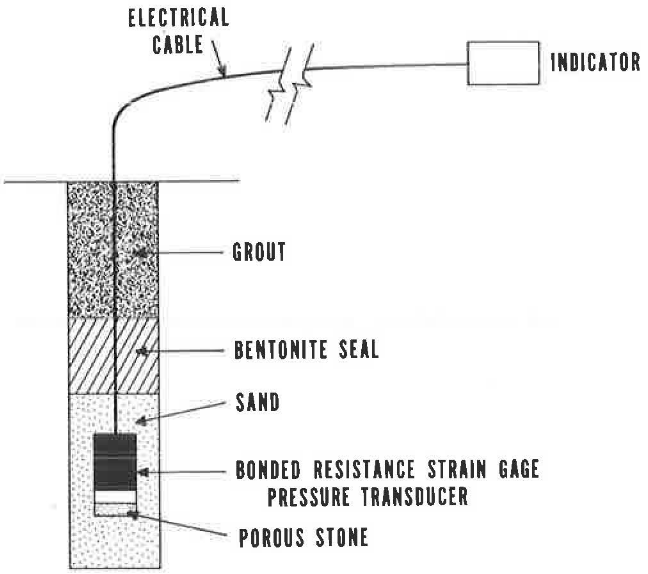


FIGURE 7 Bonded resistance strain gage piezometer.

curve or table is then used to calculate the pore pressure from the measured frequency change.

Bonded Resistance Strain Gage Piezometers

The bonded resistance strain gage piezometer (Figure 7) has an electrical pressure transducer with a diaphragm in direct contact with the pore water. Strains induced in the diaphragm by the pore pressure are sensed by strain gages, bonded to the diaphragm. Hence, the transducer output signal can be used as a direct measure of pore pressure.

Hydrostatic Time Lag

When pore water pressure changes, the time required for water to flow to or from piezometers to effect equalization is called the hydrostatic time lag. It is dependent primarily on the permeability of the soil, the type and dimensions of the piezometer, and the magnitude of change in pore water pressure. Open standpipe piezometers have a much greater hydrostatic time lag than do diaphragm piezometers because a greater movement of pore water is involved. The term "slow response time" is used to describe a long hydrostatic time lag. Methods of estimating time lag are presented by Hanna (*16*), Hvorslev (*20*), and Terzaghi and Peck (*21*).

Selection of Type of Instrument

General guidelines on the selection of instruments are given in Chapter 2. Advantages and limitations of each type of instrument for measuring pore pressure are summarized in Table 5.

Reliability and durability are often of greater importance than sensitivity and accuracy. The fact that the actual head may be in error by 1 ft (0.3 m) as a result of time lag may not matter in some cases provided the piezometer is functioning properly. If a malfunction occurs it is of little importance that the apparent head can be recorded to 0.01 in. (0.25 mm). Assuming that the instrument is installed correctly, that it is functioning, and that no time lag remains, the accuracy of all piezometers can be within 6 in. (150 mm) of water head. High accuracy requirements necessitate selection of high accuracy components, such as "test quality" pressure gages in pneumatic indicators.

In highly permeable soils, when perched or artesian water tables are absent, an observation well can be used to measure the groundwater level. If pore water pressure observations are required, an open standpipe piezometer with a minimum diameter standpipe may be appropriate provided the time lag and the other limitations listed in Table 5 are acceptable. A drive-in type may be used in soft soils, and a pressure gage can be added if the piezometric level is likely to rise above the standpipe.

For less permeable soils or where vertical standpipes would interfere with or be damaged by construction activities, the choice is between twin-tube hydraulic, pneumatic, vibrating-wire, and bonded resistance strain gage piezometers, subject to the limitations listed in Table 5. The twin-tube hydraulic or pneumatic type is generally preferable because of its good track record. The vibrating-wire piezometer, which also has a good track record, may be preferred where negative pore pressures could develop or where automatic recording or transmission of data over long distances is required. Bonded resistance strain gage piezometers are suitable for dynamic pore pressure measurements, for automatic data recording, and for measuring negative pore pressures, but they are not generally recommended where reliable readings are required for extended periods of time.

In monitoring pore water pressures, the base reference corresponding to equilibrium conditions must be known. It is, therefore, also often necessary to install observation wells.

MEASUREMENT OF EARTH PRESSURE

Earth pressure measurements fall into two basic categories: (a) measurement of total stress at a point within a soil mass and (b) measurement of total stress or contact stress against the face of a structural element. Earth pressure cell sensing systems are generally similar to diaphragm piezometer sensing systems, and advantages and limitations are generally as described earlier in this chapter.

Comprehensive evaluations of various types of commercially available earth pressure cells, along with criteria for cell design and manufacture, are given by Dunnicliff and Sellers (*2*), Dunnicliff (*3*), Hvorslev (*22*), O'Rourke (*23*), Reese et al. (*24*), Selig (*25*), the state of California (*26, 27*), and Weiler and Kulhawy (*28, 29*). A 1981 report by the International Society for Rock Mechanics (ISRM) includes a comprehensive description of the pneumatic and hydraulic types of cells in addition to guidelines on installation, reading, calculation, and reporting procedures (*30*).

TABLE 5
ADVANTAGES AND LIMITATIONS OF OBSERVATION WELLS AND PIEZOMETERS

TYPE	ADVANTAGES	LIMITATIONS AND PRECAUTIONS
Observation Well	Simple, inexpensive, universally available.	Not applicable if perched or artesian water tables present. Metal elements may corrode. Long time lag.
Open Standpipe Piezometer	Simple, inexpensive, reliable. Long performance record. Self-de-airing if inside diameter of standpipe is greater than 0.4 in.	Porous filter can plug due to repeated water inflow and outflow. Long time lag. Tubing must be raised nearly vertical. Cannot be used if piezometric level is above top of standpipe. Freezing problems. Subject to damage by construction equipment and consolidation of soil around standpipe.
Twin-Tube Hydraulic Piezometer	Simple, reliable. Long experience record. Less time lag and less prone to damage than open standpipe piezometer.	Freezing problems. Tubing must not be significantly above piezometric elevation. Periodic de-airing required.
Pneumatic Piezometer	Stable. Short time lag. Capability of purging lines. Minimum interference to construction. Level of tubes and readout independent of level of tip. No freezing problems.	Dry gas should be used. Check valve displacement should be minimal (can be as low as 0.002 cc). Models with tube to soil side of diaphragm may increase time lag. More expensive than above types.
Vibrating-Wire Strain Gage Piezometer	Easy to read. Can be used to read negative pore pressures. Short time lag. Minimum interference to construction. Level of wires and readout independent of level of tip. Suitable for automatic recording. Frequency signal permits data transmission over long distances. No freezing problems.	Not suitable for dynamic readings. Overvoltage protection and grounding system necessary in regions of thunderstorm activity. More expensive than pneumatic piezometers.
Bonded Resistance Strain Gage Piezometer	Easy to read. Can be used to read negative pore pressures. Short time lag. Suitable for dynamic measurements and automatic recording. Minimum interference to construction. Level of wires and readout independent of level of tip. No freezing problems.	Some versions sensitive to temperature. Long-term stability not yet verified. False data can result from transmission over long distances. Overvoltage protection and grounding system necessary in regions of thunderstorm activity. More expensive than pneumatic piezometers.

Commercially available earth pressure cells include the following types: pneumatic, hydraulic, vibrating-wire strain gage, bonded resistance strain gage, and unbonded resistance strain gage.

In general, cells for field use include a liquid-filled chamber subjected to soil pressure. The pressure in the liquid is sensed using one of the types of pressure transducers previously described in the section on measurement of pore pressure. A typical pneumatic earth pressure cell is shown in Figure 8. Advantages and limitations of transducers are generally as described in Table 5.

Limitations Imposed by Soil Environment

Measurement of total stress at a point within a soil mass requires: (a) an earth pressure cell that will not appreciably alter the state of stress within the soil mass because of its presence (conformance); (b) that the sensing area be large enough to average out local nonuniformities; and (c) a method of installation that will not seriously change the state of stress. The last requirement limits these measurements to fills and other artificial soil conditions. However, some success has been achieved in measuring horizontal stress in situ in soft clays by pushing specially designed earth pressure cells downward into natural ground. Attempts to measure horizontal stress in situ by advancing a large-diameter borehole, inserting earth pressure cells in a vertical plane, and backfilling are not likely to provide valid data.

Measurement of earth pressure against a structure requires a pressure cell that behaves similarly to the structure. Hence, local arching around the cell caused by differential deflection between the cell and surrounding structure must be minimized through proper design. Another problem is that although the contact pressures may be reasonably uniform for the structure as a whole, they are usually very irregular over areas the size of most earth pressure cells [6 to 18 in. (150–450 mm) in diameter]. Thus earth pressure cell measurements commonly show considerable scatter that is difficult to interpret. Better results can often be obtained if earth pressures over a large area are determined by such procedures as isolating a portion of the structure and measuring loads or stress in the structure. This approach has been used successfully in the determination of earth pressures in braced excavations from measurements of support loads.

Factors Affecting Measurements

Studies of the factors affecting performance of earth pressure cells by Hvorslev (*22*), Selig (*25*), and Weiler and

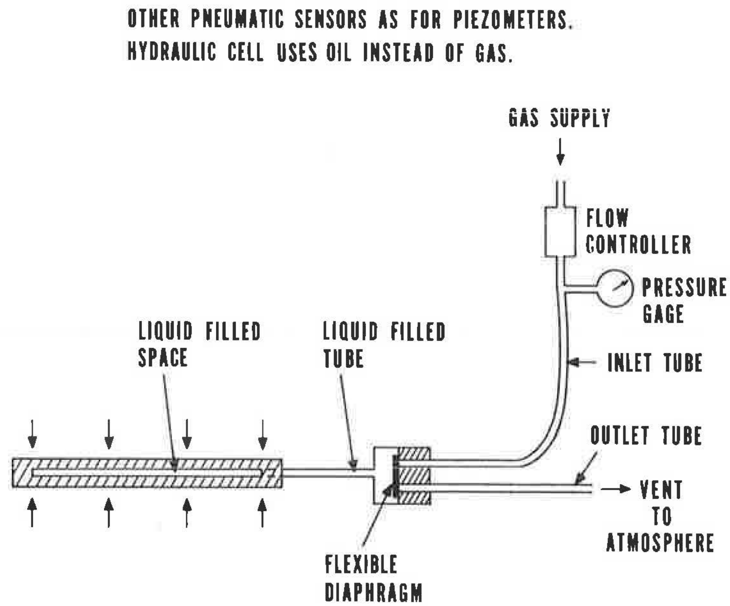


FIGURE 8 Typical pneumatic earth pressure cell.

Kulhawy (*28, 29*) indicate that the gage should (a) have as small a thickness as possible, in the direction of the measured pressure, in relation to the gage diameter; (b) be much stiffer than the soil; (c) have a sensing area many times the average soil particle diameter; (d) be calibrated for principal stress rotation effects if such effects are expected; (e) have a simple geometry and sufficient durability to permit good bedding and adequate compaction during installation; (f) have adequate frequency response and approximately match the soil mass density to minimize errors in dynamic stress measurement; and (g) be adequately protected from deterioration by corrosion and malfunction caused by moisture.

For measurements of total stress at a point within a soil mass, Weiler and Kulhawy (*28*) state:

> The present need to calibrate the cells in the soil in which they will be used, as well as the significant amount of time needed to acquire a familiarity with stress cell behavior, makes the use of stress cells uneconomical for most projects. When the cells are "economically" used (meaning no in-soil calibration and no time spent investigating how stress cells behave in soil), the results are nearly always unusable if not incredible. Accurate stress cell measurements are still almost exclusively limited to well-conducted laboratory model investigations.

Most manufacturers of commercial earth pressure cells provide a calibration chart prepared during loading with air or water, but, in general, such calibrations are insufficient. Thus, unless installations are to be made in soft clay, each cell should be calibrated in a large calibration chamber using the soil in which it will be embedded, and installed using the intended field procedures. Suitable chambers are described by Hadala (*31*), Hvorslev (*22*), and Selig (*32*), and in a 1972 report by the state of California (*33*). For embedment in sand fill, Bozozuk (*34*) calibrated pressure cells in a heavily reinforced plywood box constructed in two sections that fit one on top of the other. The calibration load was applied through a footing placed on the surface of the sand. At each load, the two parts of the box were pried apart and Teflon shims installed, forming a uniform separation at the level of the cell. When the shims were removed, all of the applied load was transmitted across this horizontal boundary in grain-to-grain contact because none of the load could be transmitted across the void by wall friction.

In addition, a common method of installation affects measurements of total stress at a point within a soil mass. With this method, fill is compacted with heavy equipment, the cells installed in an excavated trench, and backfill compacted by hand tamping or light machine. Although this method usually prevents damage to the cells, and there appears to be no better alternative to this procedure, substantial underregistration can occur.

MEASUREMENT OF DEFORMATION

Instruments to measure deformation are grouped in the categories listed in Table 6, which also indicates the type and location of measured deformation. There is a vast array of instruments for monitoring deformation. However, Peck (*7*) warns:

> An instrument too often overlooked in our technical world is a human eye connected to the brain of an intelligent human being. It can detect most of what we need to know about subsurface construction. Only when the eye cannot directly obtain the necessary data is there a need to supplement it by more specialized instruments. Few are the instances in which measurements by themselves furnish a sufficiently complete picture to warrant useful conclusions.

Details of devices to measure deformation are presented in Cording et al. (*9*), Dunnicliff (*3, 35, 36*), Dunnicliff and Sellers (*2*), Gould and Dunnicliff (*37*), USBR (*17*), and Wilson and Mikkelsen (*18*).

TABLE 6
CATEGORIES OF INSTRUMENTS FOR MEASURING DEFORMATION

Category	Type of Measured Deformation →	↓	↗	·̅	·̲
Surveying Methods	●	●		●	
Portable Deformation Gages			●	●	
Single Point Monuments	●	●		●	
Vertical Pipe Settlement Gages		●			●
Remote Settlement Gages		●			●
Heave Gages		●			●
Inclinometers	●				●
Borehole Extensometers			●		●
Soil Strain Gage			●		●

LEGEND:
→ Horizontal deformation
↓ Vertical deformation
↗ Axial deformation (→ or ↓ or in between)
·̅ Surface deformation
·̲ Subsurface deformation

Benchmarks

All measurements of settlement and heave should be referenced to a benchmark, and all measurements of horizontal movement to a stable reference point. Requirements for benchmarks are discussed by Cording et al. (*9*) and Gould and Dunnicliff (*37*). If no suitable permanent structure is available at a location remote from all possible vertical movement due to construction activities, a deep benchmark should be installed to a depth below the seat of vertical movement. Such a deep benchmark consists of a pipe, anchored at depth, surrounded by and disconnected from a sleeve pipe to protect the inner pipe from vertical movement caused by soil movement (*38*). Requirements for a stable reference point to be used when making measurements of horizontal movements are discussed by Cording et al. (*9*).

Surveying Methods

Surveying methods include optical leveling, offset measurements from transit lines, chaining distances, triangulation, electronic distance measurement, lasers, and photogrammetry. These methods are described by Gould and Dunnicliff (*37*) and the British Geotechnical Society (*39*) and summarized by Wilson and Mikkelsen (*18*). The last publication includes information on range, accuracy, advantages, limitations, precautions, and reliability of each method.

Portable Deformation Gages

Portable deformation gages are used for monitoring changes in crack width in buildings or on the ground surface. Advantages and limitations of portable deformation gages are listed in Table 7.

Single Point Monuments

Single point monuments are used for monitoring surface deformation by surveying methods. They are installed at the surface of natural ground or fills or on structures. Two types are in common use: settlement rods and control stakes. A settlement rod consists of a length of steel rod sleeved above the frost line with a steel pipe. Details of fabrication, installation, documentation, and data collection are given in a 1979 report by the state of New York (*40*). A control stake, consisting of a graduated T set several feet into the ground, is used for measuring surface horizontal and vertical movements. Problems in using control stakes include vandalism, disturbance due to construction activities, and lack of precision. In addition, when movement is discerned it is often "too late." Hence, control stakes should be used with caution.

TABLE 7
ADVANTAGES AND LIMITATIONS OF PORTABLE DEFORMATION GAGES

INSTRUMENT	ACCURACY	ADVANTAGES	LIMITATIONS AND PRECAUTIONS
Graduated scale	± 0.02 in.	Simple, inexpensive.	Limited accuracy. Short span.
Survey tape	± 0.1 in.	Simple, inexpensive.	Limited accuracy.
Mechanical strain gage	± 0.0002 to 0.0005 in.	Precise.	Very short span.
Micrometer or dial gage	± 0.0001 in.	Simple, inexpensive.	Short span.
Portable tape or rod extensometer	± 0.001 to 0.1 in.	Simple, precise.	Accuracy limited by sag.

Vertical Pipe Settlement Gages

Vertical pipe settlement gages are used to measure settlement below the ground surface and under embankments and surcharges by means of a vertical pipe, rod, or tube extending from a measurement point to the ground surface. Five gages are described below. Advantages and limitations are given in Table 8.

A settlement platform consists of a square plate of steel, wood, or concrete placed on the original ground surface to which a riser pipe is attached. Optical survey measurements to the top of the riser provide a record of plate elevations. Details of fabrication, installation, documentation, and data collection are given in a 1979 report by the state of New York (*40*).

A Borros anchor (Figure 9) consists of steel prongs, mechanically set at the bottom of a borehole, to which a riser pipe is attached. A larger-diameter sleeve pipe protects the riser pipe from vertical movement of soil above the prongs. Although a frequently used and simple device, a problem can arise due to binding between the bottom of the sleeve pipe and the riser rod, such that downdrag on the sleeve causes downward movement of the prongs. Therefore the device should not be used in weak soils. The problem can be minimized by installing an O-ring bushing or a length of greased garden hose in the annular space at the bottom of the sleeve pipe. A 1979 report by the state of New York (*40*) includes details of fabrication, installation, documentation, and data collection.

The spiral-foot gage (*41*) overcomes the limitation on the use of the Borros anchor in weak soils. As shown in Figure 10, the gage consists of a bronze screw connected to a riser pipe that is protected with a pipe casing. It is installed in a hole bored to within a few inches of the required depth and then screwed down to the desired elevation. The casing is retracted to a position 1 to 2 ft (0.3–0.6 m) above the spiral foot. Oil is pumped down the inner pipe, out through holes provided just above the bronze screw, and up into the pipe casing, providing protection against corrosion and damage caused by freezing. Settlements are measured by running precise level surveys to the riser pipe, which projects above the casing.

An inductive coil gage (Figure 11) consists of a corrugated plastic pipe installed in a vertical borehole, with stainless-steel wire rings around the pipe at 5- or 10-ft (1.5- or 3-m) intervals along its length. The annular space between pipe and borehole wall is grouted with a material having modulus and undrained shear strength as similar to the soil as possible. A probe containing an inductive coil is lowered within the pipe on the end of an electrical cable and survey tape. The proximity between probe and each steel wire is established by the maximum deflection of a readout meter. Tape read-

TABLE 8
ADVANTAGES AND LIMITATIONS OF VERTICAL PIPE SETTLEMENT GAGES

TYPE	ACCURACY[a]	ADVANTAGES	LIMITATIONS AND PRECAUTIONS[b]	RELIABILITY
Settlement platform	± 0.1 to 1.0 in.	Simple.	Single-point gage only. Potential for cumulative errors due to addition of pipe lengths.	Very Good.
Borros anchor	± 0.1 to 1.0 in.	Simple.	Single-point gage only. Potential for cumulative errors due to addition of pipe lengths. False readings if outer pipe binds to inner pipe. Cannot be anchored in weak soils.	Good.
Spiral foot or auger	± 0.1 to 1.0 in.	Simple. Easy to install. Can be located precisely at required depth.	Similar to Borros anchor except that for weak soils size of foot must be related to shear strength.	Very good.
Inductive coil	± 0.02 to 0.1 in.	Multipoint gage. Can be installed in boreholes or embankments.	Readings somewhat subjective. Accuracy reduced by stray electric currents. No positive anchorage between sensing wires and soil. Grout should have modulus and undrained shear strength similiar to surrounding soil.	Good.
Telescoping inclinometer casing	± 0.1 to 1.0 in.	Multipoint gage. Simple.	Not suitable for installation in boreholes.	Good only in embankments.

[a]Depends on benchmark and survey instrument.
[b]Tendency to be damaged by construction equipment. Difficulty in compacting around the riser pipe; hence risk of inferior compaction.

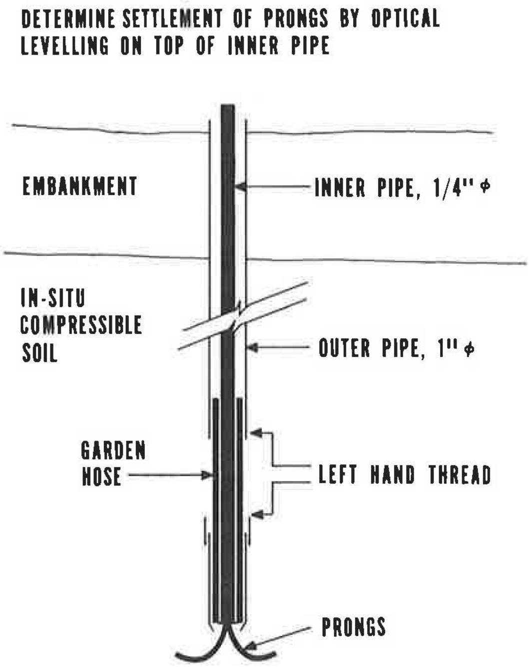


FIGURE 9 Borros anchor.

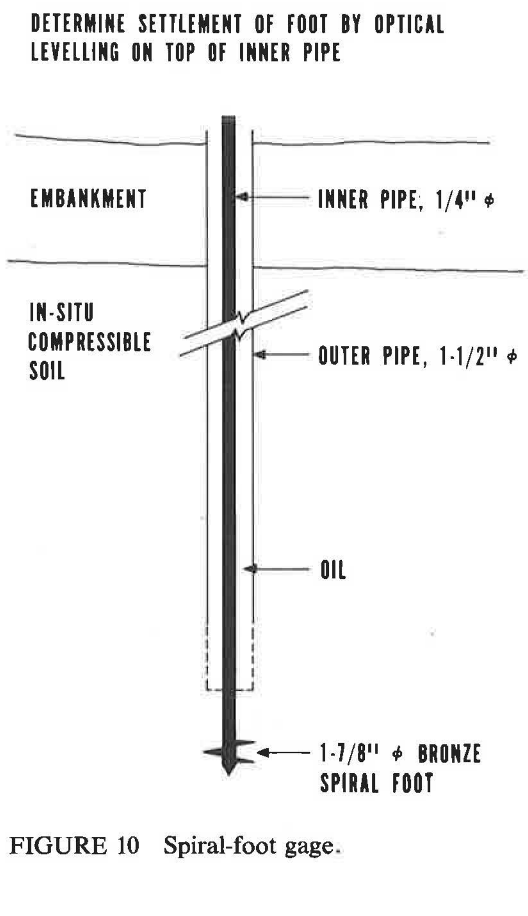


FIGURE 10 Spiral-foot gage.

ings, at the ground surface, provide data for computation of settlement. A steel ring placed at sufficient depth below the zone of vertical movement can serve as a deep benchmark for the installation.

A telescoping inclinometer casing can be used as a multipoint vertical pipe settlement gage. A mechanical settlement probe is lowered within the telescoping inclinometer casing to locate the bottom ends of each casing length. In embankments, the casing is forced to follow the pattern of soil compression by flanges attached to the outside of the casing. In boreholes, the friction between casing and backfill may be inadequate, such that telescoping of the casing may concentrate at the looser couplings, leading to false data.

Two additional multipoint vertical pipe settlement gages commonly used outside the United States are the magnet/reed switch gage (*42*) and the bellow-hose gage (*43*).

Remote Settlement Gages

Remote settlement gages serve the same purpose as settlement platforms, but overcome the need to extend a riser pipe through the embankment. Gages fall into two general categories: single-point gages and full-profile gages. Four gages are described below. Advantges and limitations are given in Table 9.

The simplest single-point gage, which is basically a manometer with one end in the buried cell and the other at the

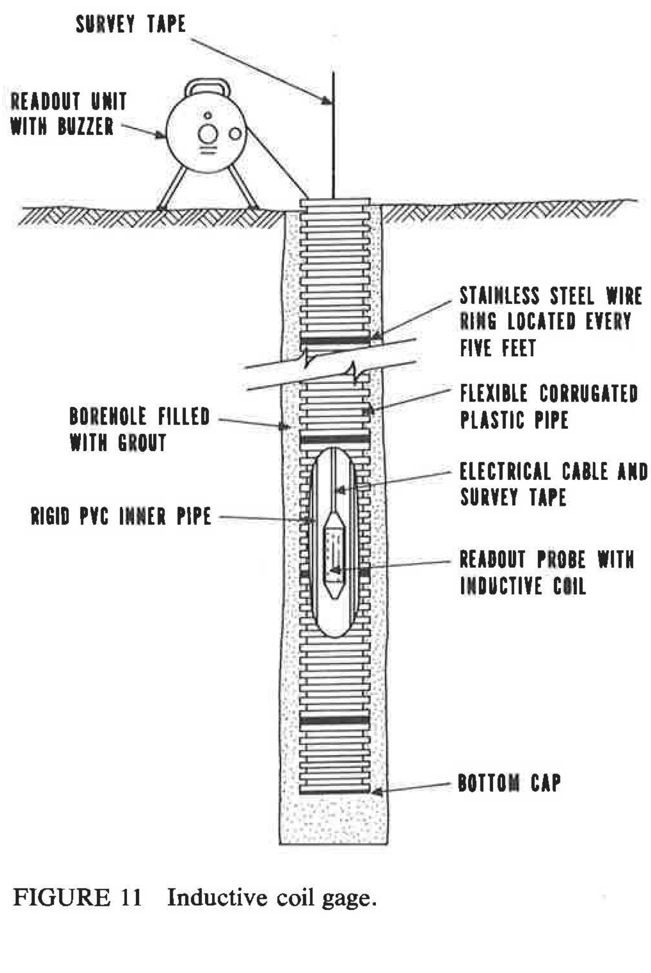


FIGURE 11 Inductive coil gage.

TABLE 9
ADVANTAGES AND LIMITATIONS OF REMOTE SETTLEMENT GAGES

TYPE	ACCURACY	ADVANTAGES	LIMITATIONS AND PRECAUTIONS[a]	RELIABILITY
Single-point gage with cell at same elevation as reading station	± 0.2 to 0.8 in.	Simple.	Both ends must be at the same elevation.	Very good.
Single-point gage with cell below reading station	± 0.2 to 1.0 in. (depends on transducer). Accuracy decreases with increased difference between elevation of cell and reading station.	Cell below reading station.		Good.
Full-profile gage with balloon	± 0.3 to 1.0 in.	Multipoint gage. Probe below reading station.	Laborious to read. Readings somewhat subjective.	Good.
Full-profile gage with electrical pressure transducer	Less accurate than balloon type.	Multipoint gage. Probe below reading station. Rapid reading.		Fair.

[a]All types require great care in excluding air bubbles, preferably using de-aired liquid prepared in a high-quality de-airing device (19). All types are sensitive to changing temperature of the liquid tube. All have freezing problems, unless antifreeze is used. Use of antifreeze increases temperature sensitivity. All types, except the first, require accurate knowledge of the liquid specific gravity.

reading station, is shown in Figure 12. A 1979 report by the state of New York (*40*) describes material, fabrication, installation, reading, documentation, and data collection. The same publication also describes a subsurface version in which the three tubes are attached to the top of a Borros anchor pipe. Forsyth and McCauley (*44*) describe a device similar to the New York gage.

Many commercially available single-point gages allow for the buried cell to be lower than the reading station, which is accomplished by installing a pressure tranducer at the bottom of a liquid column, as shown in Figure 13.

Full-profile settlement gages are essentially moveable single-point remote settlement gages that provide an unlimited number of measuring points along a line. They can also be used for surveying invert elevations along a pipeline or culvert. The balloon type is shown in Figure 14. Other full-profile gages incorporate an electrical pressure transducer. Either the transducer is pulled through a buried pipe that is permanently filled with liquid or the transducer is housed within a probe connected to a liquid-filled tube and operated as in the balloon type. In either case, the transducer indicates pressure head below a visible liquid surface and thus the elevation of the transducer.

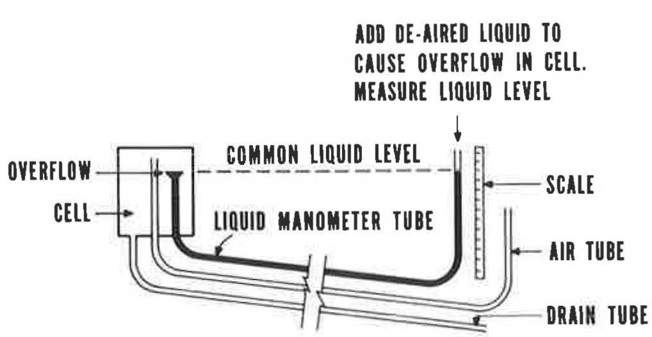


FIGURE 12 Remote settlement gage with cell at same elevation as readout.

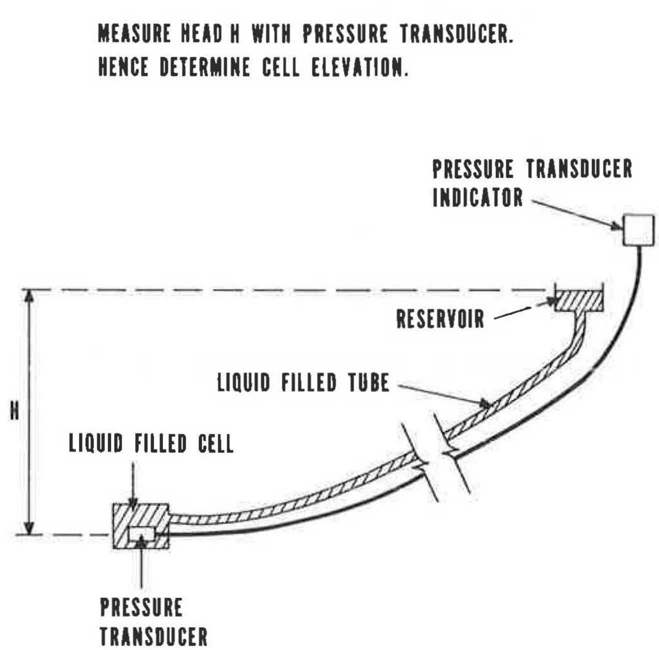


FIGURE 13 Remote settlement gage with cell below readout elevation.

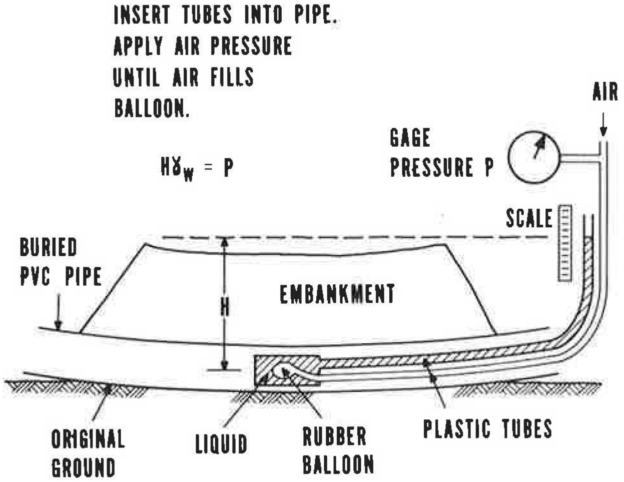


FIGURE 14 Full-profile settlement gage (balloon type).

Heave Gages

The primary reason for heave monitoring is concern for basal failure at the bottom of open-cut excavations. The simplest method is shown in Figure 15. A conical steel point is installed, facing upward, in a slurry-filled borehole at the bottom of the excavation. At any time during the excavation, a probing rod of known length is lowered down the borehole to mate with the conical point. The elevation of the top of the rod is determined by optical leveling, giving the elevation of the conical point. Coloring the slurry is often required in order to locate the instrument during construction. The gage is described by Swiger (*45*). A similar gage, consisting of a four-bladed steel vane, is described by Bozozuk (*34*). Accuracy is ± 0.2 to 1.0 in. (±5–25 mm), the major limitation being the risk of borehole caving during excavation. Electrical gages are available for more precise measurements.

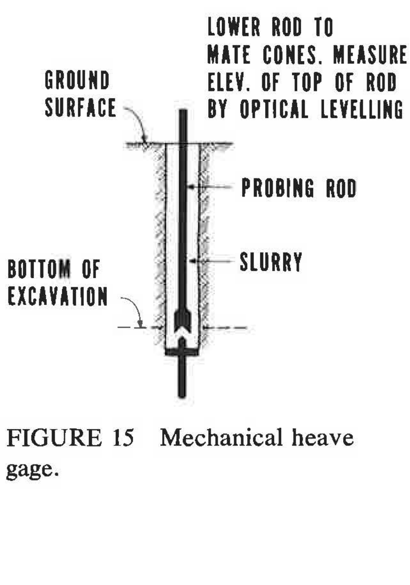


FIGURE 15 Mechanical heave gage.

Inclinometers

Inclinometers (sometimes referred to as slope inclinometers or slope indicators) are used to measure horizontal movement below the ground surface. Typical applications are determining the zone of landslide movement; monitoring extent and rate of horizontal movement at the toes of embankments on soft foundations and alongside excavations; monitoring deflection of bulkheads, sheet piling or retaining walls; and determining the alignment of piles and slurry trenches. Inclinometers are described by Gould and Dunnicliff (*37*), Wilson and Mikkelsen (*18*), and ISRM (*30*). Four types in common use in North America are described below. Advantages and limitations are given in Table 10.

The simple shear probe (or poor man's inclinometer) consists of a thin-wall polyvinylchloride (PVC) pipe installed in a nominally vertical borehole. Curvature is determined by inserting a series of rigid rods of various length and measuring the depth at which each rod stops. The device is normally used as a failure plane indicator. Forsyth and McCauley (*44*) and McGuffey (*46*) describe details of the device and the installation procedure.

A more precise inclinometer, which was developed by the Swedish Geotechnical Institute and operates within a standard PVC pipe, is described by Kallstenius and Bergau (*47*). The inclinometer is attached to 1-m (3-ft) long extension tubes connected with flexible couplings to guide it down the pipe. At the top of the pipe the tubes are connected to a diopter dial. This dial, which indicates the orientation of the inclinometer, enables measurement of the movements in a predetermined direction or direction of maximum deflection.

Other inclinometer systems consist of a pipe with internal longitudinal guide grooves, which is installed in a vertical borehole. As shown in Figure 16, a probe containing an electrical tilt sensor is lowered down the pipe on the end of a graduated electrical cable, the orientation being controlled by wheels riding in the guide grooves. The electric cable is connected to a remote readout device indicating tilt of the torpedo with respect to the vertical. Tilt readings and depth measurement enable the alignment of the grooved pipe to be determined, and changes in alignment provide horizontal movement data. One commonly used version has a tilt sensor consisting of a free-swinging, magnetically damped pendulum moving across a resistance coil. Another uses a closed-loop servo-accelerometer as a tilt sensor. A 45-minute color video-tape film presentation and reference manual (*48*) describe the principle of operation, history, inclinometer types and costs, casing installation, data acquisition and reduction, evaluation and interpretation, and instrument maintenance.

Aluminum or plastic inclinometer casing is available with rigid or telescoping couplings. Telescoping couplings should be used for installations through embankments, and also in boreholes if substantial vertical compression is anticipated. Plastic casing is easier to seal against grout intrusion, is available with a flush outside diameter after coupling, and is not subject to corrosion in soil or water conditions that could attack aluminum casing. However, greater care is required to maintain groove alignment at couplings than is necessary when aluminum casing is used. Most inclinometers will function satisfactorily in conventional square steel or aluminum tubing or pipe, with the guide wheels riding in pipe corners.

TABLE 10
ADVANTAGES AND LIMITATIONS OF INCLINOMETERS

TYPE	REQUIRES LONGITUDINAL GUIDE GROOVES IN CASING	PRECISION	ADVANTAGES	LIMITATIONS AND PRECAUTIONS	RELIABILITY
Simple "Poor Man's"	No	Very crude	Simple, inexpensive.	Poor precision. Cannot determine curvature below point of smallest curvature.	Good.
SGI strain gage	No	± 1 in. in 100 to 500 ft	Can follow direction of movement.	Slow to use. Requires visible target to orient probe.	Very good.
Resistance Coil	Yes	± 1 in. in 30 to 1000 ft		Not suitable for automatic readout. Requires four insertions in casing for movement in two axes.	Very good.
Accelerometer	Yes	± 1 in. in 300 to 3000 ft	Magnetic tape readout available. Requires only two insertions in casing for movement in two axes.		Very good.

Note: All types except for the first are operator sensitive, requiring trained operators to achieve the precision indicated.

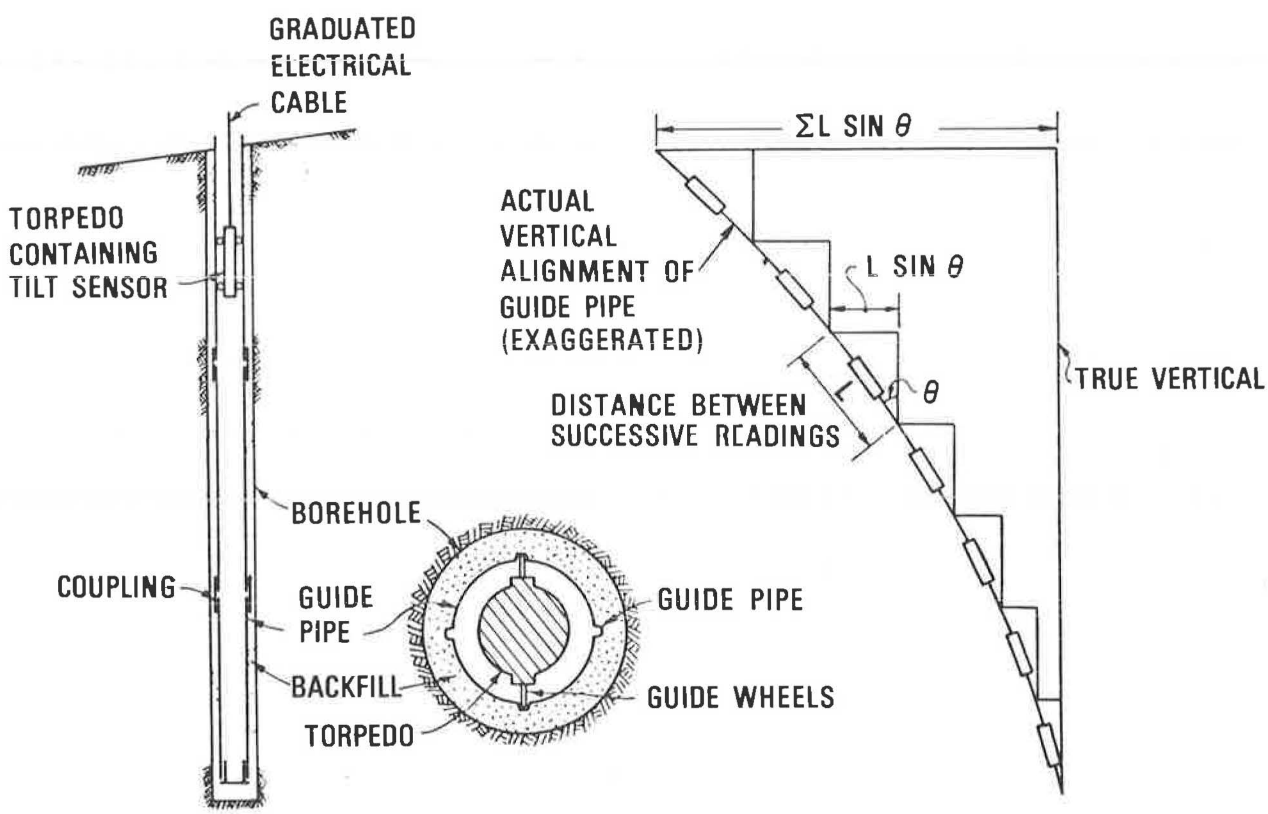


FIGURE 16 Principle of inclinometer operation.

Methods for installing inclinometer casing are described by Wilson and Mikkelsen (*18, 48*), by AASHTO (*49*), and in the instruction manuals of various manufacturers.

Borehole Extensometers

Borehole extensometers are used for measuring movements in rock and soil. They are installed inside boreholes and measure axial dimensional changes of the borehole. They consist of a series of borehole anchors with attached rods or wires. The rods or wires extend to a head at the mouth of the borehole, where any movement of the anchors is sensed by measuring the corresponding movement of the rod or wire.

Various types of extensometers are available and are described by Dunnicliff (*35*), Gould and Dunnicliff (*37*), Hawkes (*50*), and ISRM (*30*). Variables are anchor type, use of rods or wires to link anchors to head, and use of mechanical or electrical sensors in the head. Typical single anchor arrangements are shown in Figures 17 and 18.

There are four general types of anchor (*50*): expanding wedge (rock bolt), spring-loaded, groutable, and hydraulic. The expanding wedge anchor is generally preferable for single- and double-position extensometers in rock. The spring-loaded anchor is useful in competent rock where smooth uniform boreholes can be drilled. The groutable anchor is the preferred anchor for downward-directed holes in rock and for horizontal boreholes that can be angled slightly downward. The hydraulic anchor is used primarily in soft ground.

Rod-type extensometers are of a simpler design than wire types and are more easily installed, especially if only one anchor is installed per borehole. However, the advantages of rods over wires are reduced as the length of the extensometer

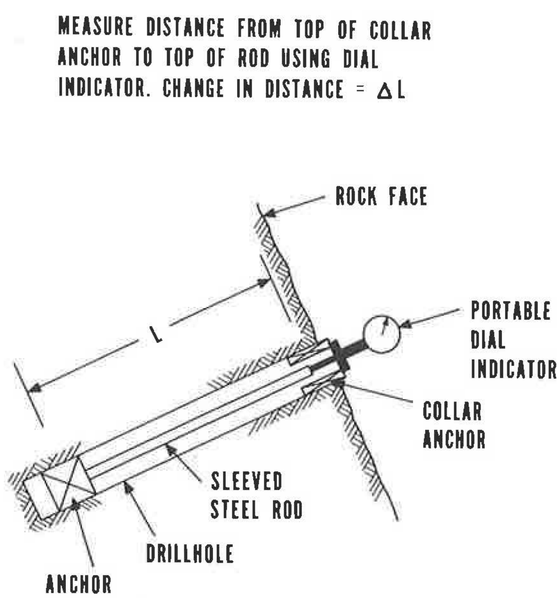


FIGURE 17 Borehole extensometer with dial gage readout.

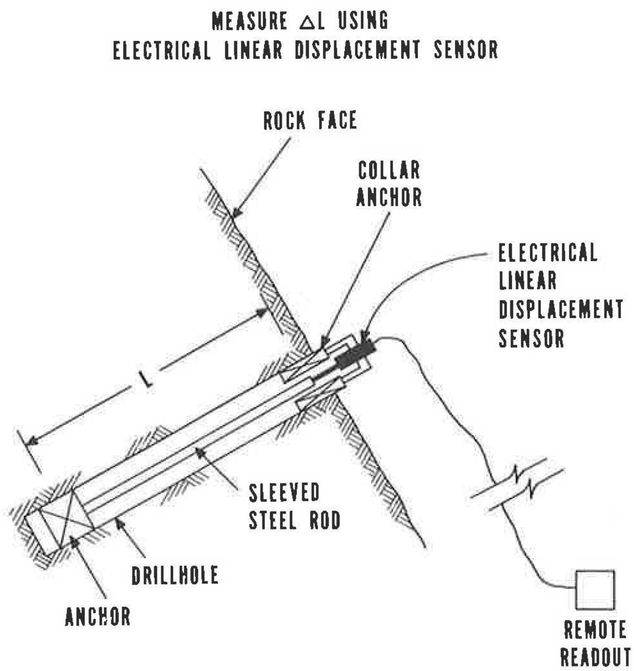


FIGURE 18 Borehole extensometer with remote electrical readout.

increases; rod extensometers longer than 300 ft (100 m) may become too heavy and costly.

Mechanical sensors are either dial indicators or depth micrometers. Electrical sensors are LVDTs, DCDTs, linear potentiometers, strain-gaged cantilevers, vibrating wires, and magnetostrictive (sonic probe) transducers. Whenever an electrical sensor is used, there should also be provision for mechanical readout as a periodic check on the accuracy of the electrical system and as a backup capability.

Advantages and limitations of commercially available borehole extensometers are given in Tables 11 and 12.

Soil Strain Gages

The soil strain gage (*51*) is used for measuring strain within earth fills. The device uses the principle of inductance coupling between two free-floating coils embedded in the soil. The two coils may be related to each other in orthogonal, coaxial, or coplanar configuration (Figure 19). One coil is connected to an oscillator to produce an electromagnetic field in the surrounding soil. An electrical current is developed in the mating coil having a magnitude that is a function of spacing between the two coils. Soil strain is determined from the change in the spacing between the coils after installation.

The primary advantage is the lack of any mechanical linkage between the coils; hence, placement is simplified and conformance with soil strains is excellent. These devices are applicable for measuring both static and dynamic strains and are not affected by soil composition, moisture content, or

TABLE 11
ADVANTAGES AND LIMITATIONS OF BOREHOLE EXTENSOMETERS WITH MECHANICAL READOUT[a]

TYPE	ADVANTAGES	LIMITATIONS	RELIABILITY
Rods	Simple, easy to install. Low cost. Rugged, blast-resistant. Large range.	Heavy and costly for length over 300 ft	Very good.
Permanently tensioned wires	Low cost. Rugged, blast-resistant.	Wire stretch problems. Requires skill to install. Interwire friction and entanglement.	Good.
Slack wires, tensioned during reading	Low cost. Rugged, blast-resistant.	Tedious readout procedure. Requires skill to read.	Very good.

[a]Precision of all extensometers is ± 0.001 to 0.005 in.

TABLE 12
ADVANTAGES AND LIMITATIONS OF BOREHOLE EXTENSOMETERS WITH REMOTE READOUT[a]

EXTENSOMETER AND SENSOR	ADVANTAGES	LIMITATIONS	RELIABILITY
Rods or wires with vibrating wire sensors	Lead wire effects minimal. Can use long lead wires.	Complicated, expensive.	Fair.
Wires with strain gage cantilever sensors	Very low hysteresis. High sensitivity. In situ calibration feature. Long history of use.	Limited range. Lead wire effects. Wire stretch effects.	Good.
Rods with magnetostrictive sensor (sonic probe)	High range. Easy to install. Easy to detach and reuse. Minimal lead wire effects.		Very good.

[a]Precision of all extensometers is ± 0.001 to 0.005 in.

temperature changes in the soil between the coils. Long-term precision is approximately 0.05 percent strain, but dynamic values as small as 0.001 percent strain can be detected.

The primary disadvantage is sensitivity to the presence of metal objects. When dynamic strains are being measured, accompanying movement of metal objects can cause a change in the electromagnetic field. This can create significant measurement errors unless adequate electrical shielding is installed. Stationary metal objects, however, generally do not cause a problem. The system is designed to operate with the two coils separated at a distance of less than 5 coil diameters.

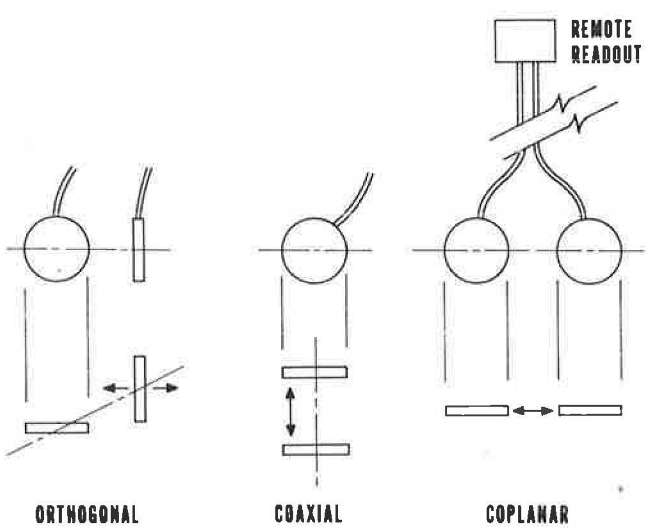


FIGURE 19 Soil strain gage configurations.

MEASUREMENT OF LOAD AND STRAIN IN STRUCTURAL MEMBERS

Instruments for measuring load and strain in structures fall into two groups: load cells and strain gages. In each case, the sensors measure small extensions and compressions. Strain gages are attached directly to the surface of the structure or are embedded within the structure to sense the extensions and compressions in th structure itself. Load cells are interposed in the structure in such a way that structural forces pass through the cells.

Load Cells

The five types of load cells in general use (*2, 3*) are briefly described below. Advantages and limitations are given in Table 13.

TABLE 13
ADVANTAGES AND LIMITATIONS OF LOAD CELLS

INSTRUMENT	ADVANTAGES	LIMITATIONS	ACCURACY (%)
Tell-tale	Inexpensive, simple. Calibrated in place.	Access problems.	± 5 to 10.
Mechanical	Direct reading. Accurate and reliable. Rugged and durable.	Expensive. Access problems.	± 1.[a]
Hydraulic	Direct reading.	Sensitive to temperature. Poor over-range capacity. Delicate.	± 5 to 10.
Vibrating-Wire Strain Gage	Remote readout. Readout can be automated. Frequency signal permits data transmission over long distances.	Expensive.	Better than ±1.[a]
Electrical-Resistance Strain Gage	Remote readout. Readout can be automated.	Expensive. Sensitive to moisture, cable length, change in connections.	Better than ± 1.[a]

[a]These are accuracies of the gaging arrangements. However, due to off-center loading and end effects, system accuracy is probably no better than ±5 to 10%.

1. Tell-tale load cells consist of an unstressed steel rod installed within a sleeve, alongside or within the structure. One end of the rod is attached to the structure while the changing distance between the other end and an adjacent reference point on the structure is measured. The change in distance divided by the length of the rod gives the strain. Load is calculated using elastic modulus and cross section of the structural member. For tie-back anchor and ungrouted rock-bolt applications, the cell is calibrated in place, using a donut-shaped load cell in series with the hydraulic jack while stressing the tie or bolt. The cell is also used for load determination in piles during load testing.

2. Mechanical load cells contain either an elastic cup spring or torsion lever system that is deformed during load application. Deformation is sensed by a dial indicator and calibrated to load.

3. Hydraulic load cells incorporate a flat oil chamber designed to be trapped between two bearing plates. A central hole can permit use with tie-backs or rock bolts. Hydraulic pressure is measured either directly, using an attached pressure gage, or remotely by electrical, hydraulic, or pneumatic means.

4. In vibrating-wire load cells, deformation of the load bearing member is measured by three or more vibrating-wire strain gages. Outputs from each vibrating-wire strain gage must be measured and averaged.

5. Electrical-resistance strain gage load cells (Figure 20) usually consist of a steel or aluminum cylinder. The load acts on the ends of the cylinder, and compressions are measured by electrical resistance strain gages bonded to the outer periphery of the cylinder at its midsection, or bonded inside holes drilled through the cylinder at its midsection. Several strain gages are used at regular intervals around the periphery. Half the gages are oriented to measure tangential strains and half measure axial strains. They are connected together to form a single full bridge network.

The major sources of inaccuracy in donut-shaped cells are off-center loading and end effects. Most load cells for measuring compressive loads have solid-center design, and the loads are applied to the cell through a raised center section incorporating a spherical seat to ensure that loads are applied axially. This arrangement is not possible with donut-shaped load cells. Eccentric loading must be minimized by using deformable, angle or spherical-seated washers. The cell must be gaged at several intervals around the periphery so that strains can be averaged to compensate for eccentric loading. End effects can be minimized by using longer load cells so that the midsection is relatively uninfluenced by end effects. The height of the donut-shaped load member should preferably be at least 1.4 times the outside diameter; however, there are many flat designs of load cells on the market and their compact design is claimed as an advantage.

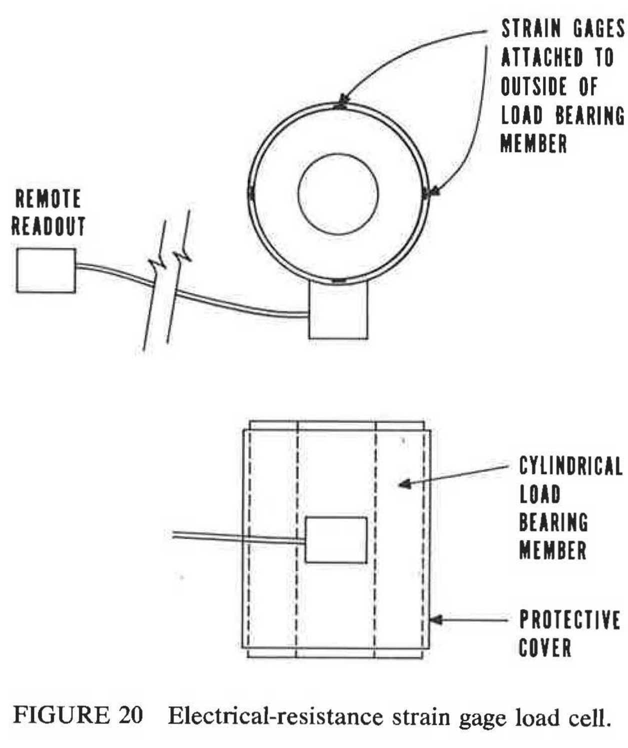


FIGURE 20 Electrical-resistance strain gage load cell.

Load-cell calibrations should model field conditions, using similar bearing plates, washers, and range of possible off-center loading. During hydraulic jack calibration the jack should be the active member with the testing machine merely providing passive restraint, so that during loading the hydraulic piston on the jack is traveling in the same direction as it would while loading the structural member. This is contrary to the normal procedure. The amount of piston travel during calibration should also model field conditions, and the effect of off-center loading on jack performance should be investigated.

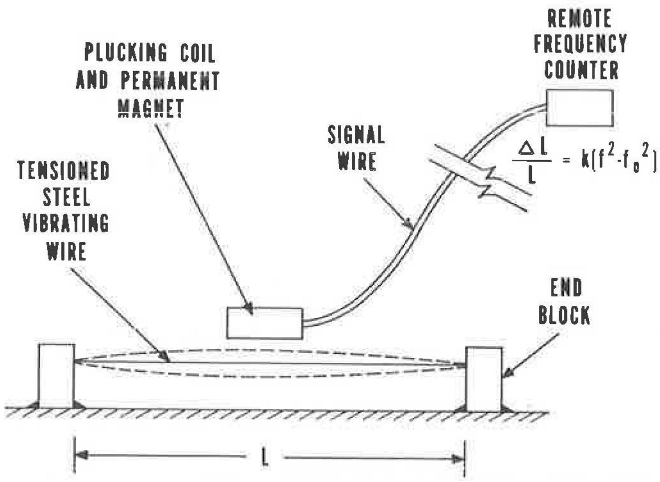


FIGURE 21 Surface-mounted vibrating-wire strain gage.

Strain Gages for Use on Structural Surfaces

Mechanical, electrical-resistance, and vibrating-wire strain gages (*2, 3*) for attachment to structural surfaces are available. Advantages and limitations are given in Table 14.

Mechanical gages are used to measure small changes of length between two studs attached to the structural member. The two most common types are the Whittemore and Demec gages.

Electrical-resistance strain gages are either of the bonded or weldable type. Bonded gages are bonded to a surface using epoxy adhesive, a process requiring skill and experience. Success depends on many painstaking steps, including surface preparation, bonding, waterproofing, and physical protection. Under field conditions success is difficult to attain. If designed, installed, and used correctly, these gaging systems can be very stable and reliable, but "do-it-yourself" use of bonded resistance strain gages is not likely to be successful. Weldable resistance strain gages consist of a resistance element, bonded or welded at the factory to a thin piece of stainless-steel shim stock. The surface of the metal structure is cleaned of all rust and sanded smooth, and the gage welded in place, using a capacitive-discharge spot welder.

Vibrating-wire strain gages (Figure 21) consist of a length of steel wire tensioned between two end blocks. The blocks are arc-welded or bolted to the surface being studied. Strain of the surface causes the blocks to move relative to each other and the tension in the steel wire to change. The tension is measured by plucking the wire, using an electrical coil, and measuring the frequency of its vibration. Frequency change is calibrated to strain. There has been a history of zero-drift problems with vibrating-wire gages caused by stretching or creep in the wire or by slippage at the wire grips. Most manufacturers now combat this problem by heat treating the wire during manufacture and by keeping the wire tension in the working range to values less than 25 percent of the yield stress. The potential for zero-drift appears to remain, however, and the use of no-load (dummy) gages is recommended. These are gages mounted on free-standing structural elements, which experience no stress but are subjected to the same environment, for the same periods of time, as the

TABLE 14
ADVANTAGES AND LIMITATIONS OF SURFACE-MOUNTED STRAIN GAGES

GAGE TYPE	ADVANTAGES	LIMITATIONS	SYSTEM ACCURACY (μ in./in.)	RELIABILITY
Mechanical	Simple, inexpensive. Waterproofing not required.	Requires skill in reading. Cannot be read remotely. Not very accurate. Needs temperature compensation.	30 to 100	Very good.
Bonded Electrical Resistance	Small size. Low cost. Remote reading. Can be temperature compensated.	Needs great skill to install. Lead wire effects.	5 to 100	Poor to good.
Weldable Electrical Resistance	Remote reading. Factory waterproofing. Easy installation. Temperature compensated.	Lead wire effects. Less accurate than good bonded types. Care needed in welding. Weld points need waterproofing to prevent corrosion.	15	Good.
Vibrating Wire	Remote reading. Lead wire effects minimal. Factory waterproofing. Long history of use.	Small range. Cannot measure dynamic strains.	5	Good.

active gages. Any drift on these no-load gages can be applied as a correction to readings from the active gages. Alternative versions of vibrating-wire strain gages, which are installed in the same way as the weldable resistance strain gage, are available.

Embedment Strain Gages

Strain gages for concrete embedment are either of the electrical-resistance or vibrating-wire type. Advantages and limitations are given in Table 15.

Electrical-resistance gages can be subdivided into four types:

1. Foil gages bonded to a short length of reinforcing steel. A calibration factor is required to relate strains in the steel to strains in the surrounding concrete. The two are not the same because the bar is stiffer than the concrete.
2. Ailtech gages, consisting of a thin resistance element between two end flanges.
3. Unbonded gages, in which the resistance element consists of separate loops of fine steel wire wrapped around ceramic posts. The most common is the Carlson gage.
4. Plastic-encased gages, consisting of standard wire-type strain gages to which lead wires are attached and hermetically sealed between thin polyester resin plates. The resin is then coated with a coarse grit to promote bonding to the concrete.

Vibrating-wire strain gages are similar to the surface-mounted versions except that large end flanges replace the end blocks.

Stress/Strain Conversion

Because the user is normally interested in stresses created by structural loads, measured strains require conversion to computed stresses. Strain gages, of course, can be used only for the determination of stress *changes*. If an initial reading cannot be made under a no-stress condition, determination of absolute stress requires use of a strain relief procedure (*52*).

Stress/strain conversion for steel is relatively straightforward; however, the procedure is complex for concrete structural members. The modulus of concrete is variable within structural members and also with time. Other complications can be caused by temperature; Poisson's ratio effects; creep, shrinkage, or swell; and curing. If the gage is slender and offers no resistance to concrete deformation, the indicated strains will be those for the concrete. If the gage is stiffer than the concrete, the measured strain will be less than the concrete strain. The effect of modulus mismatch between gage and concrete has been studied by Loh (*53*), who concluded that the gage should be kept as slender as possible ($1/r > 10$) and the gage modulus should always be less than that of the concrete. If this cannot be achieved, a calibration is necessary. Experience has also shown that a calibration is advisable, even if Loh's recommendations are satisfied. Changes of concrete modulus with time, creep, and shrinkage are handled by measurements taken on laboratory samples kept, if possible, under the same conditions of temperature and humidity as those in the field. The problem can also be approached by means of measurements on no-load gages embedded in the concrete in such a way that they are isolated from the stress field. Temperature effects must be compensated for by the application of correction factors, as determined from laboratory tests.

TABLE 15
ADVANTAGES AND LIMITATIONS OF EMBEDMENT STRAIN GAGES

GAGE TYPE	ADVANTAGES	LIMITATIONS	SYSTEM ACCURACY (μ in./in.)	RELIABILITY
Bonded Electrical Resistance on Rebar	Factory waterproofing. Rugged.	Lead wire effects. Requires calibration due to high gage stiffness.	5 to 100	Poor to good.
Bonded Electrical Resistance (Ailtech)	Factory waterproofing. Compliant.	Very delicate. Lead wire effects.	15	Good.
Unbonded Electrical Resistance (Carlson)	Long history of use. Factory waterproofing. Compliant.	Limited range and sensitivity. Lead wire effects.	15	Good.
Plastic Encased	Low cost. Compliant.	Unstable in long term. Lead wire effects. Temperature effects. Waterproofing problems.	15	Good short term; very poor long term.
Vibrating Wire	Lead wire effects minimal. Can use long lead wires. Long history of use. Factory waterproofing. Compliant or modulus matched.	Cannot measure dynamic strains. Limited range.	5	Good.

CHAPTER SIX

GENERAL GUIDELINES ON THE USE OF INSTRUMENTATION

A substantial part of this chapter is based on guidelines presented by Cording et al. (*9*). Instrument calibration, installation, and maintenance, and data collection, processing, and interpretation are discussed.

INSTRUMENT CALIBRATION

Instruments delivered from the manufacturer usually receive rough treatment in transit and must be checked to ensure correct functioning before installation. Manufacturers should supply written step-by-step acceptance test procedures to be performed by the user when the instruments arrive. Calibration charts or factors supplied with the instruments should be checked if the appropriate apparatus is on hand. When this is not the case, quick, simple tests should be performed to check that the instruments are working.

The various gages may be connected to the readouts and tilted, pressurized, squeezed, or pulled to induce changes of magnitude consistent with the calibrations supplied. The zero readings of the gages should agree with the readings supplied by the manufacturer. Other instruments, such as dial indicators, depth micrometers, and mechanical strain gages, can be checked against standards (e.g., gage blocks) provided by the manufacturer. Piezometers can be checked by immersion under known depths of water, and inclinometers may be tested by placing in sections of inclinometer casing kept fixed at some constant, known angle in the laboratory. Instruments must also be tested in the laboratory for temperature stability and for waterproof characteristics.

Where an absolute standard of accuracy is required, manufacturers can supply certificates of traceability indicating that the calibrations were performed using instruments whose accuracy is traceable to the National Bureau of Standards.

Portable readout devices should be recalibrated frequently by using reference standards and no-load gages. This recalibration may be performed at commercial calibration houses, using equipment traceable to the National Bureau of Standards. A sticker on the instrument should indicate the last and next calibration date.

INSTRUMENT INSTALLATION

Contractual arrangements required to ensure that installations are performed correctly are described in Chapter 4.

Locations should be selected in accordance with the guidelines given in Chapter 2. The locations should be surveyed accurately according to the plans, or should be changed according to geologic findings.

Installation procedures should be planned in accordance with guidelines given in Chapter 2 and in the instrument instruction manual. During installation a record should be made of all factors that may be relevant to subsequent data interpretation on forms specially made for each project and instrument. Items to be recorded should include project name, instrument type and number, location in plan and elevation, personnel responsible for installation, a log of appropriate subsurface data, installation date, and actual and unusual features of the installation including a record of all appropriate lengths, volumes, etc.

Each instrument should have a specified deadline, coordinated with construction activity, for installation and operation. Instruments installed early will provide initial readings for establishing reliable base conditions and measurements of changes caused by construction. Early installation will also provide information on faulty gages so that they can be repaired or replaced before construction begins.

INSTRUMENT MAINTENANCE

Maintenance requirements vary with each instrument and should be stated in the manufacturer's instruction manual. Periodic inspections should be made of all terminals to ensure that they are clean and functioning and to ensure the accessibility and integrity of enclosures and barricades. Portable instruments should be kept dry and clean and the manufacturer's lubrication instructions followed. Battery charging instructions should be followed closely.

DATA COLLECTION

Instrumentation Personnel

The instrumentation program should be under the supervision of a geotechnical engineer, who is responsibile for: securing the cooperation of all parties; coordinating the efforts of the owner, the designer, and the contractor; training and supervising technicians; recording geology and other subsurface conditions; recording construction details; reviewing data; and advising the owner, the designer, or the contractor of any condition requiring their attention.

One or more competent technicians will be required. The technicians must understand how the instruments work, what they are supposed to measure, and why they are necessary, and must be able to recognize a faulty instrument so that it can be rapidly corrected. They must know how to install, maintain, and read the instruments properly, and should be instructed on what to look for in the way of changes in the data so that significant changes can be rapidly brought to the attention of the engineer. Technicians should be encouraged to take an interest in the instrumentation program and be given as much responsibility as they can handle, thereby creating a sense of involvement and motivation and permitting the engineer to concentrate on interpretation of the data.

Field Books or Field Data Sheets

Readings can be recorded either in a field book or on specially prepared field data sheets. In either case it is important that the latest readings be compared immediately with previous readings so that changes can be verified as real or as errors caused by misreading or instrument malfunction. If field data sheets are used, they should be made specially for each project and instrument in order to record all important information, including project name, instrument type, date, time, observer, readout unit number, instrument number, readings, remarks, weather, temperature, construction activity, and any other factors that might possibly influence the readings. One or more sheets will be used for each date, with later transcription of data to one calculation sheet for each instrument. Raw data should be copied and the copy and original stored in separate safe places to guard against loss.

Automatic Data Acquisition Systems

There is a growing trend toward the use of electronic equipment, automatic data acquisition systems, and computer analysis of the data. Advantages of these systems include:

- Increased reading sensitivity and accuracy;
- Reduced manpower costs for reading instruments and analyzing the data;
- More frequent readings;
- Retrieval of data from remote or inaccessible locations;
- Instantaneous transmittal of data over long distances using telemetry;
- Measurement of rapid fluctuations, pulsations, and vibrations; and
- Electronic data storage in a format suitable for direct computer analysis and printout.

Disadvantages include:

- High initial cost;
- Complexity and lack of reliability requiring an initial "debugging" period;
- Need for a reliable and continuous source of power;
- Susceptibility to damage caused by weather conditions and construction activity;
- Inability to record environmental factors and details of construction activity that influence the readings;
- Possibility of generating an excess of data, encouraging a "file and forget" attitude; and
- Replacement of the knowledgeable observer by an inexperienced computer programmer, resulting in a "garbage in, garbage out" program of data interpretation.

Frequency of Readings

The frequency of readings should be related to construction activity and to the rate at which the readings are changing. Too many readings overload the processing and interpretation capacity, whereas too few may cause important events to be missed and prevent timely actions from being taken.

Several sets of initial readings are required to establish a reliable base, ideally unaffected by construction activity. When construction commences and approaches the instrumented location, readings should be taken frequently; i.e., once a week, once a day, once a shift, or even more frequently in relation to construction activity (such as before and after each blast, during pile driving, or during the placement or removal of surcharge, etc.). It is often wise to increase the frequency of readings during heavy rainfalls. As construction activity moves away from the instrument location or ceases altogether and when readings have stabilized and remained constant, the frequency may then be decreased.

DATA PROCESSING

The aims of data processing should be to (a) provide a rapid assessment of the data in order to detect sudden changes requiring immediate action, and (b) summarize and present the data in order to show trends and compare observed with predicted behavior for determination of the appropriate action to be taken.

Calculation Sheets

The raw field data are first transcribed from the field book or field data sheets onto calculation sheets for converting readout digits into movements, pressures, strains, loads, etc., in engineering units. Usually this task should be accomplished within 24 hours of taking the readings.

Calculation sheets should be made specially for each project and instrument to record project name, instrument type and number, date and time of readings, initials of person making and checking calculations, readings transcribed from field data sheets or field books, equations used for calculations (including any calibration or correction factors), and any remarks. Numbering the columns and using these numbers in defining each calculation step at the head of subsequent columns can be helpful.

Summary Sheets

Calculation sheets generally contain too much detail for the supervisory engineers, the contractor, or the owner. Therefore, the data, now expressed in engineering units, should be summarized showing the date, time, readings, and remarks, and then transmitted to all interested parties.

Data Plots

The data should always be summarized in graphical form so that trends and real changes can be distinguished from wild readings, miscalculations, or noise in the data due to a lack of reading precision.

Graphs are necessary for two purposes. First, engineers closely involved in the supervision of the instrumentation program on a routine basis use these plots, which should be updated daily, to make sure that important data are not overlooked and to pinpoint local variations in the general trend for further investigation. Second, a summary of the first plots can be used by individuals who are responsible for the construction but may not have the time, or technical background, to understand or digest the mass of observations. Although it is usually best to plot the data from the summary sheets, it is sometimes advisable to plot the raw data.

The proper display of data is important, because poorly plotted data may obscure significant trends or be completely misleading. Good display requires a full knowledge and understanding of the instrumentation program combined with imagination, ingenuity, and some trial and error. It is important to use a standard scale for all plots, so that comparisons can readily be made of data at various times and at various locations.

DATA INTERPRETATION

It is unwise to rely too heavily on computer programs for analyzing and interpreting data. The input of the intelligent observer during data interpretation is indispensable, and trained, experienced personnel are essential. The first step is to assess the correctness of the readings and to decide if an adverse situation exists that calls for immediate action. The second step is to correlate the instrument readings with other factors (cause and effect relationships) and to study the deviation of the readings from the predicted behavior.

When faced with data that on first sight do not appear to be reasonable, there is a temptation to reject the data as false. However, such data may be real and may in fact carry an important message. A significant question to ask is: Can I think of a hypothesis that is consistent with the data? The resultant discussion, together with the use of appropriate procedures for ensuring reading correctness (as mentioned in Chapter 2), will often lead to an assessment of data validity.

Instrument programs have failed because the data generated were never used. If there is a clear sense of purpose for an instrumentation program, the method of data interpretation will be guided by that sense of purpose. Without a purpose there can be no interpretation.

REFERENCES

1. DiBiagio, E., "Field Instrumentation—A Geotechnical Tool." *Proc.* First Baltic Conference on Soil Mechanics and Foundation Engineering, Gdansk, Vol. 1 (1975) pp. 37–59. (Reprinted in Publication 115, Norwegian Geotechnical Institute, 1977.)
2. Dunnicliff J., and J. B. Sellers, "Notes for Training Course on Geotechnical Instrumentation." Implementation Division, Offices of Research and Development, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. (1980).
3. Dunnicliff J., *Field Instrumentation for Geotechnical Engineering*. John Wiley & Sons, Inc., New York (in preparation).
4. DiBiagio, E., and F. Myrvoll, "Field Instrumentation for Soft Clay." *Soft Clay Engineering* (R. P. Brenner and E. W. Brand, Eds.), Elsevier, New York (1981) Ch. 10.
5. Dunnicliff, J., D. Hampton, and E. T. Selig, "Tunnel Instrumentation: Why and How." *Proc.* Rapid Excavation and Tunneling Conference, San Francisco (1981) pp. 1455–1472.
6. Peck, R. B., "Influence of Nontechnical Factors on the Quality of Embankment Dams." *Embankment-Dam Engineering, Casagrande Volume,* John Wiley & Sons, Inc., New York (1973) pp. 201–208.
7. Peck, R. B., "Observation and Instrumentation: Some Elementary Considerations." *Highway Focus,* Vol. 4, No. 2 (June 1972) pp. 1–5.
8. Dunnicliff, J., "Long-Term Performance of Embankment Dam Instrumentation." *Proc.* Symposium on Recent Developments in Geotechnical Engineering for Hydro Projects, Instrumentation Reliability and Long-Term Performance Monitoring of Embankment Dams. American Society of Civil Engineers, New York (1981) pp. 1–22.
9. Cording, E. J., A. J. Hendron, W. H. Hansmire, J. W. Mahar, H. H. MacPherson, R. A. Jones, and T. D. O'Rourke, "Methods for Geotechnical Observations and Instrumentation in Tunneling." Report No. UILU-E 75 2022. Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana (1975).
10. Schmidt, B., and J. Dunnicliff, "Construction Monitoring of Soft Ground Rapid Transit Tunnels, a Definition of Needs and Potential Developments." Report No. UMTA-MA-06-0025-74-13.1 and 13.2. Offices of Research and Development, Urban Mass Transportation Administration, U.S. Department of Transportation (1974).
11. American Society of Civil Engineers, "Consulting Engineering, a Guide for the Engagement of Engineering Services." Manual No. 45. New York (1981)
12. American Consulting Engineers Council, "Directory." Washington, D.C.
13. Association of Soil and Foundation Engineers, "Membership List." Silver Spring, Maryland.
14. Bozozuk, M., "Description and Installation of Piezometers for Measuring Pore Water Pressures in Clay Soils." Building Research Note No. 37. Division of Building Research, National Research Council of Canada, Ottawa (1960).
15. Corps of Engineers, "Instrumentation of Earth and Rockfill Dams. Part 1: Groundwater and Pore Pressure Observations." Engineer Manual 1110-2-1908. Office of the Chief of Engineers, Department of the Army (1971).
16. Hanna, T. H., *Foundation Instrumentation*. Trans Tech Publications, Cleveland, Ohio (1973).
17. Bureau of Reclamation, *Earth Manual*. 2nd ed. U.S. Department of Interior, Washington, D.C. (1974).
18. Wilson, S. D., and P. E. Mikkelsen, "Field Instrumentation." *TRB Special Report 176* (1978) Ch. 5.
19. Walter Nold Company, "The Nold DeAerator Process." Natick, Massachusetts (1980).
20. Hvorslev, M. J., "Time Lag and Soil Permeability in Groundwater Observations." Bulletin No. 36. U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi (1951).
21. Terzaghi, K., and R. B. Peck, *Soil Mechanics in Engineering Practice*. John Wiley & Sons, Inc., New York (1967) p. 672.
22. Hvorslev, M. J., "The Changeable Interaction Between Soils and Pressure Cells: Tests and Review at the Waterways Experiment Station." Technical Report No. S-76-7. U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi (1976).
23. O'Rourke, J. E., "Soil Stress Measurement Experiences." *Journal of Geotechnical Engineering Division, ASCE*, Vol. 104, No. GT 12 (December 1978) pp. 1501–1514.
24. Reese, L. C., J. C. Brown, and H. H. Dalrymple, "Instrumentation for Measurements of Lateral Earth Pressure in Drilled Shafts." Research Report 89-2. Center for Highway Research, University of Texas at Austin (1968).
25. Selig, E. T., "A Review of Stress and Strain Measurement in Soil." *Proc.* Symposium on Soil-Structure Interaction, University of Arizona, Tucson (1968) pp. 172–188.
26. State of California, "Evaluation of Commercial Soil Pressure Cells." Research Report No. M & R 636342. Materials and Research Department (1968).
27. State of California, "Field Performance Evaluation of Soil Pressure Cells." Research Report No. M & R 632954-1. Materials and Research Department (1971).
28. Weiler, W. A., and F. H. Kulhawy, "Behavior of Stress Cells in Soil." Geotechnical Engineering Report 78-2. School of Civil and Environmental Engineering, Cornell University (1978).
29. Weiler, W. A., and F. H. Kulhawy, "Factors Affecting Stress Cell Measurements in Soil." Paper presented at ASCE Convention, Atlanta, Georgia (October 1979). (Submitted to *Journal of Geotechnical Engineering Division, ASCE.*)
30. Brown, E. T. (Ed.), *Rock Characterization, Testing and*

Monitoring. Suggested Methods. International Society for Rock Mechanics, Pergamon Press, New York (1981).

31. HADALA, P. F., "The Effect of Placement Method on the Response of Soil Stress Gages." Technical Report No. 3-803. U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi (1967).
32. SELIG, E. T., "Soil Stress Gage Calibration." *Geotechnical Testing Journal, ASTM,* Vol. 3, No. 4 (December 1980) pp. 153–158.
33. State of California, "Calibration and Bedding Material Study for Earth Pressure Cells." Research Report No. CA-HWY-MR 632954 (2)-72-03. Materials and Research Department (1972).
34. BOZOZUK, M., "Field Instrumentation of Soil." *Proc.* Conference on Design and Installation of Pile Foundations and Cellular Structures, Lehigh University. Envo Publishing Co., Inc. (1970) pp. 145–157.
35. DUNNICLIFF, C. J., "Equipment for Field Deformation Measurements." *Proc.* 4th Panamerican Conference on Soil Mechanics and Foundation Engineering, San Juan, Vol. 2 (1971) pp. 319–332. (Reprinted in *Highway Focus*, Vol. 4, No. 2 (June 1972) pp. 89–103.)
36. DUNNICLIFF, C. J., "Schematic Arrangements of Various Types of Soil Mechanics and Rock Mechanics Measuring Instruments," *Highway Focus*, Vol. 4, No. 2 (June 1972) pp. 134–144.
37. GOULD, J. P., and J. DUNNICLIFF, "Accuracy of Field Deformation Measurements." *Proc.* 4th Panamerican Conference on Soil Mechanics and Foundation Engineering, San Juan, Vol. 1 (1971) pp. 313–366. (Reprinted in *Highway Focus*, Vol. 4, No. 2 (June 1972) pp. 7–88.)
38. BOZOZUK, M., G. H. JOHNSTON, and J. J. HAMILTON, "Deep Benchmarks in Clay and Permafrost Areas." ASTM STP 322 (1962) pp. 265–279.
39. British Geotechnical Society, *Field Instrumentation in Geotechnical Engineering*. John Wiley & Sons, Inc., New York (1974).
40. New York Department of Transportation, "Settlement Gages and Settlement Rods, Construction Details and Procedural Requirements." Soil Control Procedure SCP-7, Official Issuance, No. 7-41-3. Soil Mechanics Bureau (1979).
41. BOZOZUK, M., "The Spiral Foot Settlement Gauge." *Canadian Geotechnical Journal*, Vol. 5, No. 2 (1968) pp. 123–125.
42. BURLAND, J. B., J. F. A. MOORE, and P. D. K. SMITH, "A Simple and Precise Borehole Extensometer." *Geotechnique*, Vol. 22, No. 1 (1972) pp. 174–177.
43. BOZOZUK, M., and B. H. FELLENIUS, "The Bellow-Hose Settlement Gauge." *Canadian Geotechnical Journal,* Vol. 16, No. 1 (1979) pp. 233–235.
44. FORSYTH, R. A., and M. MCCAULEY, "Monitoring Devices to Control Embankment Construction on Soft Foundations." Course Notes Chapter 9, Slope Stability and Foundation Investigation. Institute of Transportation and Traffic Engineering, University of California, Berkeley (1973).
45. SWIGER, W. F., "Subsurface Investigations for Design and Construction of Foundations of Buildings, Parts III and IV." *Journal of Soil Mechanics and Foundation Engineering Division, ASCE*, Vol. 98, No. SM 7 (July 1972) pp. 749–764.
46. MCGUFFEY, V. C., "Plastic Pipe Observation Wells for Recording Ground Water Levels and Depth of Active Slide Movements." *Highway Focus*, Vol. 3, No. 3 (1971).
47. KALLSTENIUS, T., and W. BERGAU, "In Situ Determination of Horizontal Ground Movements." *Proc.* Fifth International Conference on Soil Mechanics and Foundation Engineering, Paris, Vol. 1 (1961) pp. 481–485.
48. WILSON, S. D., and P. E. MIKKELSEN, "Foundation Instrumentation-Inclinometers." Report No. FHWA TS-77-219 (color video tape, film and reference manual). Implementation Division, Offices of Research and Development, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. (1977).
49. American Association of State Highway and Transportation Officials, "Standard Method for Installing, Monitoring and Processing Data of the Traveling Type Slope Inclinometer." Designation T 254-78. Washington, D.C. (1978) pp. 941–950.
50. HAWKES, I., "Measurement of Mine Roof Movement." Final Report Contract H0366033. U.S. Bureau of Mines (1978).
51. SELIG, E. T., "Soil Strain Measurement Using Inductance Coil Method." *Performance Monitoring for Geotechnical Construction*. ASTM STP 584. (1975) pp. 141–158.
52. "Measurement of Residual Stresses by the Blind Hole Drilling Method." Technical Data Bulletin TN-503, Measurements Group, Inc., Raleigh, North Carolina (1981).
53. LOH, Y. C., "Internal Stress Gauges for Cementitious Materials." *Proc.* Society for Experimental Stress Analysis, Vol. XI, No. 2 (1952).

APPENDIX

EXAMPLES OF INSTRUMENTATION APPLICATIONS

The material in this appendix has been excerpted from a technical paper by DiBiagio and Myrvoll (*4*). The authors provide a general review of contemporary instrumentation concepts and procedures as applied to geotechnical engineering projects in soft clay. The need for instrumentation is discussed, and the types of measurements most frequently required as well as the measurement techniques generally employed are described. A number of hypothetical case studies are presented in order to demonstrate the need for observation programs and to indicate the function of instrumentation in relation to the principal geotechnical problems that are characteristic of the examples cited.

Because the technical paper will not be readily available to many users of this synthesis, the entire section on hypothetical case studies is presented here. Although this material only describes projects in soft clay, these projects have broad relevance in demonstrating the reasons for using instrumentation in or on other soils.

It should be emphasized that the case studies have been selected to reflect a wide variety of geotechnical problems, and that the extent of instrumentation shown in the figures is not usually necessary for routine construction projects. The extent of instrumentation will, in practice, depend on factors specific to each project, including both technical and financial considerations.

EXAMPLES OF INSTRUMENTATION APPLICATIONS FOR PROJECTS IN SOFT CLAY

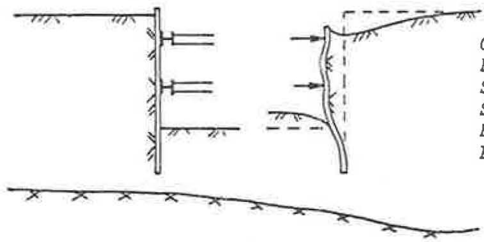
In order to summarize present day instrumentation concepts and procedures the remainder of this article is devoted to hypothetical examples that illustrate the use of instrumentation for the most frequently encountered engineering projects in soft clay. Projects that generally require extensive amounts of instrumentation have been selected for presentation in order to illustrate as many different types of instrumentation applications as possible within the limited number of examples given. The following eight examples are included:

(1) Strutted excavations
(2) Embankments
(3) Tunnels
(4) Excavated slopes
(5) Tie-back anchors
(6) Driven piles
(7) Cast-in-place piles
(8) Slurry trench excavations

The examples are based on the authors' experience and on case studies reported in the literature. It is the hope of the authors that these examples will illustrate current instrumentation practice and give the reader an impression of the merits as well as the limitations of instrumentation programs.

A complete appreciation of the rôle that instrumentation plays in an engineering project is not possible unless the reasons for initiating the observational program in the first place are fully understood. Therefore, in each of the following examples a brief description is given of the relevant geotechnical and design or construction problems that are peculiar to the project, and the function of instrumentation in relation to these problems is pointed out. The scopes of routine and specialized monitoring programs are summarized and an attempt has been made to illustrate how instrumentation can be used to solve or provide a better understanding of the relevant geotechnical and practical problems.

STRUTTED EXCAVATION



GENERAL BACKGROUND AND NEED FOR INSTRUMENTATION

The illustration above depicts a typical strutted sheet-piled excavation in soft clay for the case where the sheet piles are not driven to bedrock or underlying firm stratum. Design and construction of excavations of this type are based for the most part on empirical design procedures, and past experience. Because the consequences of a failure may be catastrophic, they are frequently well instrumented. Monitoring programs for braced excavations will generally include the following parameters:

Routine instrumentation for measurement of:

settlements, heave, strut loads, ground water level, and horizontal displacements.

Specialized instrumentation for measurement of:

pore pressure in soil, earth pressure and water pressure on sheeting stresses in sheeting and wales, frost pressures and penetration.

FUNCTION OF INSTRUMENTATION IN RELATION TO PRINCIPAL GEOTECHNICAL PROBLEMS

Instrumentation can be useful in evaluating the overall stability of an excavation and provide assurance that the work is proceeding safely. Results of measurements will document causes and extent of damage to adjacent structures and utilities. Alterations to proposed excavating and/or bracing procedures can be initiated on the basis of measurements in order to assure adequate safety or for reasons of economy. Well instrumented and documented case histories provide a base for improved knowledge and refinement in design procedures. Common instrumentation applications are given below.

Factor of safety against bottom heave failure may be low

Install instrumentation to permit bottom heave measurements. Monitor heave and settlement frequently as excavation level approaches the critical depth. Pay particular attention to settlement and heave rates. Horizontal displacement of lower part of sheet piling will indicate instability of excavation.

Danger of overloading individual struts

Monitor strut loads on as many struts as is practical or economically justified. Have reserve struts available for immediate installation if measurements indicate allowable limits have been reached.

Ground movements due to deformation of sheeting and bottom heave may damage nearby structures or utilities

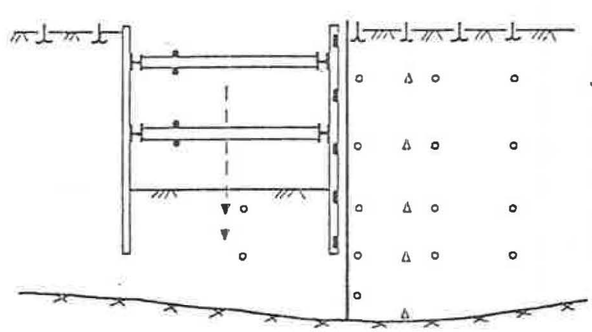
Establish reference points for monitoring settlement of ground surface and structures adjacent to the excavation. Deep settlement reference points should be established near important underground utilities. Monitor horizontal displacement of sheeting and on several profiles in the soil mass behind sheeting if there is danger of damage to structures or utilities.

Prolonged lowering of ground-water table may cause serious consolidation settlements over a large area

Measure pore pressure in permeable layers and if economy permits monitor pore pressure with depth along several vertical sections behind the sheeting. Monitor elevation of ground water table near to and remote from the excavation.

Total load and distribution on bracing system is unknown

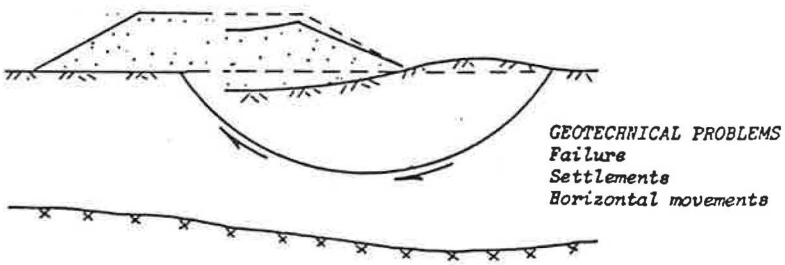
Monitor sufficient struts on vertical sections in order to allow computation of point of application of resultant or measure force transmitted to wales from sheeting at each strut level. Instrument sheeting to permit direct measurement of magnitude and distribution of earth pressure and water pressure against both sides of the sheeting.



REFERENCES

Instrumentation applications of this kind are found in references 2, 3 and 9.

EMBANKMENTS



GENERAL BACKGROUND AND NEED FOR INSTRUMENTATION

Embankments are frequently built on layers of soft clay for highways, reservoirs and levees, or as full-scale loading tests carried out to investigate the engineering properties of the underlying soil. In spite of a long and universal record of embankment construction throughout the history of civil engineering, embankments that are designed with a factor of safety greater than unity fail embarrassingly often. On the other hand, some test embankments that are designed to fail intentionally, never do. In recognition of this, it is not surprising that embankments are frequently and extensively instrumented. Monitoring programs for embankments on soft clay will usually include the items listed below.

Routine instrumentation for measurement of:

settlements of embankment and natural ground, pore pressure in soil, and horizontal spreading of the toe of the embankment.

Specialized instrumentation for measurement of:

settlements at different depths, horizontal displacements of subsoil and fill, location of failure plane, horizontal strain in base of embankment, in-situ stresses and permeability, and surface loading caused by the embankment.

FUNCTION OF INSTRUMENTATION IN RELATION TO PRINCIPAL GEOTECHNICAL PROBLEMS

To be successful an embankment must be designed and constructed such that neither the embankment material nor the underlying soil are overstressed to the point where the resulting deformations exceed the limit that is acceptable for the intended use of the embankment. Instrumentation is required, therefore, to monitor deformations as well as the factors that can be correlated to deformation and stability. Another need for instrumentation is to document that improved stability and a reduction in post construction settlements can be achieved by means of special construction procedures such as, sand drains, ground reinforcement, berms and preloading.

Settlement data reflects overall performance of an embankment

Provide for systematic observations of settlement of the ground surface adjacent to and beneath the embankment. Additional deep settlement points are useful, in particular if the subsoil is stratified. Both magnitude and rate of settlement are important to an evaluation of post construction performance. In addition the initial "elastic" settlement caused by each increment of loading as the fill is placed, provides a basis for an appraisal of stability during construction.

Pore pressures may provide first indications of incipient failure

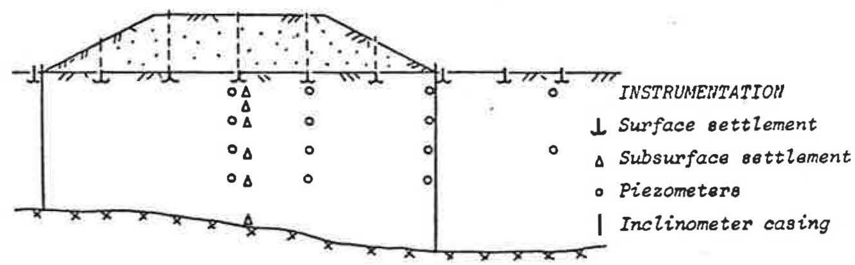
A warning of impending failure of an embankment can often be disclosed from a careful study of measured settlements, deformations and pore pressures. A number of documented cases in soft clay show, however, that measured pore pressures may give a better first indication of failure conditions developing than can be derived from displacement data. Thus, if the factor of safety is low or questionable, and if the consequences of a failure are high, pore pressures should be monitored. In order to be certain of having instruments located in the zones of initial yielding, a relative large number of piezometers may be required unless experience and proven methods of analysis can be used to locate the critical zones that require instrumentation. Pore pressure measurements are also essential to evaluation of progress of consolidation settlements and to aid in establishing the rate at which an embankment can be constructed.

Lateral yielding of ground is an important evaluation and control parameter

Measure horizontal strains at ground surface, including movement of the toe and spreading of the embankment material. Install inclinometer casing at several distances from the center of the embankment and monitor horizontal displacements frequently during placement of fill.

Location of failure plane is important for post-failure analysis

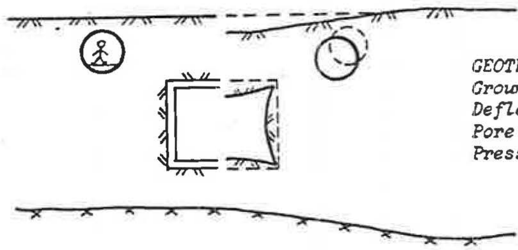
Test embankments that are to be deliberately failed should be instrumented with mechanical and/or electrical devices that will permit location of the rupture surface.



REFERENCES

Instrumented embankments are described in references 4, 5 and 6.

TUNNELS



GEOTECHNICAL PROBLEMS
Ground movements
Deflection of lining
Pore pressure reduction
Pressure on lining

GENERAL BACKGROUND AND NEED FOR INSTRUMENTATION

Tunnel construction in soft ground has always been an important civil engineering activity, and these structures are becoming increasingly more important because of the need to locate utilities and transportation systems underground in congested metropolitan areas. Tunnels in soft clay are designed and built primarily on the basis of empirical rules and experience. As they are generally built in congested areas, tunnel projects may cause serious damage to overlying structures and utilities. For this reason monitoring programs are commonly carried out on tunnel projects in order to verify that the work is proceeding safely, to provide information for improving future designs, or to obtain facts to be used in legal proceedings if damage claims arise. Instrumentation programs for tunneling in soft clay will generally include the parameters listed below.

Routine instrumentation for measurement of:

settlements of ground surface and tilt of nearby structures, ground water level, horizontal displacements, and deflection of lining.

Specialized instrumentation for measurement of:

water pressure and earth pressure distribution or lining, stress or strain in lining, and pore pressure in soil.

FUNCTION OF INSTRUMENTATION IN RELATION TO PRINCIPAL GEOTECHNICAL PROBLEMS

Instrumentation is needed in many cases to verify that the tunnel can actually be built in a safe manner using the prescribed construction procedure. This is generally investigated by thoroughly instrumenting a representative section of tunnel, called a test section, at the start of tunnel driving. Instrumentation is also needed to detect conditions, such as large soil movements or lining deflection, that may lead to excessive settlements and damage to overlying structures, or to document the extent and causes of such damage for use in legal proceedings. Finally, instrumentation is needed to check that the performance of the completed tunnel is in accordance with plans and specifications.

Tunnels cause settlements and settlements cause damage

Establish reference points at the ground surface above the centerline of the tunnel and some cross sections, to permit monitoring settlement of buildings as well as the size and shape of settlement trough as the tunnel advances. Deep settlement reference points should be established near important underground utilities and foundations.

The displacement field around tunnel face is 3-dimensional

Install casing and monitor horizontal displacements within the clay mass close to the tunnel. Combine this information with subsurface settlement data to obtain a complete picture of the displacements caused by tunneling.

Lining deflections may aggravate settlements and deformations

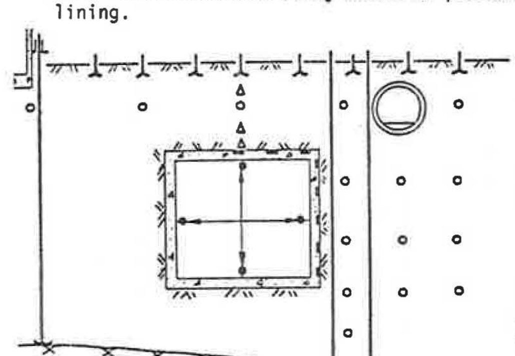
Measure changes in diameter of tunnel lining along vertical and horizontal axes.

Prolonged lowering of ground-water table may cause serious consolidation settlements over a large area

Monitor elevation of ground-water table near to and remote from the tunnel. Measure pore pressure in the clay mass and in particular in or near permeable seams, if any, in the clay. Measure water pressure on the completed lining.

Total load and distribution of stress in lining is unknown

Install strain gauges on lining to monitor distribution of strains. Measure the tangential force transmitted through the lining by means of load cells mounted between lining elements or alternately with the use of specially instrumented and calibrated lining elements. The magnitude and distribution of earth pressure and water pressure on the lining can in some cases be monitored by means of pressure transducers mounted on the lining.

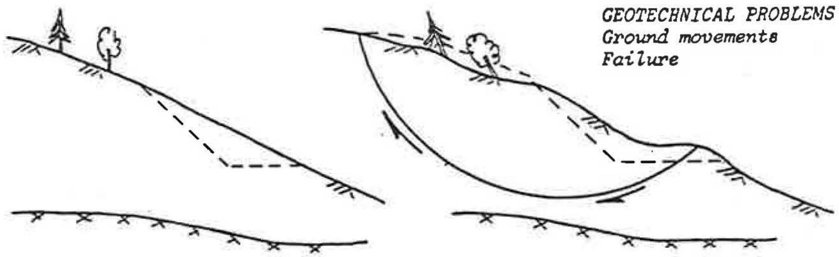


INSTRUMENTATION
Surface settlement
Subsurface settlement
Precision settlement gauge
Piezometer
Inclinometer casing
Earth pressure gauge
Deflectometer

REFERENCES

Examples of instrumented tunnels in clay are given in references 7, 8 and 9.

EXCAVATED SLOPES



GENERAL BACKGROUND AND NEED FOR INSTRUMENTATION

Construction of highways, canals and grading of building sites often require that excavations with sloping sides, as shown above, be made in soft clay. Many of these are permanent slopes that must be stable indefinitely, whereas others are only temporary. Thus the principal geotechnical design problem is to provide a slope with the required short-term or long-term stability. Consequentially, the role of instrumentation is to document whether the performance of the excavated slope is in accordance with the predicted behaviour or not. Instrumentation programs for natural slopes are essentially the same for natural slopes as for post construction manmade slopes. The principal parameters monitored are ground movements and pore pressures as indicated below.

Routine instrumentation for measurement of:

surface strains, i.e. vertical and horizontal movements of points on the surface.

Specialized instrumentation for measurement of:

pore pressure and horizontal displacements within soil mass.

FUNCTION OF INSTRUMENTATION IN RELATION TO PRINCIPAL GEOTECHNICAL PROBLEMS

Instrumentation required for excavated slopes must provide information relative to the stability of the slope, both during excavation and on a short or long-term basis thereafter. Results of measurements can be used as a basis for modification of the designed slope angle, in order to assure adequate safety or for reasons of economy. Instrumentation is also needed to document the effectiveness of ground reinforcement techniques and other specialized construction procedures for improving slope stability. Common instrumentation usages are given below.

Knowledge of initial conditions is essential

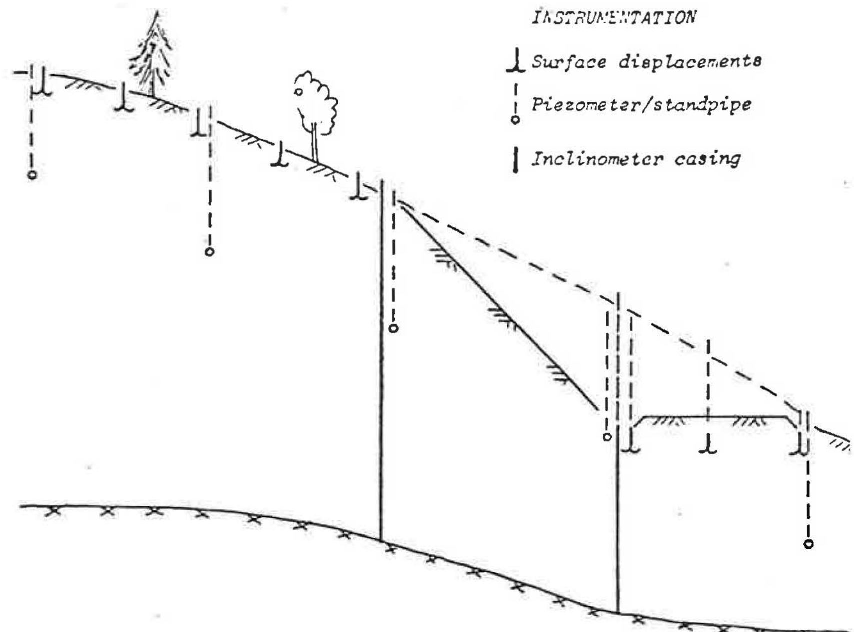
Install observational wells and piezometers to monitor pore pressure and ground water level in the area before excavation of the slope is started. Knowledge of seasonal variations in water level can be useful. To the degree that it is possible, instrumentation systems and reference points for measurement of surface strain, settlement and horizontal displacements should be installed and initial measurements taken before excavation starts.

Observations during excavation provide clues to the performance of the completed slope

Measured changes in pore pressure and observed displacements during excavation of the slope can be used in back computations to assess the validity of the soil parameters used in the original design computations. On the basis of these computations, new values can be estimated and used to predict the performance of the final slope.

Systematic monitoring necessary to evaluate long-term performance of slope

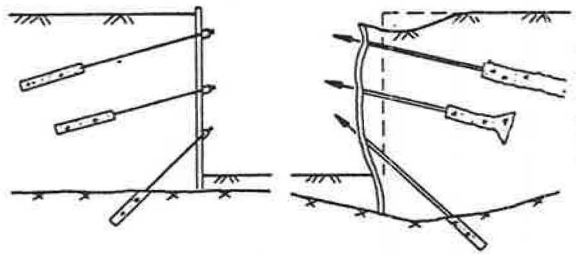
Development of shear zones or failure planes can generally be seen in the data obtained from the inclinometer surveys used to measure horizontal displacements of casings installed in the ground. Observed creep rates and pore pressure data may indicate instability and local yielding in the ground.



REFERENCES

Typical instrumented cut slopes are contained in references 10, 11 and 12.

TIE-BACK ANCHORS



GEOTECHNICAL PROBLEMS
Anchor loads
Length of anchor
Anchor deformation
Creep
Quality of grouted body

GENERAL BACKGROUND AND NEED FOR INSTRUMENTATION

Ground anchors are being applied to an increasing number of construction projects in soft clay, as for example in tie-back excavation as illustrated above. Tie-back anchors have the advance over traditional bracing systems, such as struts and raker beams, in that the supporting elements are external and do not interfere with construction activities within the excavation area. In principle tie-back systems for excavations consist of groups of parallel wires and spun cables or individual steel rods anchored at one end in a cement-grout body embedded in the soil or bedrock. The design and construction of tie-back anchors is based primarily on empirical procedures and past experience; and as the consequences of an anchor failure may be catastrophic, projects of this kind are seldom undertaken without initiating a monitoring program to check anchor performance. Instrumentation requirements for the excavation itself were dealt with in a preceding example and will not be repeated. Instrumentation for tie-back anchors normally consists of:

Routine instrumentation for measurement of:

total load on anchor, elastic strain and total elongation of anchor head.

Specialized instrumentation for measurement of:

distribution of load and strain along length of anchor, creep.

FUNCTION OF INSTRUMENTATION IN RELATION TO PRINCIPAL GEOTECHNICAL PROBLEMS

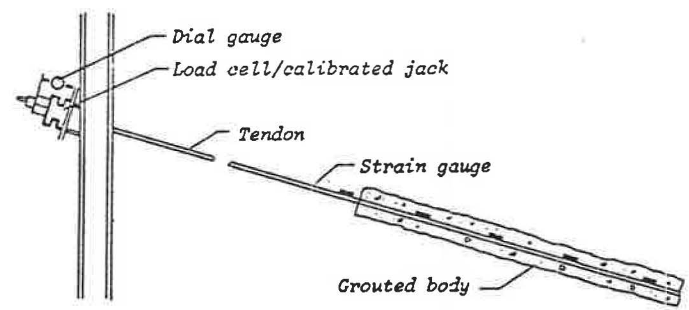
The maximum load carrying capacity of conventional supports, such as struts, can be determined accurately from material properties and dimensions of the support. The ultimate capacity of ground anchors, on the other hand, does not generally depend on properties of the tendons, but on the soil properties and the size and shape of the embedded (grouted) body of the anchor. Consequentially, computations of allowable loads for anchors are at best only rough approximations. Ground anchors should not be used on a project unless their holding power is verified by full scale tests or unless the design is so overly conservative that a failure can not possibly occur. Even this may not prevent a failure if the installation work performed by the contractor is inferior. Instrumentation procedures for evaluating anchor performance are given below.

Full scale tests are needed to evaluate length of embedded part of anchor

Construct test anchors with embedded grouted length less than, equal to, and greater than the design length. Load to failure and monitor load and displacement throughout test. Pull out anchor if possible and examine size, shape and quality of the grouted body. As a supplement, instrument anchor with strain gauges or extensometers in order to investigate distribution of load along the anchor.

All anchors should be test loaded

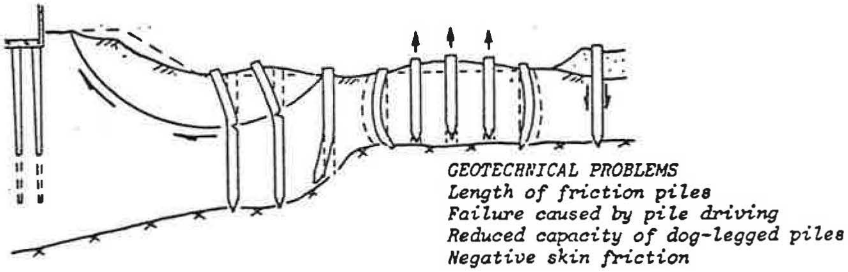
In order to detect a defective anchor or to verify that the carrying capacity is within acceptable limits, each anchor should be test-loaded to a value in excess of the designed working load. Elongation of anchor head corresponding to the maximum test load should be recorded. Loads developed in anchors during construction should be measured periodically which will depend on the anticipated rate of loading on the anchor. On critical projects, install load cells on a number of anchors to permit continuous monitoring of forces.



REFERENCES

Instrumented tie-back anchors are described in references 13 and 14.

DRIVEN PILES



GENERAL BACKGROUND AND NEED FOR INSTRUMENTATION

Pile foundations are often needed to provide adequate support for structures on soft clay. Driven piles, either as end bearing piles or friction piles, are commonly used for these foundations. As is the case with most piles, the design of driven piles involves assumptions and uncertainties that need to be checked by means of instrumented full scale tests. Furthermore, certain types of driven piles cause large displacements and pore pressure changes in the surrounding soil; these may in turn have a detrimental effect on neighboring piles or on the stability of the site as a whole. Therefore an instrumentation program is needed to monitor the effects of pile driving as well as to establish the load-deformation characteristics of the piles. Monitoring programs for driven piles in soft clay will generally include the parameters listed below.

Routine instrumentation for measurement of:

load-settlement characteristics for pile, heave and horizontal movement of ground surface during driving.

Specialized instrumentation for measurement of:

pore pressures, subsurface horizontal movements of soil and piles already driven, distribution of vertical load along length of pile, bending stresses in laterally loaded piles, load due to negative skin friction and distribution of load in pile groups.

FUNCTION OF INSTRUMENTATION IN RELATION TO PRINCIPAL GEOTECHNICAL PROBLEMS

Pile foundations must be able to carry the design loads safely and without excessive settlement. Full scale tests on driven piles are necessary, therefore, to check geotechnical design procedures and driving criteria or to document whether the load-settlement characteristics for a driven pile fall within acceptable performance limits. Field tests may be required to establish the length of friction piles or to monitor long-term loading caused by surface settlements and negative skin friction. Instrumentation is necessary to monitor pile driving operations and to detect factors, such as badly deformed piles or large bending moments, which may lower the bearing capacity of a pile.

Common instrumentation applications for driven piles are given below.

Failure at site may be triggered by driving displacement piles

If topography and site conditions suggest that a slide or failure may be initiated by driving displacement piles, establish settlement reference points, install piezometers and inclinometer casing to monitor ground movements and pore pressure. Some types of piles can be fitted with inclinometer casing before driving and surveyed later to determine displacement caused by driving neighboring piles.

Designed length of friction piles may be uncertain

Carry out full scale load tests. Evaluation of results is simplified if load cell can be mounted on tip of pile in order to separate total load into point resistance and skin friction.

End bearing piles driven to irregular bedrock surface may have reduced capacity

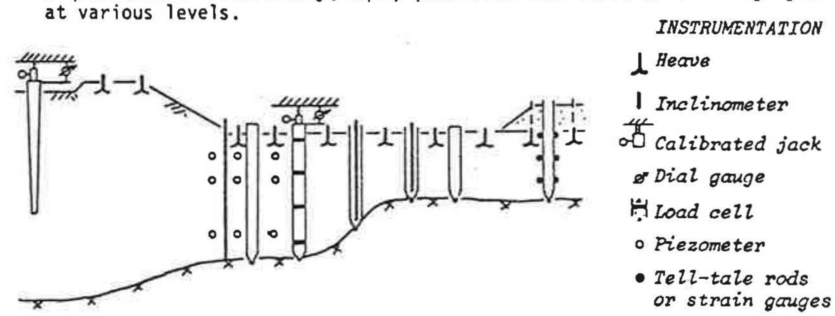
Dog-legged piles, caused by the pile deflecting from a sloping bedrock surface may have reduced end bearing. Confirm radius of curvature of pile by means of inclinometer measurements or alternately test load.

Lateral yielding of soil may induce large bending stresses in pile

Nonuniform surface loading may cause substantial horizontal ground movements in soft clay, thereby causing displacement and undesirable bending stresses in the piles. When these conditions are anticipated, instrument pile with inclinometer casing, if possible, and/or strain gauges to permit determination of lateral movements and stresses.

Negative skin friction may cause overload of end bearing piles or increased settlement of friction piles

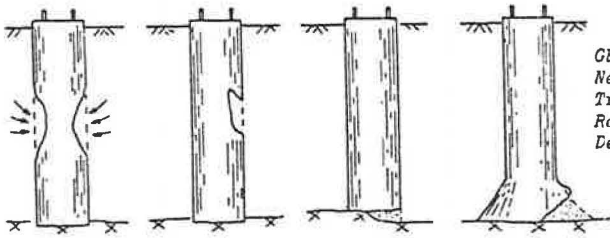
If large surface settlements are expected, instrument pile to measure long-term build up of load. Precise mechanical extensometers to measure incremental strain along pile are advisable because of long-term stability requirements. Alternately, equip pile with load cells or strain gauges at various levels.



REFERENCES

Instrumentation applications of this kind are found in references 15 and 16.

CAST-IN-PLACE-PILES



GENERAL BACKGROUND AND NEED FOR INSTRUMENTATION

Cast-in-place point-bearing piles are commonly used for foundations in soft clay in order to avoid construction problems associated with ground movements caused by driving displacement piles. These piles are made by drilling a hole into the ground and backfilling the hole with fluid concrete. A temporary outer casing is generally required in soft clay and water or drilling mud may be used in advancing the borehole. In this case the fluid in the hole is replaced by tremie concrete as the casing is withdrawn. Although assumptions must be made concerning design parameters for side shear and end bearing for cast-in-place piles, the principal problems encountered with the use of this type of pile in soft clay are not related to design but to matters of construction techniques and control. Instrumentation is required, therefore, primarily for control purposes. The principal instrumentation applications are listed below.

Routine instrumentation for measurement of:

load-deformation characteristics of completed pile.

Specialized instrumentation for measurement of:

integrity of pile and quality of concrete, distribution of vertical load in pile, amount of end bearing and side friction, lateral movements, and profiling of belled pile if visual inspection of bell is not possible.

FUNCTION OF INSTRUMENTATION IN RELATION TO PRINCIPAL GEOTECHNICAL PROBLEMS

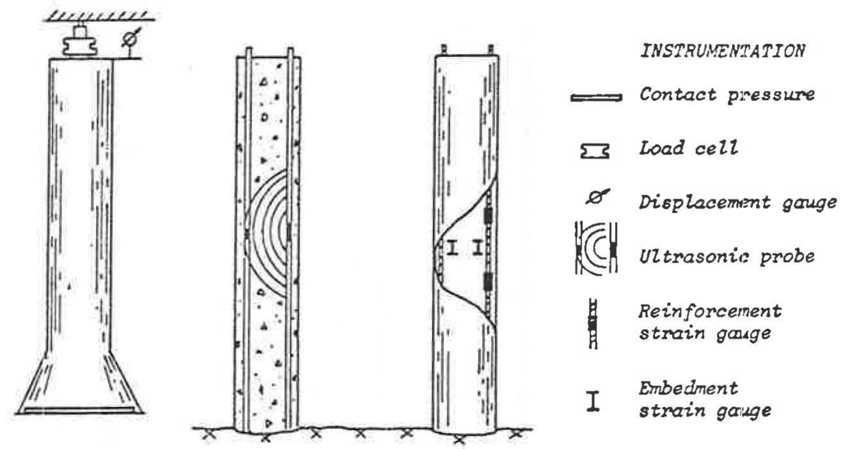
The danger of having an undetected flaw in a pile is without doubt the most worrisome aspect of using cast-in-place piles in soft clay. This is particularly so for those cases where the temporary casing is pulled out during concreting, or when the hole is excavated with the aid of a fluid and concrete is placed by the tremie method. In these situations the chances of having a necked-down pile or one containing a pocket of clay or drilling mud trapped between soil and concrete are high. This is particularly true if the contractor is unexperienced or careless. Thus, the main objective of instrumentation is to provide information that can be used to evaluate the soundness of the completed pile. Several possible applications of instrumentation for control purposes are given below.

Load tests demonstrate pile capacity and may indicate defective pile

Conventional load tests will document capacity of pile. Strain gauges, hydraulic load capsules, pressure cells at the base and precision extensometers or other special instruments to monitor load transfer and compressibility will provide information useful to interpretation of pile behaviour. Unexpected low capacity may be because of serious defect in pile, such as a large clay-filled void or that the pile is badly necked down. Large observed settlement of a pile designed to carry significant load in end bearing may be a result of remoulded clay and mud trapped beneath the pile because the bottom of the hole was not properly cleaned before pouring concrete.

Nondestructive methods can be used to investigate integrity of concrete

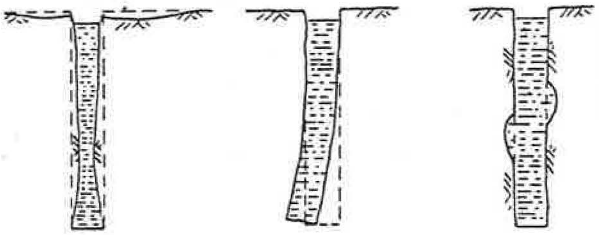
Continuous diamond core drilling is sometimes used to obtain samples to assess quality of concrete and detect flaws. However, this method is expensive, time consuming and can be complicated and misleading because of alignment problems on long piles. An alternate procedure to detect flaws is to survey the pile with an ultrasonic borehole probe or similar type of device that can detect variations in modulus of elasticity of the concrete. These can be operated in a single hole or cross-hole techniques can be used depending on the type of instrument and size of pile. The casings required for the survey can be cast integral with the pile during concreting.



REFERENCES

Examples of instrumentation of this kind is given in references 17, 18 & 19.

SLURRY TRENCH EXCAVATIONS



GEOTECHNICAL PROBLEMS
Ground movements
Stability of trench
Alignment vertical
Local failure

GENERAL BACKGROUND AND NEED FOR INSTRUMENTATION

Slurry trench excavations, above, are supported by an internal fluid instead of conventional structural bracing systems such as struts and sheeting. Otherwise the design, control and performance monitoring problems and also the consequences of a failure are similar to those encountered with braced excavations; consequently the instrumentation requirements are analogous in many ways.

There is, however, one fundamental difference between a conventional braced excavation and a slurry-filled trench that illustrates the need for instrumentation of the later. In a braced excavation an experienced observer can see things, such as, unusually large deformations of the sheeting or signs of overstressing in the bracing system, that may give a warning of unexpected performance or even impending collapse. In many instances serious difficulties have been avoided by initiating remedial action based on simple visual observations alone. On the other hand, it is not possible to see anything in a slurry-filled trench. Therefore, unexpected events and even a failure could occur suddenly and without warning unless a suitable instrumentation program for monitoring the performance of the excavation has been provided for. Monitoring programs for slurry trench excavations in soft clay will generally include the following observations.

Routine instrumentation for measurement of:

settlements, horizontal displacements, level of slurry and ground water table, and physical properties of slurry.

Specialized instrumentation for measurement of:

profiling of trench (width), creep of sides, vertical alignment of excavation, pore pressure in soil, loading and deformations when trench is concreted, stresses and deformations in the completed wall, distribution of water and earth pressure on completed wall.

FUNCTION OF INSTRUMENTATION IN RELATION TO PRINCIPAL GEOTECHNICAL PROBLEMS

Although contractors have extensive experience with the use of slurry to stabilize deep excavations in many types of soil, this construction procedure has not been generally applied to soft clays. For this reason a considerable effort has recently been devoted to instrumentation of slurry trench excavations in soft clays in order to obtain answers to even the most elementary design assumptions.

On slurry trench projects it may not always be feasible or possible to integrate all aspects of planned instrumentation and monitoring programs into the contractor's work routine. Thus a full-scale instrumented test panel at the site may be necessary in order to verify critical design assumptions before the main contract work begins. Common instrumentation philosophy and applications are given below for a single panel excavation.

Ground movements provide simple and reliable indications of stability

Monitor settlement of ground surface, guide walls and adjacent structures. Settlements may be quite small and settlement rate is a key factor in evaluating overall stability. Therefore include at least one precision settlement gauge close to the excavation that can be read quickly and frequently. Install at least one inclinometer casing close to the edge of the excavation and monitor horizontal displacements frequently.

Position of ground-water table relative to level of slurry is important

Monitor elevation of top of slurry inside the excavation as well as the elevation of ground-water table near to and remote from the excavation. Account for unexpected loss of slurry.

High density slurry is expensive and can complicate concreting operations

Some form of observational program is required in order to establish the acceptable minimum density of the slurry to be used on a project. This fundamental parameter can be evaluated of course on the basis of a series of full scale tests using slurries of different density, but this is not always practical or economical. An alternate procedure is to excavate one panel using a slurry with a high initial density and subsequently diluting the slurry in stages until the observed deformations or rate of deformation become excessive or a collapse occurs. Tests of this kind require very accurate and frequent measurements of settlement and horizontal displacements in order to correlate creep rate to density and time. Measurements of pore pressure versus time are also valuable in this respect. To obtain adequate creep data for the inward movement of the walls, it is advisable to install extensometers inside the trench at a number of levels.

End effects influence the maximum length of panel that can be excavated

The limiting length to width ratio for which a single panel can be excavated safely can be established on the basis of full scale test panels of varying length. Comprehensive measurements of the displacement field are needed to evaluate the restraint provided by the soil at the ends of a trench.

Configuration of completed excavation may deviate from designed shape

As it is not possible to examine visually a completed excavation, one must rely entirely on instrumentation for a final inspection. The width of the excavated panel at any point can be determined with remote reading caliper tools lowered into the trench. The same instrument can also be used to search for local failures or overbreak particularly in fissured clay where blocks of material may fall out during or subsequent to excavation.

Errors in vertical alignment may have serious consequences on certain applications. Verticality can be measured using conventional inclinometer surveying techniques inside flexible casing lowered temporarily into the trench and pressed against one side by small pneumatic jacks, for example.

How long may an excavated panel be kept open?

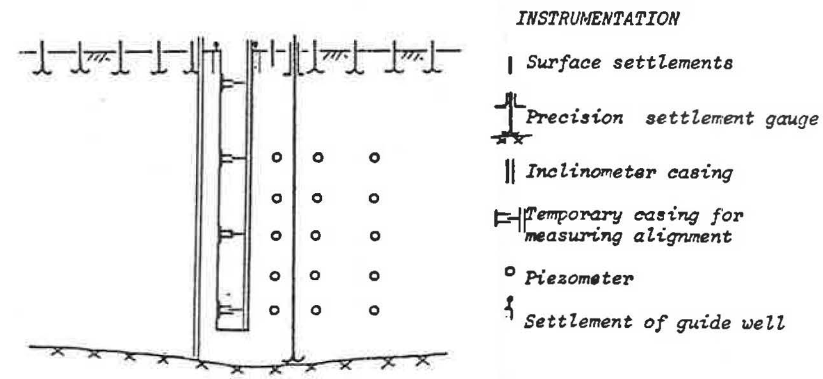
As a rule contractors will complete a section of slurry trench wall as quickly as possible in order to minimize the time the excavation is kept open. There are occasions, however, when an excavated panel must be kept open for longer periods of time and the effect of time on overall stability becomes an important factor to consider. One way to evaluate this factor is to monitor settlements and lateral displacements very carefully with time, as described above, and make a conclusion based on the magnitude of observed deformations and whether the rate of deformation is increasing or decreasing with time. Trends in measured pore pressure in the surrounding soil can also serve as a guide to indicate how fast overall stability is deteriorating with time.

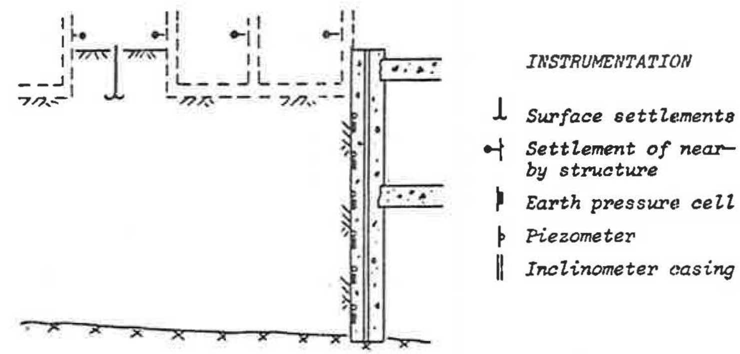
Local stability of excavation may be uncertain during concreting

Filling a deep slurry trench excavation with fresh concrete causes a significant increase in loading on the bottom and sides of the trench with respect to the slurry that is displaced. As a result large local deformations may occur in very soft clay, and there may even be a chance of a bearing capacity type failure of the bottom or sides of the excavation during concreting. Therefore lateral deformations and settlements and pore pressures, if available, should be monitored closely during concreting of the first panel.

Cast-in-place diaphragm walls can be instrumented for performance measurements

Embedment strain gauges and instrumented reinforcing steel or similar instruments can be attached to the reinforcing steel cage before it is lowered into the trench. If the completed wall is to be used as a earth retaining structure, inclinometer casings for measurements of horizontal displacements can be installed prior to concreting. Furthermore, special procedures have been developed for installation of transducers flush with the surface of the final wall for subsequent monitoring of earth pressure and pore pressure on the completed wall.





REFERENCES

Instrumented slurry trench projects are described in reference 20 and 21.

REFERENCES

1. DiBiagio, E. (1975)
Field instrumentation - a geotechnical tool.
Baltic Conference on Soil Mechanics and Foundation Engineering, 1.
Gdansk 1975. Proceedings, Vol. 1, pp. 37-59.
Also publ. in: Norwegian Geotechnical Institute. Publication, 115, 1977.

2. Karlsrud, K. and F. Myrvoll (1976)
Performance of a strutted excavation in quick clay.
European Conference on Soil Mechanics and Foundation Engineering, 6.
Wien 1976. Proceedings, Vol. 1.1, pp. 157-164.
Also publ. in: Norwegian Geotechnical Institute. Publication, 111.

3. Cunningham, J.A. and L.D. Carpenter (1975)
Monitoring of two braced excavations in Chicago.
American Society for Testing and Materials. Symposium on Performance
Monitoring for Geotechnical Construction, Wash., D.C. 1974.
ASTM Special technical publication, 584, pp. 20-31.

4. Eide, O. and S. Holmberg (1972)
Test fills to failure on the soft Bangkok clay.
American Society of Civil Engineers. Specialty Conference on Performance
of Earth and Earth-Supported Structures. Purdue Univ., Lafayette, Ind.
1972. Proceedings, Vol. 1, Pt. 1, pp. 159-180.
Also publ. in: Norwegian Geotechnical Institute. Publication, 95, 1973.

5. McKenna, J.M. and M. Roy (1974)
Performance of the instrumentation used to monitor the M5 motorway
embankments built on soft ground between Edithmead and Huntworth.
Field Instrumentation in Geotechnical Engineering; Symposium org. by the
British Geotechnical Society 1973. London, Butterworths, pp. 275-286.

6. Ladd, C.C. (1972)
Test embankment on sensitive clay.
American Society of Civil Engineers. Specialty Conference on Performance
of Earth and Earth-Supported Structures. Purdue Univ., Lafayette, Ind.
1972. Proceedings, Vol. 1, Pt. 1, pp. 101-128.

7. Rebull, P.M. (1972)
Earth responses in soft ground tunnelling.
American Society of Civil Engineers. Specialty Conference on Performance
of Earth and Earth-Supported Structures. Purdue Univ., Lafayette, Ind.
1972. Proceedings, Vol. 1, Pt. 2, pp. 1517-1535.

8. Müller-Salzburg, L. and G. Spaun (1977)
Soft ground tunnelling under buildings in Germany.
International Conference on Soil Mechanics and Foundation Engineering,9.
Tokyo 1977. Proceedings, Vol. 1, pp. 663-668.

9. Peck, R.B. (1969)
Deep excavations and tunneling in soft ground; state-of-the-art report.
International Conference on Soil Mechanics and Foundation Engineering,7.
Mexico 1969. State of the art volume, pp. 225-290.

10. Blondeau, F. and D. Queyroi (1976)
Rupture d'une fouille experimentale dans les alluvions recentes fortement plastiques.
European Conference on Soil Mechanics and Foundation Engineering, 6.
Wien 1976. Proceedings, Vol. 1.1, pp. 4-14.

11. Wilson, S.D. and D.E. Hilts (1972)
Instrumentation applied to slope stability problems.
American Society of Civil Engineers. Proceedings, Vol. 98, No. TE 3,
pp. 563-576.

12. Tice, J.A. and C.E. Sams (1974)
Experiences with landslide instrumentation in the Southeast.
Transportation Research Record, No. 482, pp. 18-29.

13. Ostermayer, H. (1975)
Construction, carrying behaviour and creep characteristics of ground
anchors.
Conference on Diaphragm Walls and Anchorages. London 1974. Proceedings,
pp. 141-151.

14. Oosterbaan, M.D. and D.G. Gifford (1972)
A case study of the Bauer earth anchor.
American Society of Civil Engineers. Specialty Conference on Performance
of Earth and Earth-Supported Structures. Purdue Univ., Lafayette, Ind.
1972. Proceedings, Vol. 1, Pt. 2, pp. 1391-1401.

15. Fellenius, B.H. and T. Haagen (1968)
Pålkraftmätare. (Pile force gauge).
Väg- och vattenbyggaren, No. 12, pp. 781-782.
Also publ. in: Ingeniörsvetenskapsakademien, Stockholm. Pålkommissionen. Särtryck och preliminära rapporter, 13.

16. Johannessen, I.J. and L. Bjerrum (1965)
Measurement of the compression of a steel pile to rock due to settlement in the surrounding clay.
International Conference on Soil Mechanics and Foundation Engineering,6. Montreal 1965. Proceedings, Vol. 2, pp. 261-264.
Also publ. in: Norwegian Geotechnical Institute. Publication, 65.

17. Frischmann, W.W. and W.G.K. Fleming (1962)
The use and behaviour of large diameter piles in London clay.
Civil Engineering and Public Works Review, Vol. 57, No. 676, pp. 1449, 1451.

18. Whitaker, T. (1963)
Load cells for measuring the base loads in bored piles and cylindrical foundations.
Building Research Station, Garston. Current papers. Engineering series, 11. 9p.

19. Paquet, J. (1969)
Controle des pieux par carottage sonique.
Institut technique du batiment et des travaux publics, Paris. Annales, Vol. 22, No. 262, pp. 1486-1501.

20. DiBiagio, E. and F. Myrvoll (1972)
Full scale field tests of a slurry trench excavation in soft clay.
European Conference on Soil Mechanics and Foundation Engineering, 5. Madrid 1972. Proceedings, Vol. 1, pp. 461-471.
Also publ. in: Norwegian Geotechnical Institute. Publication, 91.

21. Uff, J.F. (1970)
In situ measurements of earth pressure for a quay wall at Seaforth, Liverpool.
Conference on In Situ Investigations in Soils and Rocks. London 1969. Proceedings, pp. 229-239. Publ. by British Geotechnical Society.