- What was the durability of the instrument in the installed environment?
- Did the instrument do the job intended and, if not, why not?
- What were the lessons learned from the instrumentation experience?

This Symposium, then, attempts to address reliability on the basis of the experience of others. Topic reporters gathered information on reliability in the following categories of instrumentation:

- Pore pressure,
- Earth pressure,
- Load and strain in structures, and
- Deformation.

The first three categories are reported at this Symposium. Case histories include all categories. As will be seen from the papers, each reporter's approach to characterizing reliability was somewhat different. This reflects real human considerations and the diverse nature of the topic.

This Symposium is to be a focal point for exchanging information, learning, and improving future work. It is expected that future sessions can be held that will encompass deformation measurements and other geotechnical instrumentation experience. It is hoped that future presentations will report on experiences with well-planned and executed instrumentation programs with well-defined and realistic objectives of reliability.

Reliability of Pore Pressure Measurement

VERNE C. McGUFFEY

ABSTRACT

The importance of reliable pore pressure measurements and their influence on design and construction are discussed. Methods of obtaining high-quality data are related to five major items: (a) system design, (b) instrument design, (c) installation details, (d) operator knowledge, and (e) engineering interpretation methodology. Suggestions for addressing these factors are given. It is concluded that attention to detail in all phases by a responsible engineer is necessary to obtain reliable data.

Engineers have been attempting to determine the state of stress in soil by measuring excess pore water pressure for many years. The results reportedly ranged from good to unacceptable. In an effort to improve results, sophisticated electronic instruments have been developed that measure pressures as small as 1/100 psi. Results have not improved (1).

Improved reliability must, therefore, address two variables: (a) the instrument performing properly and (b) the soil system performing as predicted.

The major items that contribute to successful (or reliable) pore pressure measurements are

- System design,
- Instrument design,
- Installation details,
- Operator knowledge, and
- Engineering interpretation methodology.

Reliable pore pressure measurements can only be obtained by planning equally for all of these factors.

IMPORTANCE OF RELIABILITY

Pore pressure measurements are taken to allow the engineer to accurately predict the state of stress in the soil and to make appropriate engineering decisions. Reliable pore pressure measurements allow the engineer to use specialized cost-saving construction procedures with little risk. Undetected undependable measurements may lead the engineer into taking risks the results of which are costly or disastrous, or both.

The engineer must have a means of evaluating the reliability of all parts of the decision-making system. Some ways of ensuring reliable data for decision making are discussed in this paper.

SYSTEM DESIGN

A high-quality design must be done to allow determination of the type of instrument, location of instrument, frequency of readings, and other key features needed to ensure success of the system.

Design factors that need further discussion are

- Soil profile,
- Geotechnical model chosen for analyses,
- Vertical and horizontal soil parameters,
- Expected loading, and
- Groundwater.

Soil Profile

A pore pressure measuring device in the center of the layer under the center of the loading can be expected to read the maximum pore pressure. However, if the pore pressure measuring device is near a boundary of the compressible layer, the pore pressure will be greatly reduced. In many cases instruments reflect the pore pressures of the free draining adjacent layer because of local variations. A detailed knowledge of the horizontal and vertical variability of the soil profile is, therefore, an essential part of the design of a reliable instrumentation system.

Geotechnical Model

Choosing a suitable geotechnical model for the construction plan is necessary in order to design a reliable instrumentation package. The geotechnical model for sand drains is a relatively straightforward and accepted model. Numerous investigators have installed pore pressure measuring devices near the center of a group of sand drains and have recorded pore pressures that were extremely close to those predicted by the mathematical models for sand drain design (poor construction control of deep drains or piezometers can lead to poor response).

However, the model that is normally used for a simple embankment or abutment loading is not as well understood. The system is highly dependent on the vertical and horizontal drainage boundary conditions at the site. Normal practice is to design for vertical drainage only. This model is unacceptable for most real-life field conditions. All strip-loading situations have a major component of lateral drainage. LaCasse et al. (2) have developed a usable model for including lateral drainage in the normal design process. The New York State approximate method (3) can also be used with reasonable results.

Vertical and Horizontal Soil Parameters

The vertical coefficient of consolidation (c_v) can usually be obtained with a reasonable degree of accuracy by high-quality sampling and laboratory consolidation testing.

The horizontal coefficient of consolidation (c_h) is more difficult to obtain. Earlier work used undisturbed samples with consolidation tests taken across the sample instead of taken vertically. These tests gave reasonable results for the horizontal coefficient of consolidation when c_h was close to the value of c_v and the soil was relatively uniform. However, this approach did not work well on layered systems. A great deal of work was done by various investigators trying to use field percolation tests as a tool for predicting horizontal drainage rates. The reported results were erratic.

Some recent work done in New York State has made use of the "block permeability test" that allows permeability testing to be done in both vertical and horizontal directions on the same sample. This test produces a reliable value of the ratio of horizontal to vertical permeability for the sample. This can then be correlated, through moisture content and plasticity index tests, with the rest of the soil system being studied to arrive at a representative value of the ratio of horizontal to vertical permeability for the design.

New York State experience indicates that the ratio of horizontal to vertical permeability from backfigured field tests (a) has never been less than 1, (b) is usually more than 2, and (c) often will be in the range of 10 or more in even slightly layered systems. Because of the potential for changes within the boundary conditions in nature, it is recommended that a value of c_h over c_v greater than 20 not be used. A ratio greater than this will usually not change the design concepts, but it can give large errors in performance if conditions vary.

Horizontal and vertical coefficients of consolidation in the recompression ranges are appreciably different than those in the normally consolidated ranges. It is common to find the vertical coefficient of consolidation in a precompressed material to be 8 to 10 times the coefficient of consolidation in a normal consolidated soil even though the permeability is less.

A zone of high precompression above normally consolidated soil will not allow free vertical drainage upward because of the low permeability.

Expected Loading

The design must also consider the variation of load expected. The magnitude and shape of expected loading should be reasonably well obtained from the design of the facility being constructed. However, the type of material used for embankment construction has a variability from approximately 100 lb per cubic foot (for certain rock) to 150 lb per cubic foot (for extremely densely compacted long graded soils). Many embankment materials will be placed during a relatively dry period of the year. When heavy rains occur, there is a dramatic increase in loading as a result of the weight of water taken into the soil pores. The loadings predicted for a bridge or other structure are usually not accurately identified for the geotechnical engineer. He is usually supplied with the maximum loading, which does not occur during the construction period; he is rarely, if ever, given the loadings to be expected during construction, when pore pressures are critical.

Pile driving creates a relatively large temporary pore pressure. This pore pressure may exceed 20 psi while a group of piles is being driven. Pore pressures from pile driving have been measured 100 ft or more from the pile-driving area. Their temporary pore pressure dissipates laterally quite rapidly. An approximation to estimate lateral pore pressure dissipation from pile driving follows:

1. Assume a value of 10 psi at a distance of 20 ft from the center of the pile group and
2. Assume total dissipation at a distance of 200 ft.

The contractor's method of operation will influence pore pressure measurements. Although construction procedures cannot be predetermined, some conditions should be considered when designing an instrumentation system. Examples are temporary detours, haul roads, and structure construction. Some temporary loadings can be anticipated on the basis of good knowledge of construction practices and can be designed into the system or controlled during construction by notes in the contract. Most can only be identified during construction, however, and the designer must be prepared to reevaluate the pore pressure measuring system and his interpretation of its reliability on the basis of actual construction procedures.

Groundwater

Normal fluctuations of the groundwater system can give erroneous indications of pore pressure changes.

Most sites adjacent to water crossings have a sand cover over the compressible soil systems. This sand cover allows a relatively rapid change in the groundwater as a result of rainfall or changes in an adjacent stream, lake, or ocean. Contractors' operations--such as local dewatering for sewers, construction of temporary drainage ditches, and construction of temporary retention ponds--influence the local groundwater regimen and cause erratic readings on pore pressure measuring devices. Most of these variations can be identified and their effects eliminated by including, as part of the design of the pore pressure measuring system, a series of surface observation wells to specifically measure local variation in the groundwater table.

The five factors discussed in this section must be addressed during design or corrected for in construction to obtain high-quality pore pressure data.

INSTRUMENT DESIGN

Different instrument designs are discussed thoroughly in the NCHRP synthesis on geotechnical instrumentation (4) and, therefore, will not be discussed here except as they affect the reliability of the instrumentation system.

Many instruments presently used have characteristics that may influence their ability to give correct responses for a specific design. It is generally better to use existing instruments with known different capabilities to accommodate unusual circumstances than to design a special instrument.

Open-well-type piezometers have a good long-term record of performance, but they usually provide too slow response for low permeability soils. Pneumatic cells have demonstrated good reliability and rapid response; however, they do not have the ability to measure dynamic pore pressures. For continuous records of dynamic response an electronic pore pressure cell or a closed-system hydraulic cell may be better.

Each piezometer has its own characteristics and must be matched to the needs of the site being designed.

INSTALLATION

The effects of installation practices on the reliability of pore pressure instrumentation systems are discussed in the NCHRP synthesis on geotechnical instrumentation (4) and in AASHTO specifications (5). Some installation practices that have a direct relationship to the reliability of instrument systems will be discussed here.

One of the easiest items to check during installation is the responsiveness and accuracy of the cell as it is being installed. Pneumatic and electronic cells can be measured in the laboratory before installation and can also be checked when lowered into the installation hole by measuring the height of water above the cell and recording instrument response at different levels.

For closed-system hydraulic piezometers, it is best practice to completely fill all tubing with deaired water before installing the system in the ground. If all connections are then made quickly underwater, the system will usually respond for many years without problems.

Initial readings should be taken immediately after installation and periodically for approximately 1 week or until the pore pressure recorded reflects the groundwater system variations.

The method of installing a cell in the ground often affects the reliability of the cell during its useful life. Installing the cell beyond the tip of a steel casing and leaving the casing in the ground have resulted in many failures because when the protective casing settles it cuts the protruding measuring tubes (conversations with Vermont DOT). This can be avoided by installing the cell in the end of the casing.

Piezometer cells installed in cement grout have had similar types of problems with crimping or pinching of the tubing as a result of the movements of the soft compressible soils around the relatively rigid column of grout. Although a bentonite and sand mixture is difficult to install, it has worked for many years, even in areas of extremely large foundation settlements. On one project, however, it took nearly 2 weeks after installation before the bentonite expanded sufficiently to obtain a good seal.

Installation of leads to the readout location has resulted in numerous system failures. If the trench is too wide or not deep enough, construction traffic may damage or destroy the lines. Lines that cross each other in the trench have been crimped, making them inoperable. Leaving the lines exposed in the trench without backfilling after completion of the connections can result in damage; deterioration of tubing from ultraviolet exposure and large volume change and creation of air pockets in fluid-filled lines are examples. Immediate covering with a 6-in. bedding layer of sand is good practice.

It is essential that the installation inspector be thoroughly familiar with the type of operation he is carrying out. If there is any doubt, hire special trained help.

OPERATOR KNOWLEDGE AND ABILITY

It is New York State experience that the person responsible for reading the geotechnical instrumentation is usually the lowest paid, least experienced inspector on the project. Certain types of instruments are less susceptible to operator error and damage during the life of the project and their use should, therefore, be considered when the knowledge of operators is poor.

It is best practice to educate the operator about the purposes and characteristics of the pore pressure measuring system. It is essential that the operator know how the system operates and what to look for so that he can give early warning of potential problems. Instruction on how to check for the charge in the batteries on electronic systems; how to recharge gas systems; and how to properly store and handle equipment in dusty, hot, or freezing conditions is needed. The operator must also be aware of what to do about changing temperatures and other changes in the vicinity of the readout equipment.

Part of the education of the operator includes setting up a good line of communications between the operator and the engineer responsible for interpreting the data. This can be handled by visits, telephone or written communications, or other similar procedures. One effective way to ensure adequate communication is to periodically visit the inspector to discuss progress and agree on what to do at important times in the construction.

ENGINEERING INTERPRETATION METHODOLOGY

The method used to interpret the pore pressure and to estimate the changes within the soil system influences the interpretation of reliability. To determine what is happening within the soil and determine whether the instruments are recording properly, the following steps are helpful:

1. Obtain complete and accurate information about the construction site including elevation of

fill, adjacent loadings, change in water surface, change in river levels, and other appropriate information.

2. Obtain data immediately after readings are taken and compare the data with changes in fill height and groundwater and expected dissipation rate.

3. Investigate in detail any readings that do not respond in the direction and approximate magnitude estimated by the prediction model chosen in design. If the data obtained do not conform accurately with the prediction model, the reading is wrong or the model is wrong. Check the instrument first and then investigate alternative prediction models.

4. Plan specific check points during the project life to reassess the design model; including stages of construction with waiting periods helps. Look for activities that will cause pore pressure changes (such as structure excavation) and check responses carefully.

5. Normal accuracy of field data needs special consideration at this stage. Field survey of plus or minus two hundredths of a foot (and on ground or fill, plus or minus 1 ft) is normal. Variations of up to 30 percent in the weight of the fill can occur, but, if the weight is different at one fill location, it should be the same at all locations of similar fill.

6. Always check the final zero reading. Unfortunately, the excess pore pressure seldom returns to the "before construction" reading. This is a result of the changes that have taken place during construction. The pore pressure measuring point may have settled to a level further below the groundwater table than it was before the construction started causing a higher reading. The groundwater table may have changed as a result of the construction. When these changes are accounted for, the pore pressure reading should return to zero within the predicted time if the design and instruments are correct.

7. Check the prediction model. The geotechnical model chosen may not be the correct one. If there is not close agreement, construct a revised model using new pore pressure data as a basis for constructing the new model. If the new model is correct, it will show consistent responses through all construction activities. Changes in boundary drainage conditions, such as one-way to two-way drainage, sometimes occur in construction. If there is insufficient instrumentation to verify the change in the model, additional devices must be installed to verify the model and make correct engineering decisions.

CONCLUSIONS

The primary reason for determining the reliability of pore pressure measurement systems is to tell the engineer if the information is sufficient to make correct construction decisions. If the pore pressures are too high, a major failure may occur, destroying the structure being built. If the pore pressures are dissipating too rapidly, the engineer is wasting money on foundation treatment that is not needed. The engineer must be prepared to make decisions during construction in order to economically build the facility and to reduce the risk of a major, disastrous failure.

As can be seen from this discussion, any number of small details of design, installation, or interpretation can adversely affect the reliability of the instrumentation package. Therefore, the engineer must design checks and "memory joggers" into the process so that problems can be corrected immediately. The key to a reliable pore pressure measuring system is a qualified engineer who is responsible for all phases.

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