GEOTECHNICAL ENGINEERING

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Summary

This chapter is intended to introduce the major areas of concern in the geotechnical engineering. The methods commonly adopted in soil investigations in the field are first
introduced. These include velocity loggings and sounding techniques which are used to unearth soil profiles at a site in question. Design of foundations of structures is one of the major areas of concern. The principle and methodologies normally used in the design are described with emphasis on piles. Stability of open cuts is another problem of prime importance and the current state-of-the-art is introduced regarding the characteristics of ground movement induced by the open cuts. The ground improvement has constituted a major area in geotechnics. The main techniques being used to stabilize sandy and clayey soil deposits are introduced. Recent development in the technique of solidification of the ground is also described. This is a new subject area in association with underground work in difficult conditions. Lastly, the ground movement induced by shield tunneling through soft soil deposits is described which is an area of concern with respect to urban development. There are many other subject areas such as subgrade engineering and environmental geotechnology, but these items are not described in this report.

1. Introduction

The subject areas traditionally encompassed by geotechnical engineering are summarized in Table 1. Foundations of structures, excavations and tunnels, embankment dams, and subgrades of railways and highways are major areas of profession in which geotechnical engineers play a key role in fulfilling ultimate missions including rational grand planning, cost-effective design, and safe execution of construction work. To maintain integrity of the completed facilities and infrastructures, it is mandatory to have competent soil deposits or rock formation supporting these structures. Any kind of engineering knowledge and skills such as soil improvement and ground reinforcement associated with these operations also constitute the main area of the discipline in geotechnical engineering.

Problems related with protection and improvements of the environment have been recently recognized as a new subject area in which geotechnical engineers could play a key role. Design and construction of landfills and tailing dams are issues of concern in relation to the process of environmental control. Land contamination by hazardous liquids and measures for their containment constitute an important subject area to be tackled by geotechnical engineering.

Natural hazards such as earthquakes, floods and landslides have taken lives and destroyed properties of human beings over many years. The occurrence of these phenomena is not new, but because of proliferation of human activities, chances for people being exposed to these hazards have increased drastically in the recent times, particularly in urban areas. To cope and coexist with these natural hazards, the nature of the phenomena needs to be understood and interpreted properly from geotechnical perspectives to come up with some counter measures of practical significance in order to mitigate possible calamities.

The current state of affairs in these fields of expertise will be introduced briefly in the following. Recent developments in research and practice have been so extensive and formidable that it is beyond the ability of the writer to conduct all embracing overview of the current state-of-the-art. Thus, the following is merely a birds-eye view of several subject areas of major concern in the general framework of geotechnical engineering.
Table 1: Scope of Geotechnical Engineering

2. Subsurface Investigation for Site Characterization

To execute any plan of construction, it is always necessary, first of all, to know the conditions of the ground consisting of soils and rocks. There are several stages of investigating subsurface conditions as to what kinds of earth materials there are and how competent these are in the light of safe performance of structures after they are installed. It is widely known that, for soils, the crucial factor governing their behavior is the magnitude of shear strain to which they are subjected in the working conditions in the field. Shown in Figure 1 is a list of various testing procedures classified in this vein and also in accordance with whether they are in situ tests or laboratory tests.

![Classification of Methods of Measurement of Soil Deformation Characteristics](image_url)

Figure 1: Classification of Methods of Measurement of Soil Deformation Characteristics according to the Level of Strain Involved
In the range of small strains, several test methods based on wave propagation such as the downhole test, crosshole test and Spectral Analysis of Surface Waves (SASW) are employed to investigate the shear modulus of in situ soil deposits. In the laboratory, the techniques based on wave propagation such as resonant column test and bender element test are used to estimate the shear modulus of undisturbed samples recovered from field deposits. The precise measurement of the modulus at small strains can be made under static loading conditions as well by means of what is called Linear Differential Transformer (LDT) for undisturbed samples placed in the triaxial chamber.

The above methods in the laboratory are considered to yield fairly accurate values of shear modulus, if the samples are of high quality without being significantly disturbed. Thus, it can be mentioned that good correlation can be established directly between soil property data obtained in the laboratory and in the field, if due care is taken in handling high-quality samples. This fact is indicated in a two dimensional illustration shown in Figure 2.

![Figure 2: Correlations between In situ and Laboratory - Determined Deformation Characteristics of Soils as Governed by the Level of Strains](image)

In the range of large strains involving failure, what might be called the element tests such as triaxial and torsional tests can be performed in the laboratory on undisturbed samples to determine deformation and strength characteristics of in situ soils to a desired level of accuracy. On the other hand, it is generally difficult to conduct an element-like test in the field where uniform stress or strain is to be imposed on the soils in situ. Therefore, the in situ tests such as pressiometer test, plate-loading test and dilatometer test are performed to identify properties of soils as they exist naturally in the field. However, non-uniformity of stress or strain distribution makes it somewhat difficult to interpret the test results from the viewpoint of identifying basic soil parameters. In addition, these in situ tests are generally expensive. Thus, various kinds of sounding techniques such as the standard penetration test (SPT), cone penetration test (CPT) and vane test have been commonly used instead in routine practice. Since the soils are deformed largely during any penetration tests, these tests appear to reflect implicitly the deformation properties of soils undergoing large strains including failure.
In an important project to be implemented in the area of soft soil deposits, more detailed information is required. Recovery of intact soil samples can be sometimes executed by means of some sophisticated techniques. Undisturbed samples are tested in the laboratory to identify physical and mechanical characteristics of these soils, but a more detailed description of these techniques is beyond the scope of this chapter. In what follows, an overview will be given regarding some of the most frequently used in situ sounding tests such as SPT and CPT and also on the techniques of in situ velocity logging.

2.1. Standard Penetration Test (SPT)

One of the most frequently used procedures for monitoring the resistance of soil deposits to penetration is the standard penetration test. The arrangements of this test in the field are shown in Figure 3. The test equipment is composed of a vertical rod equipped with a sampling tube at the end. When performing the test, the rod is lowered to the bottom of a bored hole and a hammer weighing 0.622KN ≅ 63.5 kgf is dropped 75 cm along the rod until it hits a stopper attached to the rod. The energy due to the free-falling hammer is transmitted to the sampling tube which is forced to penetrate into the soil deposit beneath the bottom of the hole. The hammer dropping is repeated and the number of droppings required for the sampling tube to penetrate 30 cm is recorded. This blow count number is termed N-value in SPT. The N-value thus obtained has been widely used to assess engineering properties of in situ soils.

In the SPT the sampling tube consists of a thin-wall steel tube that can be split into two half-cylinders which are fastened together when driven into the soil deposit by the hammer dropping. The intact soil is forced to intrude into the split sampling tube from its open end during the penetration. After lifting the sampling tube on the ground, the split
tube is opened and intact soil samples can be recovered. The samples thus obtained are used for visual inspection, physical property testing in the laboratory and for soil classification based on grain composition, plasticity index and so forth. Because the sample is subjected to some degree of disturbance, it is not considered suited to determine the deformation characteristics such as stiffness and strength, but it provides several useful pieces of information on the kind and nature of in situ soil deposits. An example of a soil profile unearthed by the SPT is shown in Figure 4.

![Figure 4: An example of Soil Profile](image)

The advantage of using the SPT would be, first of all, the availability of actual soil samples for visual observation and testing in the laboratory, and secondly the blow count N-value which is indicative of the stiffness and strength characteristics of in situ soils. Thirdly, the SPT is versatile and robust enough to perform and accommodate a wide range of soil types from soft clay to gravelly soils.

The SPT is a kind of dynamic penetration test consisting of several steps in operation and hence tends inherently to create some inconsistency in the test results due to differences in machines and skill of operators. For example, the amount of energy transmitted to the sampling tube is known to vary depending upon the mechanism as to how the hammer is released for dropping, the size of the stopper and so forth. Therefore many efforts have been made to identify influencing factors and to make corrections for obtaining consistent data which are comparable among numerous SPT N-values obtained at different parts of
the world. For example, the SPT practice in U.S.A. has been identified to impart energy of about 60% of that in free fall of the weight and therefore the blow count in the U.S.A. has been denoted by $N_{60}$. In Japan the energy ratio transmitted is generally known to range between 70 and 80%.

For sandy deposits the SPT N-value is generally used to estimate the relative density $D_r$ which is known to increase with increasing resistance to liquefaction during earthquakes. Not only with the density, but the N-value is known to increase also with the effective overburden pressure $\sigma'_v$ at the depth of deposits in question. Thus, the correction is generally made to assess the relatively density by eliminating the effect of the effective overburden pressure. An empirical relation as follows may be used to estimate the relative density of sand deposits from measured N-values.

$$\frac{N}{\sigma'_v} = C_D \cdot D_r^2 \sqrt{98}, \quad (1)$$

where $\sigma'_v$ is in kPa, and $C_D$ is a constant taking values between 20 and 30 for sands. By putting $\sigma'_v = 98$ kPa in Eq. (1), $N_1$-value corresponding to $\sigma'_v = 1$ kgf/cm$^2 \approx 98$ kPa is obtained as

$$N_1 = C_D \cdot D_r^2. \quad (2)$$

It is to be noted that the $N_1$-value normalized as above is indicative of the relative density alone irrespective of the overburden pressure. The value of $C_D = N_1 / D_r^2$ defined by Eq. (2) is known to vary depending upon the grain composition of the granular materials. The outcome of compilation of many data on $C_D$ is demonstrated in Figure 5 in terms of plots against the mean grain size $D_{50}$.

![Figure 5: $N_1 / D_r^2$-Values Versus Mean Grain Size of Cohesionless Soils](image-url)
2.2. Cone Penetration Test (CPT)

The cone penetration test has received wide publicity in recent years as a useful means to identify soil properties under intact conditions in the field. An apparatus developed by Begemann (1965) in its early period of development is shown in Figure 6, where the cone device consists of the end cone and adhesion jacket. Using this device, the local skin friction could be measured in addition to the end cone resistance. The cone device as above is pushed down by the force that is applied and measured on the ground surface and thus called “Mechanical cone” as against the electrical cone as described below. Various types of the mechanical cone penetrometers are now in use widely because of their low-cost, simplicity and robustness.

Electrical cone penetrometers have also received wide publicity in recent years, because of easiness in handling and consistency in obtaining reliable test data irrespective of possible variation in skill of operators. One of the typical models is shown in Figure 7 where measurements of the cone resistance and sleeve friction can be made by independently operated load cells. The penetration of the electric cone is also performed at a constant speed automatically. Sometimes, pore water pressure could be measured during the penetration, enabling more exact identification of soil types to be made for layered structures of in situ deposits of soils. The device equipped with the probe for pore pressure monitoring is called “Piezocone”.

In the operation of the CPT, the cone tip at the end of the rod is pushed into the soil deposit at a constant rate and measurements are made continuously or intermittently of the resistance against penetration of the cone. Measurements of frictional resistance of the surface of a sleeve are also made individually or in combination with the cone resistance. The total force acting on the cone divided by the cross sectional area is called “Cone resistance” and denoted by $c_q$ and it is commonly used as a parameter to quantify the cone resistance. The total force acting on the friction sleeve divided by the surface area of the sleeve is called “Sleeve friction” or “Skin friction”, and denoted by $s_f$.

One of the disadvantages of the CPT is that it is not possible to recover actual soil samples from in situ soil deposits. Therefore, some indirect methods should be utilized instead to identify soil types in each layer of the deposits. It has been known that for sandy soils, the major component of resistance to penetration is the cone resistance $c_q$, whereas the skin friction $s_f$ constitutes the major part of resistance in the case of cohesive soils. So, the percentage of the cone resistance tends to increase with increasing proportion of cohesionless materials included in actual soils. Shown in Figure 8 is the $q_c$-value for various materials with different proportion of fines content of cohesionless soils plotted versus the skin friction $s_f$. It is obvious that the value of $q_c$ trends to increase with increase in the skin friction $s_f$, but the rate of increase in $q_c$ is known to rise from clayey to sandy soils, with increasing percentage of cohesionless materials contained in the soils. Thus, if a chart were provided plotting $q_c$ versus what is called friction ratio, $F_T$, defined by $F_T = q_c / s_f$, it would be possible to distinguish various zones which are associated with different soil types ranging from sandy to clayed soils. One of such charts proposed
by Douglas and Olsen (1981) is demonstrated in Figure 9. If a set of measured $q_c$ and $F_r$ values is plotted in the upper left part of the chart, the soil is classified as sandy. If a data point falls in the lower right portion, the soil is identified as clayey. More detailed classification chart was proposed by Robertson (1990).

The advantage of using the CPT is the fact, first of all, that it is speedy and easy to execute and robust. Secondly, it permits coherent data to be obtained being less influenced by the skill of the operator, and thirdly, data processing can be automated without difficulty, if the electrical cone is used. The shortcoming of the CPT is that it becomes impossible to penetrate to a target depth if the CPT encounters stones or gravels during its penetration.

Figure 6: Begemann Type Cone with Friction Sleeve
Figure 7: Electrical Cone

Figure 8: Soil Classification from Cone Resistance and Sleeve Friction Readings (Begemann, 1965)
Figure 9: Simplified Soil Classification Chart for Standard Electric Friction Cone (Douglas and Olsen, 1981)

Bibliography

Aboshi, H., Mizuno, Y. and Kuwabara, M. (1990). Present State of Sand Compaction in Japan, ASTM STP 1089, pp.32-46. [The methods of installing compacted columns of sand for stabilizing loose sand deposits are described along with their advantages and disadvantages of usage. Focus is put on the techniques developed recently in Japan.]

Attewell, P.B., Yeates, J and Selby, A.R. (1986). Soil Movements Induced by Tunneling and their Effects on Pipelines and Structures, Blackie, Glasgow. [The ground displacement accompanied by tunneling and its effects on existing structures and foundations is described. Basic concepts and results of observations are included.]
Begemann, H.K.S. (1965). The Friction Jacket Cone as an Aid in Determining the Soil Profile, Proc. 6th International Conference on Soil Mechanics and Foundation Engineering, Montreal, Vol. 1, pp. 17-20. [As an in situ technique for identifying soil profile and stiffness of soils, cone penetration is used. The cone technique in which point resistance can be monitored separately from the skin friction is described.]


Clough, G.W. and Schmit, B. (1981). Design and Performance of Excavations and Tunnels in Soft Clay, Soft Clay Engineering, pp. 569-634, Elsevier. [In the design of tunnels in soft clay deposits, bracing is to be considered to prevent failing of the excavated surface. The design of bracing and its performance is designed in this section.]


Douglas, B.J. and Olson, R.S. (1981). Soil Classification Using Electric Cone Penetrometer, Symposium on Cone Penetration Testing and Experience, Geotechnical Division, American Society of Civil Engineers, St. Louis, pp. 209-227. [Electrical cone widely in use now for sounding for in situ soil conditions is introduced as an effective and versatile means to investigate the soil profile. Chart for identifying soil types based on the cone resistance and skin friction is presented for use in practice.]

Fang, Y.S., Lin, J.S. and Su, C.S. (1994). An Estimation of Ground Settlement due to Shield Tunneling by the Peck-Fujita Method, Canadian Geotechnical Journal, Vol. 31, pp. 431-443. [Shield tunneling tends to induce a varying degree of ground settlements depending upon the method of construction. The paper summarized the currently available actual data observed in situ in the course of advancement of shield machine. The bowl-shaped distribution of the settlements across the tunnel axis is shown to be a characteristic feature of the sag.]


Fujita, K. (1989), Special Lecture B: Underground Construction, Tunnel, Underground Transportation, 12th International Conference on Soil Mechanics and Foundation Engineering. Rio de Janeiro, Vol. 4, pp. 2159-2176. [Comprehensive report is presented as to the state of the art on the underground construction. Historical reviews are made over the development of basic concepts, methods of construction and outcome of field observation. Useful charts are provided based mainly on Japanese experiences to be utilized for the design purposes.]

Fujita, K. (1994). Soft Ground Tunneling and Buried Structures, 13th International Conference on Soil Mechanics and Foundation Engineering, New Delhi, Vol. 4, pp. 89-108. [The state of the art report is provided concerning the tunneling in soft clays and buried structures most based on the construction experiences in Japan. Observed data are summarized and arranged in ways that can be used for the design.]

Hansbo, S. (1993). Band Drains, Chapter 3, Ground Improvement, M.P. Moseley, pp. 40-64, Blackie Academic & Professional. [Methods of improving soft clay deposits by inserting band-shaped fibers or geotextile into the ground are described in some detail. Methods of installation and its effectiveness are presented with several examples.]

Holz, R.D., Christopher, B.R., and Berg, R.B. (1997). Geotechnical Engineering, BiTech Publishers, Vancouver. [Techniques for improving soft clay deposits by means of the vertical band drain are described. Some charts and formulae are presented to facilitate the design of the drain system.]

Kulhawy, F.K. and Phoon, K.K. (1993). Drilled Shaft Side Resistance in Clay Soil to Rock, Des. & Perf. of Deep Foundations, ASCE, Special Publication 38, pp. 172-183. [The resistance of piles mobilized by the side surface depends largely on how the piles have been installed. In the case of the piles placed in the drilled holes, the skin resistance is known to be smaller than that mobilized when the piles were forcibly driven into the soil. The paper discusses this issue based on many data obtained in situ.]


O’Neil, M.W. (2001). Side Resistance in Piles and Drilled Shafts, 34th Terzaghi Lecture, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, No.1, pp. 1-16. [Accurate evaluation of the side resistance of piles has always been a challenge for the designs of foundation piles. A number of cases of field measurements are collected together with the data from model tests and strictly controlled field tests. The author summarized his experiences and proposed several charts or empirical formulae to be used in the design of piles.]

O’Reilly, M.P. and New, B.M. (1982). Settlement above Tunnels in the United Kingdom - Their Magnitude and Prediction, Tunneling 82, London, IMM, pp.173-181. [Measurements of ground settlements due to tunneling were made at a number of locations in UK and the paper summarize the outcome of these measurements.]


Robertson, P.K. (1990). Soil Classification Using the Cone Penetration Test, Canadian Geotechnical Journal, Vol. 27, No. 1, pp.151-158. [Cone penetration tests provide two kinds of in situ soil data, i.e., the point resistance and skin friction. The ratio of these two quantities and point resistance are used for the purpose of identifying soil types at a given depth. The paper proposes a revised chart for soil type identification reflecting upon new test data.]

Rowe, R.K. (2001). Geotechnical and Geoenvironmental Engineering Handbook, Kluwer Academic Publisher, Norwell, USA. [Overview of the recent issues of concern in the expertise of geotechnical and geoenvironmental engineering. Basic concepts, supporting data and the design methodologies are described in compact manner.]


Slocombe, B.C. (1993). Dynamic Compaction, Chapter 2, Ground Improvement, M.P. Moseley, pp. 20-39, Blackie Academic & Professional. [Dynamic compaction consists of dropping a heavy concrete-made block about 1-5ton in weight from a height of 5-15m. Weight dropping is conducted at a spacing of 10-15m.
This operation has been used to improve loose sands, soft clays and garbage deposits. The paper describes current state of practice in this technique.


Terzaghi, K. and Peck, R.B. (1986). Soil Mechanics in Engineering Practice, John Wiley & Sons, Inc. [The classic textbook on geotechnical engineering which has been used over the decades. The book describes basic concepts and their application to practice of soil engineering.]


Biographical Sketch

Kenji Ishihara had served as a professor of soil mechanics and geotechnical engineering at the University of Tokyo from 1977 to 1995 and then became a professor of civil engineering at the Science University of Tokyo from 1995 on to 2001. He now teaches soil mechanics and foundation engineering at Chuo University in Tokyo, Japan. He served as President of the International Society for Soil Mechanics and Geotechnical Engineering for the term 1997-2001.