Influence of soil behaviour on structural design

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Influence of Soil Behaviour on Structural Design

Influence du comportement des sols sur le dimensionnement des structures

Einfluss des Bodenverhaltens auf die Bemessung von Bauwerken

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SUMMARY

Compared with structural materials, soils are highly complicated and variable, requiring more conscious efforts in evaluating their properties and in coordinating design and construction. Participation of a geotechnical engineer in the earliest stage of project planning is highly desirable.
Selected topics in new problems (environmental problems and offshore structures) and recent developments in geotechnical engineering are discussed briefly. Well-documented case histories are particularly valuable in geotechnical engineering, and their publication should be encouraged.

RESUME

Comparés avec les matériaux de construction, les sols sont de caractère beaucoup plus complexe et varié et exigent bien plus d'efforts pour évaluer leurs caractéristiques et pour coordonner le projet et la construction. La participation d'un expert en géotechnique est très recommandée dès le premier stade du projet.
Différents problèmes nouveaux (problèmes d'environnement, constructions "off-shore") et quelques développements récents dans la géotechnique sont exposés brièvement. La publication d'expériences pratiques ("case-studies") bien documentées, est particulièrement précieuse pour le développement de la géotechnique appliquée, et de telles publications doivent donc être vivement encouragées.

ZUSAMMENFASSUNG

Verglichen mit den üblichen Baumaterialien sind die Baugrundeigenschaften weit komplexer und variabler und erfordern demzufolge einen grösseren Aufwand zur Abschätzung ihrer Eigenschaften sowie zur Abstimmung von Entwurf und Bemessung. Der Baugrundspezialist sollte deshalb schon in einer früheren Entwurfsphase beigezogen werden.
Es wird über ausgewählte neuere Fragestellungen berichtet (Umweltprobleme, "Off-shore"-Bauten), und es werden die neuesten Entwicklungen im Bereich der Geotechnik kurz dargestellt. Die Schilderung von Beispielen aus der Praxis anhand von gut dokumentierten Fallstudien ("case-studies") ist für die Entwicklung der Geotechnik äusserst wertvoll, und solche Publikationen sollten demzufolge gefördert werden.

1. INTRODUCTION

The writer was given the task of preparing an introductory report on the Influence of Soil Behavior on Structural Design that was to be subdivided into the following topics.

a) Collaboration between the structural engineer and the geotechnical engineer:
   —What does the structural engineer expect from the geotechnical engineer?
   —What does the geotechnical engineer expect from the structural engineer?
   —Ways for cleverer cooperation and mutual responsibilities
   —New procedures and design methods in geotechnical engineering

b) Case histories. Examples of soil-structure (and of geotechnical engineering-structural engineering) interaction in eminent structures all over the world (foundations, dams, etc.).

With ever increasing sophistication in analysis and design, and with a deluge of reports and papers, it is now next to impossible for an engineer to stay abreast with the latest developments in more than one specialty. This probably explains the reason why it is difficult for the structural engineer to understand what the geotechnical engineer is doing, and vice versa. Rather than trying to understand each other completely, we should therefore try to cooperate with the understanding that differences do exist. Let us review such differences in the following chapter.

2. SOILS VS STRUCTURES

The design process as described in Fig. 1 may be applicable to both geotechnical and structural engineering. But the underlined items are peculiar to geotechnical engineering or require more conscious efforts in geotechnical engineering, primarily because soils are much more complicated than steel and concrete.

Soils are usually nonhomogeneous and anisotropic, and exhibit nonlinear stress-strain relationship even at very small strains. The marked nonlinearity is due to the fact that soils consist of uncemented particles whose mechanical behavior is primarily governed by intergranular friction. With regard to saturated soil, interaction between soil skeleton and pore water, represented by the concept of effective stress, is a particularly important point that distinguishes soil from structural materials. Because of the presence of pore water, even a simple one-dimensional compression problem becomes a boundary value problem with time-dependent deformation called consolidation. The presence of pore water may also cause a catastrophic failure called liquefaction.

Besides having complicated material properties, soils are natural materials and their properties vary from place to place. This makes subsurface investigation essential in geotechnical engineering, and perhaps led Terzaghi to draw analogy between foundation engineering and medicine in which diagnosis is essential. Thus, soil mechanics and geology are comparable to physiology and pathology that must be mastered by those who practice either art. The Initial Observation in Fig. 1 consists of macroscopic grasp of the soil profile and groundwater conditions compatible with local geology and construction experience, and evaluation of relevant soil properties through tests.

Because of the complicated and variable properties of soil and our limited ability to evaluate them, the Model for Analysis in Fig. 1 may be considerably different from the Real Problem, and the Analytical Method may contain inaccuracies; therefore Correction is necessary when we apply the Result of Analysis to Design. The engineer who makes the correction must be thoroughly familiar

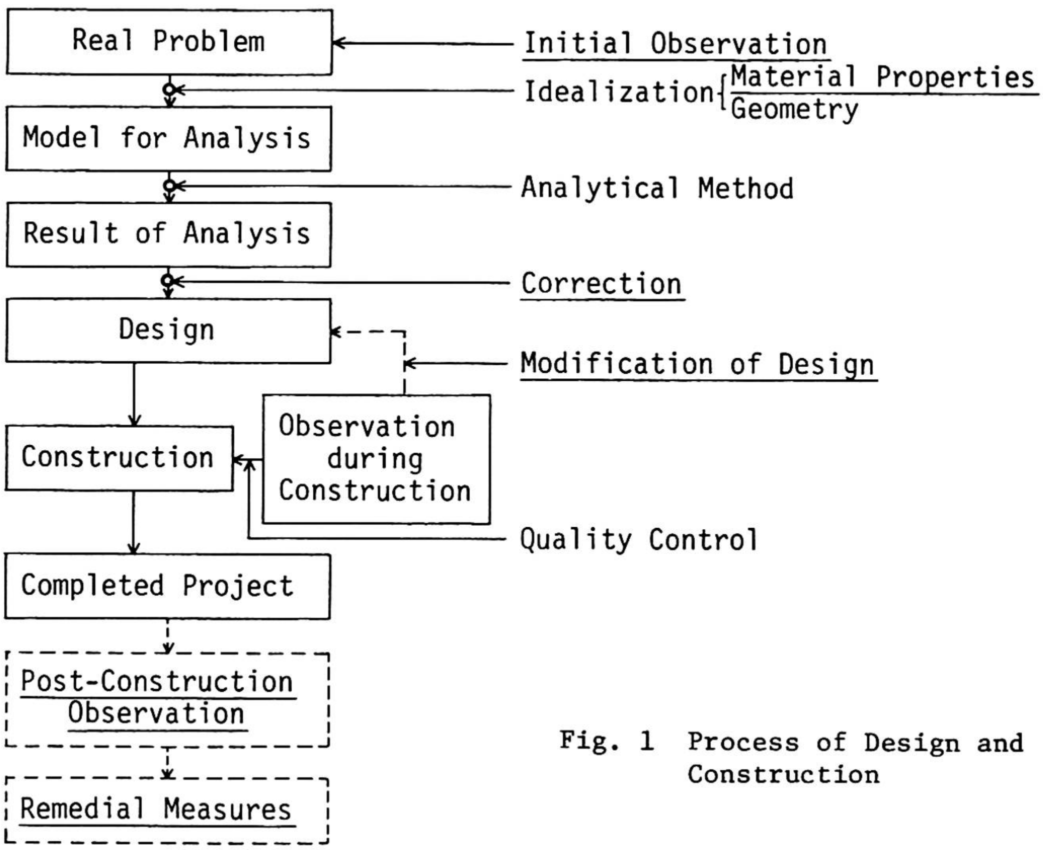


Fig. 1 Process of Design and Construction

with the soil profile, the idealization process and the limitations of the analytical method.

Compared with superstructures which are constructed by well-proven methods with man-made materials of predictable properties, soils require much closer coordination between design and construction. This topic was discussed at the Specialty Session on Relationship between Design and Construction in Soil Enginering during the 9th International Conference on Soil Mechanics and Foundation Engineering [5], in which emphasis was placed on the interaction between design and construction concerning the performance of foundations and the influence of construction procedures and construction schedule on the prediction of foundation behavior.

Observation During Construction is made for the following purposes:

- For quality control of construction
- For the "observational method" [16] in which design is modified during construction
- To provide information for future projects.

Our knowledge of a soil profile generally improves as we proceed with construction. For example, excavation for basement reveals full cross-sections of the soil for which we previously had only limited access through a few boreholes. Heave of the bottom of an excavation gives reliable measure of the stress-strain relationship of the ground as a whole.

Careful comparison between our prediction before construction and the soil behavior observed during construction allows us to check our design and improve its reliability. Substantial economies can be achieved if an original design which has turned out to be overconservative can be modified during construction.

The observational method was successfully practiced by Terzaghi, and its advantages and limitations were discussed by Peck [16]. According to Peck, the prerequisite for the observational method is that "the engineer is thoroughly conversant with his problem, makes continuous alternations of designs and procedures as the information is obtained and has the authority to act quickly upon his decisions and conclusions."

Earth structures such as dams and embankments are particularly conducive to design modifications during construction. Attempts have been made to apply the observational method to embankment construction in which reliability-based design concept is utilized [12]. The probabilistic approach to geotechnical engineering problems will be discussed in Chapter 5 of this report.

When slow processes such as consolidation settlement and creep deformation are involved, or when the design is governed by future events such as earthquakes, strong winds, etc., post-construction observations are necessary if we want to compare our designs with the actual soil behavior. The post-construction observations are made either to provide information for future projects or with a definite intention to take remedial measures when necessary. Attempts have been made in Japan to observe the seismic response of structures and foundations by installing accelerometers on buildings, bridge piers, dams, piles, etc., and the results of the observation are being utilized in structural and foundation design. Zeevaert described a case in which possible tilt of a 43-story building could be rectified by differential pumping of groundwater from deep wells which had been installed below the structure [24].

Usually, a change in the absolute elevation of a structure is not detrimental. For example, a settlement of say 30 cm of a structure may not affect its function, safety or appearance, provided that the structure settles uniformly and that provisions are made with the utility lines and entrances to accommodate the settlement. Where the ground itself undergoes movements, e.g., subsidence or heave, it may even be more desirable to let the structure move with the ground.

What we must avoid is differential settlement that occurs after a structure has been completed and all important connections have been made. Probably because of the prevalence of masonry structures which are sensitive to differential settlement, extensive studies have been made in Great Britain on settlement prediction and design criteria based on differential settlement. Burland and Wroth [3] and Burland et al [4] presented excellent state-of-the-art reviews on the topic. Mexican geotechnical engineers have developed ingenious methods to design and construct foundations in extremely soft ground in Mexico City. Zeevaert presented an elucidating account of the science and art of foundation design for difficult soil conditions [25].

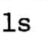
3. COLLABORATION BETWEEN THE STRUCTURAL ENGINEER AND THE GEOTECHNICAL ENGINEER

Before we attempt to discuss possible ways for better collaboration between the structural engineer and the geotechnical engineer, let us remember that there are other parties who often have vital influence on the decision concerning design and construction. They are the owner, tenant, architect, mechanical engineer, contractor, building authorities, insurance company, neighbors, and public. The manner in which these parties interact each other depends on the sociopolitical system and may, therefore, vary from place to place. The writer wishes to concentrate on the following two topics which may be considered common in many countries:

- Reasonable criteria for design
- Early participation of the geotechnical engineer.

3.1 Reasonable Criteria for Design

Criteria for design are determined on the basis of function (serviceability), safety, comfort, economy, and visual appearance, the priority of one to another depending on the objective of the project under consideration. Although some of the above items are subjective, we must eventually decide on certain quantities to define the criteria in order to proceed, i.e., safety factor and allowable movements (settlement, heave, or lateral movement), or their probabilistic counterparts in reliability-based design.

For the sake of simplicity, let us confine our discussion to allowable movements. Both laymen and engineers other than geotechnical engineers tend to consider the ground as a solid mass. Even structural engineers who are accustomed to computing deformations of a superstructure often assume that the base of each column is restrained against displacements. Would it be possible that those idealized line drawings of structural frames having the symbols  or  at the lower end of each column have a subconscious effect?

Being used to working with close tolerances measured with a micrometer, mechanical engineers tend to demand equally close tolerances for foundation movements. Peck [18] cited an example in which the base of a tracking radar station was not allowed to move more than 0.06 mm. It is noteworthy that "it took at least a year for the members of the various diciplines involved in the design and construction of the tracking radars to learn enough of a common language to appreciate the nature of the problem, [and to agree that] the original tolerances were utterly unrealistic and unnecessary" [18].

It is hoped that the structural engineer who, is usually closer to the source of information concerning functional restrictions on foundation movements can help the geotechnical engineer by checking the limiting movement to see if it is unrealistic or unnecessary. If it is unnecessary, by all means reprove it. If it is unrealistic but necessary, it must be accommodated by providing adjustable connections in the superstructure or mechanical system.

3.2 Early Participation of the Geotechnical Engineer

It is not uncommon that the geotechnical engineer is asked to participate in foundation design after the site has been selected and architectural plans have been completed, or after troubles have developed during construction. There have no doubt been many instances in which earlier participation of competent geotechnical engineers could have prevented foundation failures or waste of money. On the other hand, there are many foundations which have been successfully designed by structural or civil engineers in a routine manner.

The question is: "shall we need a geotechnical engineer for the next project?" Under favorable conditions, the question may be answered on the basis of local experience alone. In general, however, it is desirable to consult a geotechnical engineer for his advice on that specific question. That can best be accomplished by letting him join a design team consisting of the owner, architect, structural engineer, et al, as shown in Fig. 2. The design team will decide whether or not the foundation design should be carried out by a geotechnical engineer, and review the finished design in either case.

Fig. 3 shows an example in which the soil conditions dictated the location of 12-story residential buildings as well as the method of soil stabilization and the type of foundation. The site is part of a flat reclaimed land along the coast of Tokyo Bay, and the soil profile consists of 5-m thick hydraulic fill, 10-m thick loose alluvial sand, and soft (normally consolidated) alluvial silty clay having variable thicknesses (26 to 42 m), and dense diluvial sand [19].

It can be seen in Fig. 3 that most buildings are located along the contours and away from steep slopes of the bearing stratum. To overcome the problems of low bearing capacity, high liquefaction potential, and consolidation settlement, the hydraulic fill and the upper part of the alluvial sand were densified by vibroflotation, and the buildings were supported by steel pipe piles driven into the dense diluvial sand. The upper part of some of the piles was sheathed in larger steel pipes to reduce downdrag forces from the surrounding soil. Of the total cost including landscaping, 0.26 % was spent for the subsurface investigation and field pile load tests, 1.36 % for the soil stabilization, and 13.6 % for the piles [19]. Despite the high cost, long point-bearing piles are often used in Japan because of the high seismic risk.

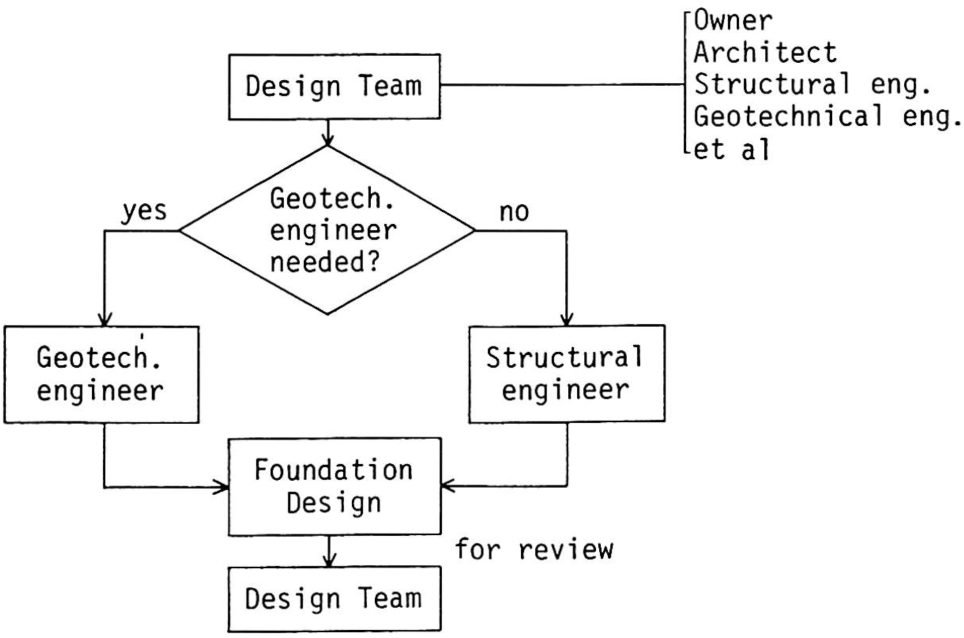


Fig. 2 Suggested Method to Share Responsibility for Foundation Design

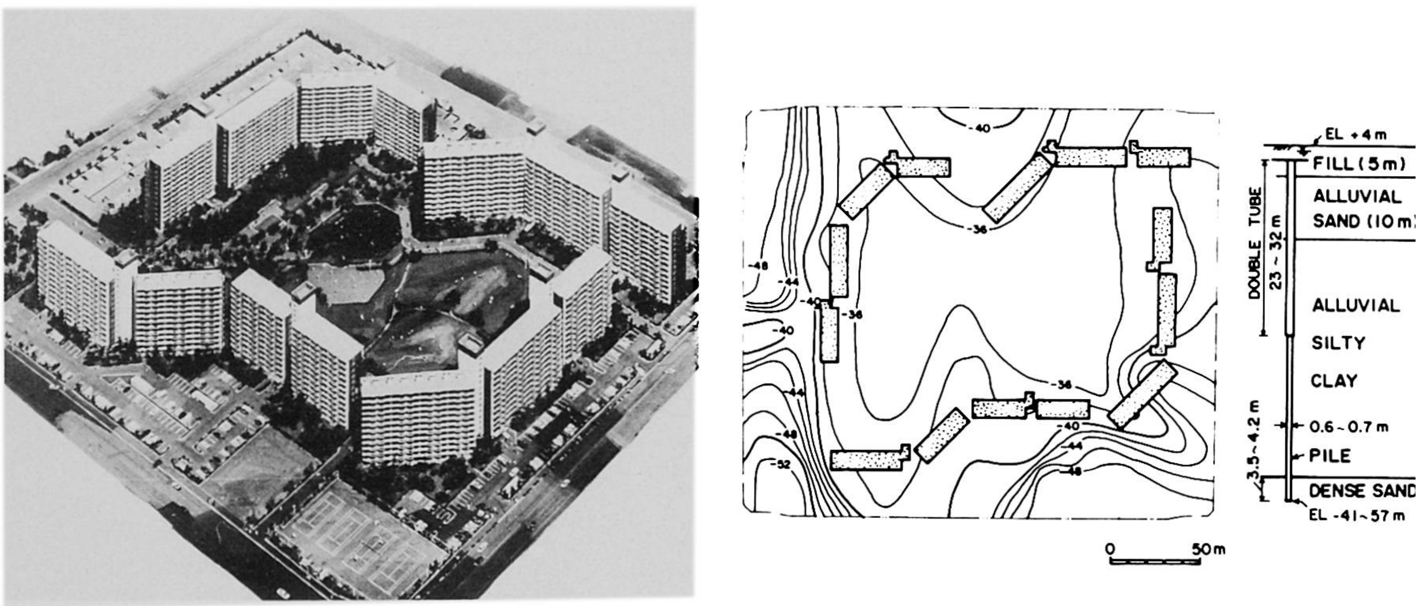


Fig. 3 High-Rise Residential Buildings in Urayasu, Japan. (Numbers along contours show elevations of dense sand supporting point-bearing piles. Photo courtesy of Oriental Land Co., Ltd.)

Referring to Fig. 2 again, the structural engineer will take charge of the foundation design when the design team decides so. The routine design of foundation by the structural engineer may be expedited by suitable design manuals. Such manuals are widely used in Japan [2, 8]. The most voluminous one is the 667-page Design Standards for Building Foundations [2] and its publisher, the Architectural Institute of Japan*, has sold 42,000 copies of its latest edition since 1974. The popularity of the manual is probably due to the fact that it gives specific guidance on how to carry out numerical calculations, and that it has earned recognition of the building authorities. There are criticisms, however, that the use of the manual is often overextended by some structural engineers and building officials to situations beyond routine design.

4. NEW PROBLEMS IN GEOTECHNICAL ENGINEERING

The geotechnical engineer must face more challenging problems as the structures become taller and heavier, the available sites become less favorable, and the public becomes less tolerant of nuisances associated with soil behavior during and after construction. Two topics, i.e., environmental problems and offshore structures are briefly discussed here as examples of new problems facing the geotechnical engineer. The awareness of these problems by the geotechnical engineering community was demonstrated by the fact that they were selected as session topics for the last and the next International Conference on Soil Mechanics and Foundation Engineering (ICSMFE), as follows:

- Geotechnical Engineering and Environmental Control, Specialty Session 11, 9th ICSMFE, Tokyo, 1977 [15]
- Environmental Control, Session 6, 10th ICSMFE, Stockholm, 1981
- Geotechnical Problems in Ocean Engineering, Specialty Session 7, 9th ICSMFE, Tokyo, 1977 [13].

4.1 Environmental Problems

Ground movements in adjacent sites caused by excavation, dewatering, and settlement are not new. Under difficult soil conditions, it is not feasible to eliminate those problems completely, and reasonable compromise should be sought concerning allowable movements.

Chemicals used for soil stabilization may contaminate groundwater, and must be handled with caution [1]. In Japan, all chemicals except sodium silicate have been banned, and any user of sodium silicate grout is required by the government to monitor the quality of the groundwater around the site. Specifically, the owner of the project must do the monitoring before, during, and for six months after the grouting, and must be prepared to stop the grouting as soon as the quality of the groundwater fails to meet certain standards [14].

Pile driving in urban areas has been blamed as a major nuisance in terms of noise, ground vibration, ground displacements (settlement, heave, lateral movement), and air pollution, of which noise is the most objectionable. Because hammer driven piles are considered superior to bored piles in terms of load carrying capacity, reliability, and installation costs, selection of a less

* Structural and foundation engineering for buildings are covered by the Institute, not by the Japan Society of Civil Engineers. Likewise these subjects are taught in a Department of Architecture and Building Engineering, not in a Department of Civil Engineering, in college and technical high school.

noisy alternative results in inferior performance or economic loss. Attempts have been made to muffle the noise of driving piles by means of covers attached to the rig as shown in Fig. 4.

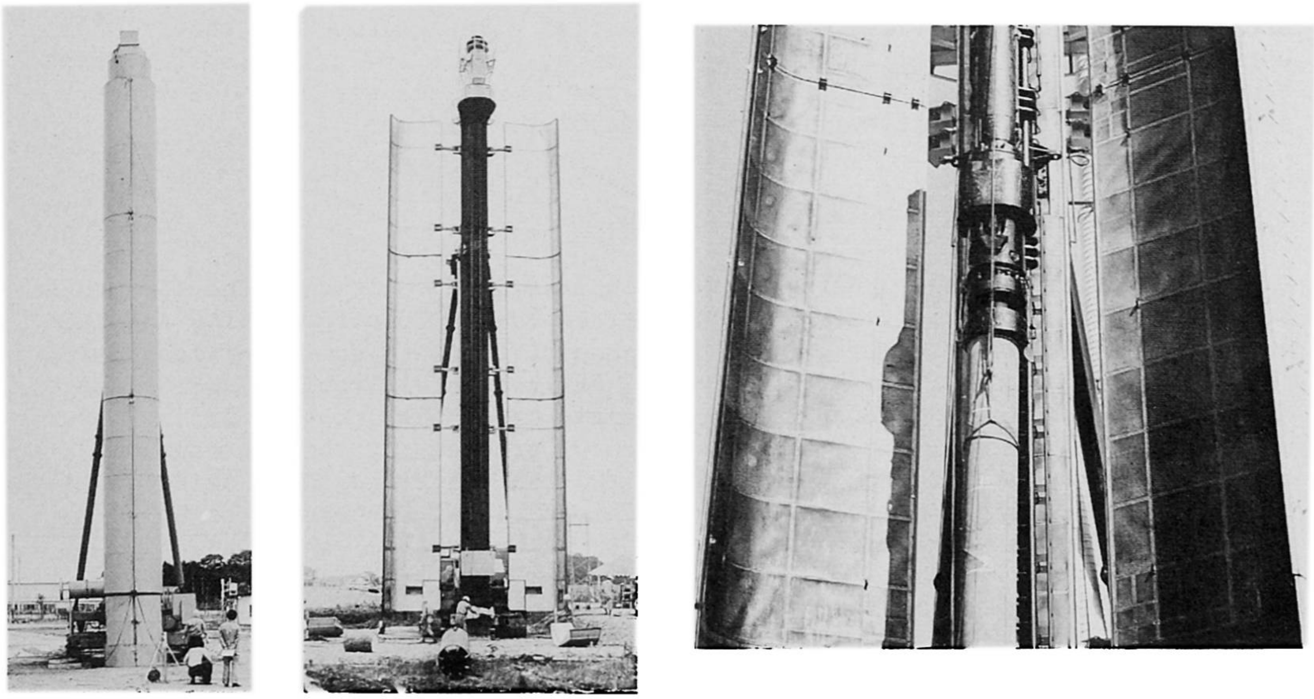


Fig. 4 Noise-Reducing Cover for Pile Driving Rig (Photo courtesy of the Japan Association for Steel Pipe Piles)

4.2 Offshore Structures

Offshore drilling platforms have become comparable in size to high-rise buildings as we attempt to explore the continental shelf to ever increasing depths, as deep as 300 m. These enormous structures challenge the skills of the geotechnical engineer as well as the structural engineer, particularly by severe dynamic loading conditions, i.e., irregular cyclic loading by storm waves and possible collisions with ships or ice. Where epicenters of major earthquakes are located offshore as in Japan, offshore structures are expected to encounter extremely violent ground motions for which we have had no previous experience.

The loadings themselves affect both the structural engineer and the geotechnical engineer, but the geotechnical engineer must face the additional task of subsurface investigations below the ocean floor for estimating the bearing capacity of the foundation against the dynamic loading involving possible liquefaction problems [11]. Unlike the liquefaction of saturated soil due to earthquakes that may be approximated by undrained conditions, dissipation of excess pore water pressures during wave loading may be significant in the soil supporting offshore structures. Analytical methods are now available for treating two-dimensional problems of soil liquefaction involving simultaneous pore pressure generation and dissipation [21].

5. RECENT DEVELOPMENTS IN GEOTECHNICAL ENGINEERING

Recent developments in geotechnical engineering may be classified into the following categories:

- Subsurface investigation and laboratory tests
- Construction methods
- Analysis and design

In view of its vital importance in geotechnical engineering, subsurface investigation has long been studied very seriously. Recent advances in our analytical capabilities, e.g., the finite element method, have stimulated renewed efforts to seek more reliable stress-strain relationships of soils and rocks. Some attempts for undisturbed sampling of sands below groundwater table [7, 23] and self-boring pressuremeters [10] have produced encouraging results. Significant advances have been made in laboratory and field testing methods to determine dynamic properties of soils [22].

In Japan, slurry trench walls have been used extensively in urban areas in order to minimize noise and displacements of the surrounding ground. Recent efforts have been aimed at providing structural joints between the wall segments so that the walls could serve as permanent shear walls capable of resisting seismic load as well as lateral earth pressure. That and other examples of recent developments in geotechnical construction in Japan were summarized by Fukuoka [6].

Modern analytical methods such as the finite element method have been used in a variety of geotechnical engineering problems for both static and dynamic loading conditions. It appears that the analytical methods have already achieved an adequate level of sophistication, considering the uncertainties in the mechanical properties of soils and in loading conditions.

Probabilistic approach to solving geotechnical engineering problems seems quite natural when we consider the inherent variability in soil properties and uncertainties involved in determination of the in situ properties. Fig. 5 shows the number of technical papers published on this subject in five journals and in the proceedings of two international conferences (the International Conference on Soil Mechanics and Foundation Engineering, and the International Conference on Applications of Statistics and Probability on Soil and Structural Engineering) [9]. Curve A in the figure includes papers on soil classification, statistical distribution of soil properties, regression or correlation among soil properties, and statistical sampling. On the other hand, Curve B consists of papers on stochastic prediction, reliability analysis, optimization in design and construction, and quality control in earthwork construction. Following a modest start, the interest in the subject has increased significantly since 1970.

Caution has been expressed on a statistical treatment of soil properties in view of the fact that natural soil deposits consist of thin discrete units which have been formed by certain geological processes [17]. An average value may have entirely different meanings depending on the soil behavior. When we want to estimate settlement which is vertical strains integrated over the depth, positive and negative deviations from the mean value tend to cancel out. On the other hand, when a failure condition is caused by local weaknesses as in the case of slope failure due to liquefaction, a mean value of soil properties straddling the weak zone will give misleading impressions.

It is perhaps too early to predict whether the reliability-based design will be accepted by practicing geotechnical engineers. But the writer hopes that the method will supplement the important but elusive "engineering judgment," and provide a common language for better cooperation betweeen the structural engineer and the geotechnical engineer.

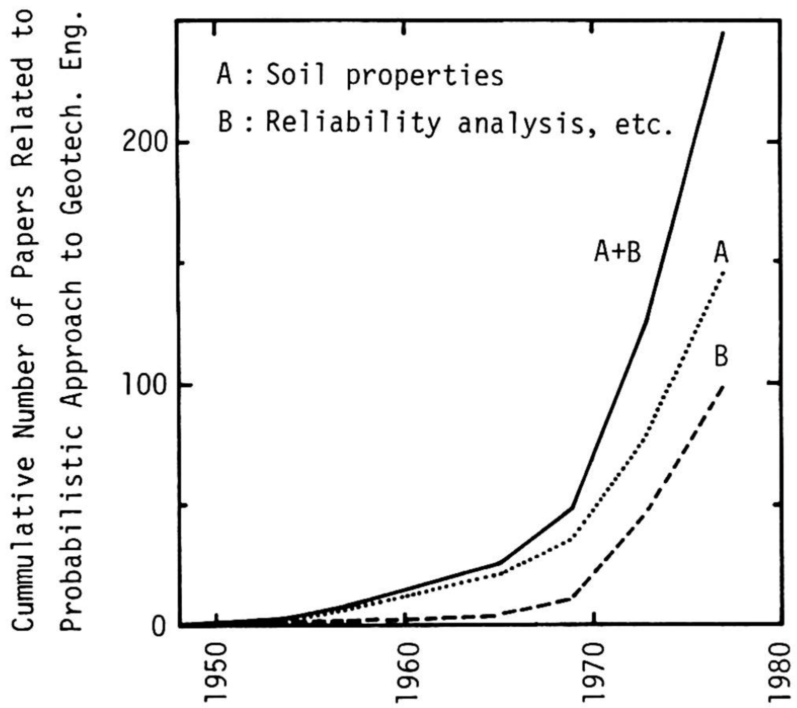


Fig. 5 Research Activities in Geotechnical Engineering Concerning Probabilistic Approach

6. CASE HISTORIES

All the foundations and earth structures that have ever been constructed may be considered full-scale tests for subsequent geotechnical projects. Because intentional full-scale tests are not feasible, well-documented case histories of the existing projects, both success and failure, are very useful. However, because soil conditions at two sites are not exactly alike, we cannot simply copy a previous design even though the superstructures may be alike. For a case history to be useful, it must contain the following:

—Detailed account of reliable observations of the soil profile, groundwater conditions, soil properties, and foundation behavior
—Rational explanation of the observed foundation behavior on the basis of the soil conditions and relevant theories.

Classical examples of excellent case histories were presented by Terzaghi [20]. Careful planning for obtaining relevant data is required to prepare a good case history. Those who are affiliated with design or construction organizations usually have better access to field data than academicians, but tend to be too busy. On the other hand, those affiliated with teaching or research organizations who have time to write do not have access to field data. In some cases, the owner does not permit publication of technical details of his project. As a result, a great deal of valuable data remain dormant. In order to stimulate outflow of case histories, the Japanese Society of Soil Mechanics and Foundation Engineering plans to publish an 800-page book of case histories in 1980 in commemoration of the Ninth International Conference on Soil Mechanics and Foundation Engineering held in Tokyo in 1977.

7. CONCLUDING REMARKS

In this Introductory Report, the writer has attempted to point out some problems concerning the relationship between the structural engineer and the geotechnical engineer. Because the presentation has been made from the viewpoint of the geotechnical engineer, the question of what the structural engineer expects from the geotechnical engineer has been left unanswered.

The writer believes that the key to success is to let the geotechnical engineer participate at the earliest possible stage of project planning so that he can assist the architect and structural engineer in selecting the basic structural format as well as helping the owner in site selection and site development.

ACKNOWLEDGMENTS

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Note: ASCE = American Society of Civil Engineers
ICSMFE = International Conference on Soil Mechanics and Foundation Engineering
SMFE = Soil Mechanics and Foundation Engineering

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