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FOUNDATIONS

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ABSTRACT

Foundation engineering emerged as a discipline of modern engineering science in 1940s.Design and analysis as well as practice of foundation engineering have made a significant progress up to the present time.This paper gives an overview of the development of foundation engineering, mainly referring to papers published in Soils and Foundations.The paper describes the theoretical development of foundation analysis and a recent increasing trend of foundation practice of adopting various hybrid foundations.The paper points out the importance of environmental considerations in foundation design and practice, including low noise and vibration reduction, reuse of existing foundations and use of natural energy through foundation elements.The paper then provides authors' views of future directions in foundation studies and practice.

INTRODUCTION

Foundation engineering emerged as a discipline of modern engineering science in 1940s, and there has been significant progress in foundation studies over these seventy years. The history of foundation study bears witness to claim that our technologies develop not necessarily linearly with time, but rather in a stepwise manner, triggered by experiences of natural disaster, the development of new materials and construction methods, the developments of new theories and analytical methods, the challenge of big projects and also changes in the design code.

There are three major aspects to understanding the behavior of the ground and foundation structures;

1) Modeling: modeling describes the element behavior of structural component members, geomaterials and the interfacs between soil and structure.
2) The Profile: the profile sets out the spatial distributions of material parameters, the initial and boundary conditions, and the external actions.
3) The Solver: the solver estimates behavior as the output based on the aforementioned two input factors.

The quality of estimation of the overall behavior obviously depends on the qualities of these three factors.

From the point of forward analysis, these three factors directly reflect the potential ability of estimating the behavior. Every single development in these factors contributes to the total improvement of the potential ability. Many contributions can be found in Soils and Foundations over the past fifty years. On the other hand, lack of certain geotechnical information is inevitable in practice, especially with regard to the spatial distributions of material properties and initial conditions. In this respect, actual construction works are carried out under a bounded rationality. The lack of geotechnical information may lead to inappropriate engineering practices, resulting in either overly conservative or unsafe decisions. To avoid such inappropriateness, the view point of inverse analysis, which estimates system input parameters based on measured output data, is necessary. Studies on the identification of input parameters can be found in Soils and Foundations.

In all scientific and engineering fields, there are significant contributions which could be considered turning points that lead to later development. Kusakabe and Lee (1999) selected five significant contributions which could be considered such turning points in our understanding and design practice in foundation engineering. They are Terzaghi's bearing capacity formula, Meyerhof's hypothesis for effective width for eccentric load, Bishop, Hill and Mott's elasto-plastic analysis of spherical cavity expansion, Broms' solutions for ultimate horizontal resistance of pile and Smith's model for dynamic response of pile.

The papers that have appeared in Soils and Foundations show that research still continue in line with these five contributions. Tsukamoto (2005) examined a fundamental question of the superposition errors in Terzaghi's bearing capacity formula. Meyerhof's effective width concept has been extended to macro element concept (e.g., Okamura et al., 2002). The cavity expansion theory is still being used (Yasufuku et al., 2001). Yenumula et al. (1999) proposed a modified method of Brom's analysis. The analysis of pile driving by Smith's model has now extended to wider applications of wave equation to pile driving control, as well as the evaluation of bearing capacity and the integrity of pile.

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The geotechnical community prepares a State of the Art Report on foundation engineering every four years at the time of an international conference, which offers valuable sources of information. Poulos et al. (2001) critically reviewed various aspects of foundation engineering and assessed the capabilities of conventional methods of analysis and design. They summarized the results of their assessment into three categories; methods which may be adopted, methods which should be adopted, and methods which may need to be discarded. Randolph et al. (2005) described design principles specifically for offshore foundations from shallow footings to piles and caisson, highlighting differences between onshore and offshore practice. More recently, Simpson et al. (2009) discussed the role of design code, comparing three major geotechnical design codes: Eurocode 7, ASSHOTO LRFD bridge specifications and Geo-code 21 of the Japanese Geotechnical Society.

This paper begins with the development of foundation analysis mainly from theoretical aspects, followed by the development of hybrid foundations such as piled raft foundation increasingly adopted in recent years. The paper then provides environmental considerations for future foundation design and practice. The paper finally offers authors' views of future directions in foundation study and practice.

DEVELOPMENT OF FOUNDATION ANALYSIS

Shallow Foundations

From Classical Analysis to Modern Analysis

There are conventionally two approaches to handle shallow foundation problems. One is the rigid-plastic analysis for the ultimate bearing capacity, and the other is load-deflection analyses, which are expressed in the frame work of the theory of elasticity. There are additional more sophisticated elasto-plastic finite element analysis and finite difference analysis readily available at the present time. The advantage of the rigid-plastic analysis is that the ultimate bearing capacity can be estimated without the information on the initial stress distributions, which cannot be ignored in elasto-plastic analysis. In contrast, the advantage of (linear) elastic analysis is the superposition of solutions.

The first practical formula for determining the bearing capacity of shallow foundations was proposed by Terzaghi. The concept of a bearing capacity factor and the superposition of three components, Nc, Nγ and Nq remains useful in practice. In the mid-1970s, there were numerous investigations focused on extensions of Terzaghi's formula, making it applicable to combined loads and various shapes of foundation. Brinch Hansen (1970) proposed the general bearing capacity formula, which is used in practice worldwide (Poulos et al., 2001). Research into improving each factor, especially Nγ, continued because of difficulties in experimental determination due to issues of grain size dependency and progressive failure, and also the difficulties presented in numerical calculations. One of the major reasons for the continued research interest in the bearing capacity problems of shallow foundation is strongly related to the new challenges posed by offshore structures, especially the energy related offshore facilities. From the considerations of cost and workability in installation and maintenance, shallow foundations are more competitive than other foundation types. Recent studies of shallow foundation problems concentrate on the detailed characteristics of bearing capacity by means of more sophisticated approaches.

Theoretical Background

Elastic analysis

In order to understand the behavior of shallow foundations, the instant deflection of foundation structures and the deformation of the ground are well evaluated by the theory of elasticity, even though plastic deformation locally occurs. Moreover, elastic analysis is used for the dynamic response of foundation structures. Fundamental analytical methods in the theory of elasticity are summarized in the literature (e.g., Selvadurai, 2007). The recent role of closed form analytical solutions is a shift from practical tools for design to the benchmarks as a means of verifying various numerical methods.

Rigid plastic analysis

There are two analytical methods to solve rigid plastic boundary value problems: the method of characteristics, and limit analysis. Comprehensive documents on rigid plastic analyses can be found in the literature (e.g., Landriani and Salencon (Eds), 1993; Kamenjarzh, 1996).

Classical approaches to the rigid plastic analysis are usually based on manual calculations. Therefore, it should be noted that their solutions are usually either an upper or lower bound solution, not an exact one. More computer-based sophisticated approaches of rigid plastic analysis have recently been established. The rigid plastic finite element method based on lower bound theorem was firstly applied to geotechnical problems by Lysmer (1970), and was followed up by Arai and Tagyo (1985) and a series of others. The rigid plastic finite element method based on the upper bound theorem was applied to geotechnical problems by Tamura et al. (1984) and others. More recently, a hybrid type formulation which solves both the upper and lower bounds simultaneously using Karush-Kuhn-Tucker condition was proposed by Kobayashi (2005).

The papers which appeared in Soils and Foundations including the applications of rigid plastic analysis for foundation engineering, cover the following topics.

1) The improvement of the vertical ultimate capacity estimation, especially the evaluation of the bearing capacity factor Nγ (Michalowski, 1997, and others)
2) The ultimate capacity under general loading conditions estimated by yield design theory (Paolucci and Pecker, 1997)
3) The ultimate capacity under specific geometrical conditions of ground, especially with regard to shallow foundations near a slope (Kusakabe et al., 1981; de Buhan and Garnier, 1998, and others).
4) The ultimate capacity of circular footing (Kusakabe

et al., 1986; Tani and Craig, 1995).

5) The seismic bearing capacity using a pseudo static method (Sawada et al., 1994; Huang and Kang, 2008)
6) The upper bound solutions of footings on anisotropic clays (Al-Sharmani, 2005)
7) The bearing capacity in low gravity accelerations (Kobayashi et al., 2009)

Elasto-plastic analysis and sophisticated methods

The highly complex behavior exhibited by geomaterials depends on the stress level and loading history. Precise responses of geomaterials may be estimated only by an evolutionary elasto-plastic analysis with sophisticated treatments.

The size dependency of the bearing capacity factor $N\gamma$ has been an issue and is now considered to be caused by 1) stress dependency of internal friction angle, 2) progressive failure along slip lines and 3) particle size relative to a footing dimension, and perhaps even a combination of these factors. Centrifugal test results showed clear progressive failure (Yamaguchi et al., 1976) and suggested the dependency of internal friction angle (e.g., Hettler and Gudehus, 1988). However, Siddiquee et al. (2001) claimed that particle size relative to a footing width plays a significant role on the size dependency.

Macro Element Concept and Its Application to Shallow Foundations

The conventional bearing capacity formula was mainly focused on the ultimate vertical bearing capacity. However, in the past three decades, much attention has been paid to estimating the horizontal and momentum capacity of shallow foundations. In order to estimate the overall characteristics of bearing capacity of shallow foundations, the failure loci of the ultimate bearing capacity of shallow foundations in the generalized load space (vertical load V, horizontal load H, moment M normalized by footing width B, M/B) have been introduced. Although, the reduction factors have a mathematical meaning identical to that of the failure loci, the bearing capacity characteristics under combined loads are better understood with the concept of failure loci. This conceptual approach is usually called ''a macro element method''. Concrete shapes of failure loci were estimated by either plastic solutions or numerical results of elasto-plastic FEM analyses and verified by model tests (Gottardi and Butterfield, 1993, and others). This concept was later extended to express the displacement behavior of foundations under combined and inclined loading conditions with the analogy of the elasto-plastic mechanics, such as a yield function and a plastic flow rule (e.g., Nova and Montrasio, 1991).

One of the advantages of the macro element method is the relative ease with which analyses of whole structure systems, such as multi-legged offshore platform, can be carried out. Also, the analsis can be done in a more systematic manner since the responses of each individual footing are expressed as a single elements. Influences of rigidity on the overall behavior of structures or the distribution of bearing loads on each footing can be readily evaluated (e.g., Dean et al., 1997; Butterfield, 2006).

Applications of the macro element method to the dynamic seismic responses of shallow foundations systems were also proposed. The kinematic hardening model for cyclic loads and the gapping-contact interaction model on the interface of the foundation and the ground were developed and implemented (Chatzigogos et al., 2009). Shirato et al. (2008) carried out a series of shaking table tests to verify its applicability.

Other Topics Discussed in Soils and Foundations

Bearing capacity of two-layered soils

Using a series of centrifuge tests, a bearing capacity problem of two-layered soils was investigated by Okamura et al. (1997), where a sand layer was overlaid over a soft clay layer. Murakami et al. (1996) carried out numerical simulations with the use of Cosserat media to take the bending resistance of the surface crust into account.

Shakedown analysis

A shakedown analysis is the generalization of the limit analysis to repeated load cases. Abdelkrim et al. (2006) applied partly an evolutionary (cycle by cycle) method to estimate the residual settlements of an elasto-plastic body obeying an explicit cyclic law due to repeated loads.

Deep Foundations

Elastic responses in the vertical direction

Working vertical load is much smaller than the ultimate vertical bearing capacity. The practical interest is therefore focused on the evaluation of a load-settlement relation. Elastic analyses have been widely accepted to estimate the settlement of piles. Among such analyses are the direct applications of theoretical elastic solutions (e.g., Mylonakis, 2001), the finite element method (FEM), the finite difference method (FDM), the boundary element method (BEM) (e.g., Kuwabara, 1991) and a simplified model consisting of bar-beam-spring-dashpot elements must also be included. For cases of pile groups, special attention is paid to the efficiency of pile groups, and takes the interaction between piles into account (Yamashita et al., 1987).

Toe vertical bearing capacity

As toe capacity is deeply related to the penetration mechanism of driven piles and penetration tests, understanding the toe capacity problem is important to understand the workability of pile installation and the evaluation of material properties by penetration tests. Evaluation methods for toe capacity are classified into 1) Analogies of shallow foundations with overburden pressure (Hanna and Nguyen, 2002), 2) Estimations of plastic pressures based on the cavity expansion theory (e.g., Yasufuku et al., 2001), 3) Evaluations of changes in stresses and pore water pressures during penetration based on the strain path method, 4) Rigorous numerical analyses based on the mechanics of particles, such as the discrete element method (DEM), smoothed particle hydrodynamics (SPH), and the material point method

(MPM). As far as soil plugging is concerned, Randolph et al. (1991) proposed a one-dimensional analysis and Matsumoto and Takei (1991) reported their experiences in measuring at the access bridge to Kansai international airport.

Skin friction and shaft resistance

For longer piles, major vertical loads are supported by the shaft resistance of pile. A sophisticated hyperbolic load transfer function for long piles was reported by Hirayama (1990) based on the construction experiences of the Honshu-Shikoku Bridge project. As the load transfer function approach is easy to handle, it is applied to the reliability design of piles (e.g. Yamato and Karkee, 2004). Friction fatigue (shaft resistance degradation) during installation and loading for displacement piles in sand has become an issue (Al-Douri and Poulos, 1994; Dejong et al., 2006).

Lateral response and capacity of piles

Poulos et al. (1995) conducted model tests with corresponding BEM analyses to investigate the lateral response of piles in the elastic range. Chiou and Chen (2007) proposed a simplified model to express a load-deflection relation. The ultimate lateral capacity subject to combined loads was investigated by Yalcin and Meyerhof (1988) and others. Otani et al. (2006) visualized the failure patterns of laterally loaded piles inside the sand with X-ray computed tomography.

Seismic responses of foundations

The seismic responses of foundations involve complex summations of several different mechanisms and exhibit extremely complicated behavior. They are combinations of repeated combined loads due to the inertia of superstructures, dynamic earth pressures caused by different responses between piles and surrounding soils, and static earth pressures caused by the lateral movement of soils due to liquefaction. In addition, strongly inelastic behavior was observed in past devastating earthquakes such as the Hyogoken-Nambu Earthquake in 1995. A simple extension of the Winkler model was proposed to cope with nonlinear gapping/contact behavior by Gerolymos and Gazetas (2005) and Maheshwari and Watanabe (2006). Takahashi et al. (2008) also investigated earth pressures acting on pile caps during excitation.

Static lateral earth pressure acting on piles due to the lateral movement of soils has become an issue for bridge abutments supported by pile foundation and was firstly examined by the method of characteristics (Randolph and Houlsby, 1984) and by centrifuge studies (Stewart et al., 1994, and others). Similar situations also arise during and after the liquefaction of soil layers. Imamura et al. (2004) and others investigated the lateral behavior of piles due to liquefaction.

As the confining (lateral) pressure decreases under the axial compression load during liquefaction, there are possibilities of structural instability of piles. A discussion on pile yielding due to excessive bending moment was given by Tabesh and Poulos (2001), and the possibility of pile bucking was discussed by Kerr (1988) and Bhattacharya et al. (2005).

Rigorous numerical analysis

Owing to the development of computational power, it is now possible to conduct sophisticated numerical calculations including the dynamics, the elasto-plasticity of materials, a couple analysis of solid and liquid phases and the three-dimensional effect. Although, rigorous numerical analysis is usually too complicated for practical use, it is of vital necessity to develop our understanding of the overall mechanism of soil and structure for the engineering challenges we face.

The lateral behavior of pile groups was numerically investigated by Wakai et al., (1997). An analysis of repeatedly laterally loaded piles was conducted statically by Zhang et al. (2000) and dynamically by Kimura and Zhang (2000). The importance of the soil constitutive model, pile size and axial force dependent behavior of piles were also pointed out by Zhang et al. (2000).

The development of sophisticated constitutive equations capable of expressing complex soil behavior in a unified way with sufficient numerical stability also makes a significant contribution to the development of rigorous numerical methods. Among such contributions are the application of the Super/subloading Yield Surface Cam clay model to bearing capacity problems (Noda et al., 2007) and the application of the subloading t_{ij} model (Zhang et al., 2005). A delayed settlement problem of structures on clayey soils over a long period of time was reported and investigated by Danno and Kimura (2009).

Identification of System Parameters

An inverse problem to determine the distributions of subsurface material properties is of importance for geotechnical engineering practice. Honjo and Kashiwagi (1991) discussed a filtering technique to overcome the ill-posedness of geotomography based on Akaike-Bayesian Information Criterion. Later, Honjo et al. (1993) reported an estimation of the Young's moduli of layered ground using a 1-D elastic pile settlement model based on pile loading test data in the Bangkok area. In a similar way, horizontal subgrade reaction coefficients were estimated based on load testing data and their relation to SPT N-values was investigated (Honjo et al., 2005).

Another approach to identify soil parameters is to use a neural network. Nagaoka et al. (2001) developed an in-situ testing device and applied a neural network to parameter identification, including the earth pressure ratio at rest K_0.

DEVELOPMENT OF HYBRID FOUNDATIONS

Introduction

The review of the foundations of historical buildings (e.g., Przewlocki et al., 2005) demonstrates that engineering wisdom existed as far back as the medieval period, when various types of hybrid foundations were used, including timber shallow foundations on short piles, and pile foundations with sheet walls, and bell shaped foundations on soil-concrete columns. They may well be considered the prototypes of recent hybrid foundations.

There is a clear and increasing trend to adopt hybrid foundations for better performance and more economical solutions (e.g., Menzoda and Romo, 1998: Fujita et al., 2003). This trend of adopting hybrid foundations will remain unchanged in the future. This section reviews the studies of three types of hybrid foundation; raft foundation combined with sheet pile, raft foundation with piles, and foundation combined with soil improvement/reinforcement.

Raft Foundation Combined with Sheet Pile

The so-called 'Skirted foundation' used in offshore foundations belongs to this type of foundation. They are steel or concrete plated foundations with a circumferential skirt beneath the periphery which penetrates the seabed confining a soil plug. Skirted foundations provide a significant uplift resistance due to the suction developed in clay. A series of numerical analysis were carried out (e.g., Yun and Bransby, 2007) as well as experimental studies (Acosta-Martines et al., 2008).

A similar type of foundation for onshore application is called 'sheet pile foundation' which combines a spread footing and sheet piles installed along the periphery of the footing mainly for foundations of railway structures on moderately stiff ground. Sheet pile foundation is considered to have the beneficial effect of increasing seismic resistance. Punrattanasin et al. (2003) described an initial set of centrifuge tests on sheet pile foundation under combined loading. Nishioka et al. (2010) conducted a series of 1 G loading tests both under vertical and horizontal loading to examine the bearing mechanism of sheet pile foundation and confirmed the effectiveness of sheet pile foundation. Case histories adopting the sheet pile foundation are steadily increasing in foundations of railway structures.

Raft Foundation with Piles

In some situations, the decision to use piles is taken because either the overall or differential settlement of footings or rafts is estimated to be too large even though the bearing capacities are adequate. Burland et al. (1977) termed these piles ''settlement reducers''. The term 'piled raft foundation' is now established to describe raft foundation with piles. Yamashita et al. (1987) presented the first Japanese application of piled raft for a four-story building in Urawa in 1987. Since then piled raft foundations have been used for many buildings, including high-rise buildings over 200 m in Japan, and case histories of the application have been published (Yamashita et al., 1994). The performance of a piered-raft foundation in China was also reported by Zhang and Zhao (2000).

Kuwabara (1989) performed a boundary element analysis based on an elastic theory to analyze the behaviour of piled raft foundation subjected to vertical load. Ta and Small (1998) presented a method of analysis for piled raft foundations on layered soils which combine both FEM for the analysis of raft and finite layer method for soil-pile groups. Horikoshi and Randolph (1999) presented a simple method of estimating the overall stiffness of piled rafts in a non-homogeneous soil with finite depth. Centrifuge model tests on piled raft foundation were also carried out (e.g., Horikoshi and Randolph, 1996).

Recently, with the view of performance of piled raft during earthquake, horizontal resistance of the piled raft foundations was examined by model tests both static and dynamic conditions (e.g., Horikoshi et al., 2003). More recently, Matsumoto et al. (2010) reported loading test results of piled raft foundation with various pile head connection conditions subjected to cyclic horizontal loading to examine the horizontal stiffness and the rotation of the foundation.

Foundation Combined with Soil Improvement/Reinforcement

The demand for constructing structures on soft clay or loose sand layers, requires soil modifications either by soil improvement or by reinforcement. Similar situations may occur in cases where structures are to be constructed near a slope.

Huang and Tatsuoka (1994), and Huang and Hong (2000) discussed the bearing capacity and settlement of reinforced sandy level ground and slopes. Bouassida and Porbaha (2004) evaluated the bearing capacity of soils improved by deep mixing by yield design theory. Tsukawa et al. (2006) discussed the mechanism of the bearing capacity of spread footing reinforced with micropiles. Tomisawa and Miura (2007) presented a comprehensive study of pile foundation design constructed in composite ground improved by the sand compaction pile method or the deep mixing method. Yamashita et al. (2008) reported a case history of piled raft foundation on grid-form soil-cement wall improved ground by deep mixing method.

ENVIRONMENT CONSIDERATIONS

Environmental Load Reduction Oriented Structures

The Japan Society of Civil Engineers (2001) published guidelines for the basic design of environmental load reduction oriented structures. The guidelines specify required functions which include scenic beauty, regional environmental load reduction, and global environmental load reduction. Regional and global environmental load reduction is of great concern in future foundation design. The issue of 'noise and vibration' is classified into the regional environmental load reduction, and 'resource recycling' and 'global atmospheric area' are categorized into the global environmental load reduction. This section describes the recent trend of developments in foundation design and practice related to the abovementioned three environmental considerations; noise and ground vibration reduction, re-use of foundations and use of natural energy from foundation elements to reduce CO_2 emission. The environmental considerations will form an essential part of foundation design and practice in the future.

Noise and Ground Vibration Reduction

Stringent environmental regulations almost exclude the use of driven piles in urban areas, and also restrict the disposal of spoil created in the process of bored pile construction. Construction methods have been developed to reduce noise and ground vibration caused by pile installation. Screwed pile and jacked-in pile are examples of such installation methods, providing advantages over other methods in terms of their ability to reduce both noise and ground vibration without creating any discharged soils.

Hashimoto et al. (1994) developed the rotary penetration steel pile method, called the 'drill pile method'. A thin-walled open-ended steel pipe pile has spiral ribs of steel rod welded to both the inner and outer circumferential surfaces at the lower part of the pile. Because of the existence of the ribs, the pile attains higher skin friction and toe resistance, which was confirmed by scaled model tests as well as field experiments. Saeki and Ohki (2003) used helical plates welded at the lowest end of an open-ended steel pile pipe, called 'screwed steel pipe pile'. The screw pile is twisted into the ground by a rotating torque, making use of the helical plates. They presented the penetration mechanism of the screw pile and the evaluation of end bearing capacity based on the field installation and loading tests. The benefit of using helical plates for screw piles/anchors for uplift resistance was examined earlier by Rao et al. (1991) and others.

Karkee (1999) summarized the developments related to the installation of low noise and vibration methods of pile installation, pointing out the drastic change in the use of impact driven or vibration driven pile installation method from 75% in early 1970s to 13% in 1980s, to other methods such as the pre-boring method, the inner excavation method and the screw-in method.

White and Deeks (2007) carried out recent research into the behavior of jacked foundation piles. One of the jacked-in machine walks along the row of piles under construction, gaining reaction by gripping the previously-installed piles, using the negative skin resistance of previously-installed piles to provide reaction force. This type of machine can be used for closely-spaced groups of piles or continuous walls. They presented a comparative study of the environmental impact, considering noise emissions, ground vibration, material and energy use, together with pile performance between jacked-in pile and driven pile, and concluded that the installation of a jacked pile involves (i) minimal noise and ground vibration, (ii) a reduced number of load cycles and (iii) direct measurement of the static resistance during installation.

Re-use of Foundation

Cast-in-place reinforced concrete pile was introduced to Japan in 1960s, and significant progress in construction technology of cast-in-place piles has been made since. Notable among them is the large diameter cast-in-place pile with an enlarged base, which offers a large bearing capacity. Because cast-in-place pile is an installation method with low-noise and vibration and cost effectiveness, such large diameter cast-in-place pile with an enlarged base has been widely accepted in building foundations. Recent social demand for the re-vitalization of urban areas sometimes requires the demolition of buildings founded on large diameter cast-in-place piles. Obviously, the demolition of existing large diameter and long reinforced concrete pile requires considerable cost and energy. The excavation and pulling out of large diameter piles may have an adverse effect on adjacent structures. Therefore, the possibility of re-using existing piles has become a challenging issue for geotechnical engineers, which forces them to focus on harmonizing with environmental considerations.

The Building Contractors Society of Japan (2003) published guidance for the re-use of existing piles. The following issues are pointed out for consideration: (i) the confirmation of the durability, integrity and bearing capacity of existing piles, (ii) compatibility with recent design requirements for horizontal resistance against earthquake loads, and (iii) geometrical compatibility with the new structures to be constructed. Loading tests and integrity tests play a crucial role in the consideration of the above issues.

Although there are no papers related to re-use of foundation published in Soils and Foundations, the issue is certainly an urgent challenge for geotechnical engineers. The proceedings of international conference (Butcher et al., 2006) and a special volume on the re-use technologies of existing foundation of Kiso-ko (2005) offers useful information for practical engineers.

In their State of the Art Report, Simpson et al. (2009) stated that foundation reuse has the potential to 'Reduce cost and construction programs', 'Reduce the impact on archaeological resources', 'Reduce disturbance to contaminated ground', 'Avoid disturbance to existing underground services and structures'. These benefits are in part countered by the need for 'Careful and advanced planning', 'Additional testing and investigation', 'More complicated design' and 'Potential increase costs in design' and 'Construction of pile caps and transfer structures.'

Use of Natural Energy

The need to reduce CO_2 emissions is a global issue, and foundation engineering also needs to contribute to the global targets. The use of natural thermal energy is a promising option. Subsurface geothermal resources have great potential to privide directly usable natural energy, which, in practical terms, could be transported through foundation elements like piles and retaining structures, combined with geothermal cooling/heating systems. Terms such as energy pile or energy foundation are often used for this type of pile/foundation. Energy piles are conventional load bearing piles which are also equipped with U-shaped tubes to carry a circulating thermal fluid. The use of energy piles has been widespread in continental Europe since the 1980s. Brandl (2006) presented the Austrian experiences and current considerations for energy pile design.

Thermal input to the energy pile leads to either the elongation or shrinkage of pile length relative to the surrounding soils due to the temperature difference, which results in changes in the axial stresses and shaft resistance of the pile. Hamada et al. (2007) described the field performance of an energy pile system consisting of a total of 26 concrete friction piles of a depth of 9 m and an outer diameter of 302 mm. They, monitored the piles for six months with respect to the thermo-dynamics aspects and cooling and heating performance of the system. Bourne-Webb et al. (2009) reported the results of a pile load test on a pile subject to thermal cycles. They concluded that the structural capacity of the pile is unaffected by the thermal cycles.

FUTURE DIRECTIONS

Role of Numerical Analyses and Physical Modeling

Rigorous numerical analysis

Rigorous numerical calculations, such as 3D elasto-plastic analyses of overall ground-structure systems, are necessary to develop a thorough understanding of the essential mechanism of the overall behavior. Rigorous numerical calculations help to elucidate such things as 1) how a system will respond under severe transient loading conditions, especially seismic loading, 2) how a system will respond as time passes over a long term of service period. These rigorous methods will play a key role in helping us address new challenges in foundation engineering, by shedding light on problems with their deep insight of various mechanisms.

For example, a numerical analysis which covers the whole construction process of pile foundations is needs to be developed to provide a quantitative understanding of the changes in the soil parameters and stress conditions during the pile installation process. This information can be utilized as initial conditions for succeeding analyses, such as a seismic response analysis and a long-term deformation analysis. However, no comprehensive numerical analyses have been yet carried out for this purpose.

Simple model for a specific case

These rigorous numerical tools are usually too complicated to be applied to the monitoring of construction processes in practice. Therefore, it is necessary to develop a simple yet sufficient model to describe the behavior of the foundation structure and the ground. At the same time, it should be noted that owing to the development of foundation engineering and relevant technologies, many (not all) problems can be solved by experimentally and numerically and be verified by field measurements. In this respect, the applicability and limitations of modern simple models can be more rigorously checked than before. As indicated by Poulos et al. (2001), to update, some simplified methods and some of the values of the parameters need to be discarded in accordance with the knowledge we now have.

Physical modeling

Model tests can be regarded as independent physical events from which much can be learned. Japan has a history of over fifty years' experience in centrifuge modeling. Much information regarding the recent development of physical modeling technology can be gathered from the International Journal of Physical Modeling in Geotechnics, (http://www.geotech.ac.titech.ac.jp/IJPMG/).

Well equipped centrifuge facilities and large-scale shaking table facilities are now available. The recent rapid development of measuring sensors, computerized actuators and data handling methods provides a great potential to use physical modeling to simulate complicated construction sequences and to observe the detailed foundation behavior up to failure condition under a given loading condition, including seismic conditions.

Recent computer information technology offers a new dimension of physical modeling. By networking with various laboratories and institutions, it is possible to perform an experiment by remote control operating systems from other institutions, and to share the experimental data on a real time basis with many research workers in various laboratories. Hybrid physical model tests can also be carried out with numerical analysis. Good examples of this type of research collaboration are the Network for Earthquake Engineering Simulation (NEES https://www.nees.org/), and the UK Network for Earthquake Engineering Simulation (UK-NEES http://www.bris.ac.uk/).

Importance of System Identification and Feedback to Construction Management

Since most geomaterials are natural products and experience unknown circumstances over an extremely long period of time, it is impossible to perfectly understand and identify all the material properties of a given material, its spatial distribution or its current in-situ states. Engineers must inevitably make appropriate yet difficult judgments for construction projects without precise knowledge or information. One feasible solution to help in the making of such judgments is by monitoring the in-situ tests and construction processes to identify the critical parameters of geomaterials and initial conditions based on the inverse analysis. Mathematically, measured quantities are too limited and biased to determine parameters uniquely. It is therefore necessary to use filtering techniques specially developed for geotechnical purposes and/or a priori information obtained from field investigations and relevant databases.

In view of performance-based design, health monitoring of foundation structures will also play a crucial role in determining the parameters in addition to the inverse analysis. The performances of structures needs to be appropriately examined by in-situ testing and construction monitoring. It is desirable to establish a Plan-Do-Check-Act cycle in the construction process such that measured performances are systematically utilized to feed back rational modifications of the original design. There seems to be much room for practical developments in such a PDCA cycle and in related techniques.

Optimal Design and Locality

The standardized approach is very useful but not always the best solution, because the localities, such as the soil conditions and the seismic hazard risk, are major factors to the design of each individual structure, especially in geotechnical engineering. Therefore, the customized optimization for individual structures is key to achieving more rational design. One innovative example is the Rion-Antirion Bridge project in Greece (Combault et al., 2005). This cable-stayed bridge is supported by 4 main pylon legs (mass gravity structures) resting on reinforced soil with short piles. Major innovation in design philosophy allows some plastic deformation of the foundation structures to occur, including slide, separation and the mobilization of bearing capacity failure, which stand for more flexible responses of foundation structures (Gazetas, 2006).

The overall behavior of structures involves a combination of the nonlinear responses of the structural components. It is of course necessary to predict complex nonlinear behavior precisely. It is also noted that quality control of construction is important. Needless to say, a foundation structure must satisfy a required bearing capacity and stiffness. However, in some cases, if a foundation has too much capacity or its behavior is too stiff, it may harm other structural components and unexpected overall behavior may occur as a result. In this sense, construction quality should be well controlled to ensure that the performances of structures are within a prescribed range (lower limit < performance < upper limit), not a one-sided inequality (lower limit < performance).

Practice in Foundation Design and Analysis

Foundation engineering has matured and a vast amount knowledge has been accumulated. Computer codes are now readily available for practical engineers. The rate of expansion of new knowledge is much faster than that of the practical implementation of new knowledge. The consequence is that a large gap exists between research and practice, and the gap is anticipated to widen in the future.

One such example in current foundation design practice, at least in Japan, is the excess use of SPT N values. SPT N values are converted to various material properties using empirically established correlations for design calculation without careful considerations. Another example is the excess use of commercially available computer codes without careful examination of their applicability and limitations. Such practices must come to an end, preferably in the near future, but this will require a critical view of conventional design practice. Code writers are primarily responsible for bridging the gap. Design must be based on a sound scientific basis. Academia should take the lead and provide more frequent State of the Art report, effectively fulfilling its responsibilities to indicate which methods should be adopted (Poulos et al., 2001).

As was stressed in the previous section, environmental considerations will certainly form a vital part of foundation design and analysis in the future. Design considerations on various environmental impacts, such as noise emissions, ground vibration, material and energy use, and the selection of construction machines, will become routine work in design processes. For the re-use of foundations, detailed documentation of the foundation during the design, construction and monitoring stages will also form a part of foundation engineering.

New Frontiers of Foundation Engineering Application

New frontiers of foundation engineering application have spread applications from land to ocean and even into space. As this transition continues to take place, geotechnical engineers face a number of challenges and are responsible for overcoming them with innovative technologies. Academic research and practical knowledge needs to be systematically integrated and accumulated to achieve these goals. Offshore wind farms, natural resource production facilities and space exploration are typical examples among such new frontiers.

Research on the foundations for offshore wind turbines which generate electric power has been carried out in this decade (for example, Byrne and Houlsby, 2003). A feasibility study was also carried out from multiple perspectives (Junginger et al., 2004). A vast amount of knowledge and experience with regard to underwater construction and operation has been accumulated in the petroleum and mining industry. Aubeny et al. (2001) summarized relevant geotechnical experiences and challenges in deep and ultra deep waters. Besides the maritime topics, US President Barack Obama made remarks outlining the space program, including sending astronauts to an asteroid and Mars by the mid-2030s (Obama, 2010). Other major countries also have their own plan to manned/unmanned mission to the moon. Substantial contributions to these new frontiers are expected from foundation engineering.

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