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The role of geotechnical engineering in the preservation of our architectural heritage

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Abstract

Geotechnical Engineering is probably the youngest branch of Civil Engineering, yet it has already provided solutions to a wide range of different problems.
This paper highlights the contributions of Geotechnical Engineering to the preservation of monuments, ancient buildings, cities and historic sites.
Special attention is given to the activities of a Technical Committee on the Preservation of Historic Sites (TC-19) of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), which has played a major influence in promoting a culture of conservation of our architectural heritage within the geotechnical community.
A methodological approach towards a widespread use of geotechnical knowledge to face the problems related to the preservation of our architectural heritage is presented and discussed, as the result of a careful review of relevant contributions in this field. In order to focus the attention on some key points of the suggested approach, reference is frequently made to a well-known case history.

1 Introduction

Structural Studies, Repairs and Maintenance of Historical Buildings (STREMAH) have successfully reached their VIII International Conference.
Over the years, they have attracted specialists and scientists from all over the world, and advances in research have been mostly due to the fruitful interaction between specialists having widely different backgrounds. It is now increasingly recognised that an interdisciplinary approach is the key to an appropriate solution for the restoration of buildings of historical and architectural value.

Geotechnical Engineering, probably the youngest branch of Civil Engineering, has long provided its contribution in this field.
In the following presentation, a brief description of Geotechnical Engineering is preliminarily given, pointing out its peculiar features. The role of Geotechnical Engineering in the preservation of the architectural heritage is subsequently presented; special attention is drawn on the influence played by some outstanding specialists who had the merit of linking this discipline to Environment, Archaeology and History, thus paving the way to the establishment of an International Technical Committee on the Preservation of Historic Sites (TC-19).
Relevant suggestions, proposals and critical remarks provided by several authors are eventually presented within the framework of a methodological approach which emerges by reviewing and assembling the numerous significant contributions collected on this topic. Reference is made to a well-known case history, in order to clarify some important issues.

2 What is Geotechnical Engineering?

The birth-date of Geotechnical Engineering is usually assumed as 1923, the year of publication of a fundamental text by Karl Terzaghi, who elucidated the mechanical role played by the water occupying the pores between soil particles.
For this milestone, and for many other contributions, having both theoretical and practical relevance, Terzaghi is undisputedly considered as the father of this discipline of Civil Engineering. Since 1923, the growth and diffusion of Geotechnical Engineering have been surprisingly fast: a few years later, an International Society devoted to the newly born discipline had already been founded, its name being initially defined as "International Society for Soil Mechanics and Foundation Engineering" (ISSMFE), and Terzaghi being appointed as its President; the first International Conference of ISSMFE was held in 1936 in Cambridge, U.S.A., and after a long pause due to the II World War, ISSMFE Conferences have re-started, reaching their XV edition in Istanbul, Turkey, in 2001, at the beginning of the new century and millennium.
The name of the Society has been recently modified into "International Society for Soil Mechanics and Geotechnical Engineering" (ISSMGE); apart from this semantic modification, it is interesting to define clearly what Geotechnical Engineering actually means, i.e., what it deals with, and how.
Geotechnical Engineering deals with all problems involving soils and/or rocks, such as slope stability, foundation engineering, deep excavations, retaining and underground structures and many others. As any other branch of engineering, it has a quantitative approach, and is thus completely different from Geology, which relies essentially on a naturalistic, qualitative approach.
In other words, any geotechnical problem (e.g., the determination of the bearing capacity of a foundation, the evaluation of the active/passive thrust acting on a retaining structure...) is defined by means of an appropriate physico - mathematical modelling, i.e., via the definition of an appropriate set of equations governing the problem itself, which are usually cast as differential equations.

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The general solution of the problem is then obtained either in analytical or in numerical form. From a practical point of view, the answer to a given engineering problem requires to assume appropriate values for the parameters of the model used in design analyses to describe soil behaviour, such as resistance and / or stiffness parameters.

Unfortunately, a mere identification of the nature of soils involved in a specific problem is far from allowing to select a priori adequate values for the relevant parameters to be used in the analyses, the behaviour of soils being heavily dependent on a large number of factors. This, in turn, requires that, for each different engineering problem, ad hoc geotechnical investigations (in situ and / or in the laboratory) are needed. More precisely, geotechnical investigations:

- need to be planned with adequate extension, with clear reference to the problem to be studied;
- need to be carried out under a skilled supervision;
- require a careful interpretation of their results.

A proper evaluation of the results of a well planned and performed programme of geotechnical investigations allows to define a model of the subsoil, i.e., a simplified, yet realistic description of the subsoil which is amenable to analyses, which can hence provide a quantitative answer to any technical problem.

A further peculiarity of Geotechnical Engineering which cannot be overlooked is the relevance of technological features. The designer can obviously benefit from all available technologies, provided a careful evaluation of their performance in the overall process of design is carried out: careless use of seemingly attractive technologies has sometimes turned into a failure.

Geotechnical Engineering has experienced a dramatic progress in less than a century's life, in terms both of theoretical advances and successful solution of challenging problems, and has enlarged its fields of application, offering its contributions in the preservation of monuments and historic sites. A key role has been played by the activities of the Technical Committee TC19 of ISSMGE, which are briefly described in the following section.

3 Technical Committee on Preservation of Historic Sites

The Technical Committee TC19 on Preservation of Historic Sites was established by the International Society for Soil Mechanics and Foundation Engineering (ISSMFE) in 1981, with the purpose of providing a forum for interchange of ideas and discussions, collection of case histories and promoting and diffusing a culture of conservation within the geotechnical community.

The birth and the first steps of TC19 were mainly due to the joint effort of two leading figures of ISSMFE: Prof. Jean Kérisel from France, who had previously served as President of ISSMFE from 1973 to 1977, and Prof. Arrigo Croce from Italy, who had just been elected as Vice-President for Europe for the quadriennium 1981-1985.

During the quadriennium 1981-1985, TC19 was chaired by Prof. Kérisel with the sponsorship of the French Member Society of ISSMFE, and was actively supported by Prof. Croce. From 1985 to 1989 both the French and the Italian

Member Societies kept the sponsorship of the Committee, with Prof. Croce as Chairman and Dr. Isnard as Secretary.
Since 1989 the Italian Society has taken over the sponsorship, under the chairmanships of Prof. R. Jappelli (1989-1993) and Prof. C. Viggiani (1993-2001), respectively assisted by Dr. P. Croce and by Dr. S. Aversa as Secretaries. For the quadriennium 2001-2005 both the Italian and the Greek Member Societies will be keeping the sponsorship of TC19, Prof. C. Viggiani and Prof. Ch. Tsatsanikos both serving as co-chairmen, and Dr. S. Aversa as Secretary.
The activities of TC19 first started focussing the attention on Mediterranian countries; in 1984 a meeting of the Committee was held in Pompeii on the occasion of an International Symposium on Humanities and Physical Sciences held at the University of Naples. The Committee's work has been subsequently developed in Europe, North Africa, Central and South America, South East Asia. The work in progress toward the definition of a methodological approach to the unique and challenging geotechnical problems posed by the preservation and restoration of old monuments and historic sites has been presented in volumes published on the occasion of the XII International Conference (Rio de Janeiro, 1989) and of the X European Conference (Florence, 1991) of the ISSMFE.
The highlight of the activities of TC19 has been the International Symposium on Geotechnical Engineering for the Preservation of Monuments and Historic Sites held in Naples in 1996. The Symposium included the presentation of special lectures, session reports, invited lectures; the vast amount of papers (about 100) collected in the proceedings of the Symposium is undoubtedly an invaluable source of reference on the subject. In the following section several relevant contributions offered at this Symposium will be mentioned.

4 A methodological approach

TC 19 has strongly supported an interdisciplinary approach to the preservation of old monuments and buildings, introducing the concept of Ground Monument System (GMS), i.e., the idea of treating as a whole system the monumental building, its foundations and the underlying subsoil, thus performing both investigations and analyses involving all the three components of system itself, as suggested by Croce [1].
In other words, the separation between the structure and its foundation and between the foundation and the ground is fictitious, and the ground-monument must be considered as a unity, as stated by Jappelli [2].
Before the general acceptance of the GMS concept, the routine approach for the restoration of an ancient building restricted the investigations only to the part of the structure above the ground level, which was very carefully represented in detailed plans and cross-sections, where the foundations and the subsoil were not included and a thick black line was drawn at the ground level, as described by Viggiani [3]. This simply means that no attention whatsoever was usually paid to the foundations and to the underlying subsoil.

Going through the significant contributions offered by geotechnical engineers in the preservation of our architectural and historical heritage, a wealth of relevant proposals, suggestions and critical remarks can be found, which can be merged to define a methodological approach to be followed to take full advantage of the use of geotechnical knowledge to face preservation and restoration problems.
For ease of presentation, the methodological approach can be thought as consisting of the following steps:

(1) investigations (covering historical, geotechnical, structural aspects);
(2) definition of the model of Ground Monument System (GMS);
(3) diagnosis (back to the past);
(4) definition of the purposes and the limits of the interventions;
(5) definition of different remedial measures (therapy), if any;
(6) evaluation of their effects (forward to the future);
(7) selection of the most appropriate solution, respecting boundary conditions;
(8) definition of a monitoring plan of the behaviour of the restored monument.

Although each step appears essentially self-explained, yet most of them deserve some appropriate remarks. In order to elucidate their meaning, remarks will be frequently referred to the Leaning Tower of Pisa, which probably represents the best known and documented case history of preservation of a monument essentially achieved through the contribution of Geotechnical Engineering.
Studies on the Tower of Pisa date back nearly to its construction period; restricting our attention to the last century, several Committees for the safeguard of the Leaning Tower have been appointed. The results of the investigations and the analyses carried out by the Committees have been reported in detail; many of such detailed reports, sometimes published as scientific papers in the Proceedings of International Conferences or in technical journals, are due to Prof. C. Viggiani [4], who has been active in a large number of these Committees, having thus the opportunity of studying the behaviour of the Tower for an overall period of nearly four decades.
The Committee which is presently in charge is chaired by a geotechnical engineer, Prof. M. Jamiolkowski [5], Past President of ISSMFE, and has the distinctive feature of including not only geotechnical and structural engineers, but also architects, historians and art critics. The successful restoration and preservation of the Tower have been achieved by means of the combined effort of this team of specialists having widely different backgrounds.

(1) Investigations.

As previously observed, geotechnical engineers are familiar with investigations, at least as far as the subsoil is concerned, since they are inevitably the first step in the solution of any engineering problem related to the subsoil.
While dealing with the preservation of an old monument or an ancient building, investigations have to be conceived, planned and carried out with a wider extension, both in space and time. The GMS concept previously presented calls for investigations concerning the (super)structure, the foundations and the underlying subsoil.

A well-known example of a unitary approach to the study of a monument is the analysis of the behaviour of the Leaning Tower of Pisa; in accordance with the GMS concept, investigations have been planned and carried out well beyond the "black line" described by Viggiani [3].
Investigations covered both geotechnical and structural aspects, and significant contributions in the definition of the GMS model were also obtained by the study of ancient documents and even paintings, thus proving Croce's belief that Human Sciences, and especially History and Archaeology, could provide a wealth of useful information.

(2) Definition of the model of the Ground Monument System
As a matter of fact, investigations are closely linked with the model of the GMS, and are actually conceived to help the definition of the model itself, which, in turn, governs the extension of the investigations. On the other side, the model of GMS should be conceived and defined as accurately as possible, as to allow a reliable assessment of the safety of the GMS (diagnosis).
Referring again to the Leaning Tower, the inclination of the structure is a significant and sensitive index of the performance of its foundation resting on the subsoil; the GMS (structure + foundation + subsoil) has to be analysed within the broader framework of the performance of the surrounding square.
A significant phenomenon to be accounted for in the analyses is the water pumping from the deep aquifer of the Pisa plain, for which there is both experimental and historical evidence.
In other words, the definition of the GMS for the Leaning Tower has required to focus the attention also on a vast portion of the Territory where the Tower rises.

(3) Diagnosis (back to the past).
Once the model of the GMS has been defined, analyses of its behaviour can be carried out. The first objective being the assessment of the actual safety of the GMS, in this step analyses are performed looking back to the past and simulating the history of the GMS.
The chain which links investigations, modelling and analyses is evident; referring once more to the Leaning Tower, the analyses of the behaviour of the system composed by the Tower, its foundation and the underlying subsoil has called for an overall analysis of the behaviour of a larger extension of the Territory, and has pointed out a clear influence of the water pumping on the increase of the inclination of the Tower.
A somewhat similar problem, analysed and successfully solved by Croce [6], were the settlements of Milan Cathedral, which were due to water pumping from the subsoil.
For both these case histories, the cause / origin of the problem was essentially geotechnical; according to Calabresi and D'Agostino [7], who presented the General Report on Intervention Techniques at the International Symposium on Geotechnical Engineering for the Preservation of Monuments and Historic sites, for most of the papers collected in the Proceedings of the Symposium the origins and the causes of the damages were in general of geotechnical nature.

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(4) Definition of the purposes and the limits of the interventions
This step enjoys the greatest benefits deriving from the contribution of a composite team of specialists having different cultural backgrounds. It seems appropriate to recall a simple and clear definition of material integrity, due to a famous Italian archaeologist, G. Gullini: "a monument consists not only of its appearance, but also of the materials it is built with, and of its structural scheme".
This concept has been completely accepted by Calabresi and D'Agostino [7], who point out a drawback of the use of micro-piles: "Micro-piles are becoming a common solution for almost any kind of remedial and restoration intervention of monuments and historic buildings. This point should be examined in detail and is worth a critical discussion. It is, in fact, evident that an underpinning with piles completely destroys any chance of analysing the sedimentary layers of the ancient construction. Foundation work based on pile structures does not provide for a survey of the ancient foundations and of the original conditions of the site and of the soils involved and modifies the structural behaviour of the whole construction, the underground part of which is an essential component." As an alternative, Calabresi and D'Agostino suggest to carry out a scientific study of existing foundations through an appropriate series of excavations, carried out in conjunction with expert archaeologists. In many cases, ancient foundations might turn out to be still able to perform satisfactorily with minor (if any) modifications / integrations. This opinion is shared by the author [8], who has reported the successful re-use of an ancient foundation of an abandoned church, after a thorough programme of investigations and analyses performed by a team of specialists of different technical backgrounds.
In a few words, the key issue for this step is the careful selection of intervention techniques which are respectful of the material history and of the intrinsic value of the monument / building, avoiding unnecessary works.

(5) Definition of different remedial measures (therapy), if any
This aspect, too, has been covered in detail by Calabresi and D'Agostino [7], who, encompassing a wide variety of remedial measures, observe that, in most cases, either structural or geotechnical interventions (or both) are selected. From a strictly engineering point of view, although a great variety of problems is to be faced "It seems that a technical solution for their specific problems is in any case available. The great improvement of construction materials and techniques has made possible almost any kind of restoration works".
Calabresi and D'Agostino also provide a useful classification of intervention techniques, which are subdivided into four different classes, and two extremely reasonable suggestions: (i) adoption of the traditional masonry underpinning work, which in many cases might turn out to be an effective remedial measure; (ii) avoidance of unnecessary works.
The latter suggestion is also supported by an interesting case history, involving one of the two Roman bridges still standing in Rome, which has been restored by means of simple interventions, without carrying out any works on the foundations.

(6) Evaluation of the effects of remedial measures (forward to the future)
A quantitative evaluation of the merits and the drawbacks of all the solutions which have been considered in the previous step has to be carried out, in order to predict the behaviour of the restored GMS.
It should be kept in mind, however, that the analysis of soil-structure interaction for ancient buildings it is even more complex than for new structures. Numerical models can be helpful to analyse the behaviour of old structures and examine the effects of different solutions, but they usually provide only qualitative results.

(7) Selection of the most appropriate solution, respecting boundary conditions;
The respect of both the material integrity and of the intrinsic value of the monument, which have been previously discussed, are to be considered as boundary conditions, once they have been specifically indicated as an a priori requirement. Solutions which would violate this requirement should thus be discarded.
An example is provided once again by the long history of the Leaning Tower of Pisa. In 1977 a solution of underpinning the Tower by means of a pile group reaching a firm sand layer was actually discarded. The present Committee, charged with the task to select and design appropriate measures to halt the increase in Tower tilt and (partially) recover it, has succesfully adopted a soft, reversible technique based on a controlled removal of soil from the upper side.

(8) Definition of a monitoring plan of the behaviour of the restored monument
Once the most appropriate remedial measures have been selected and carefully designed, the behaviour of the monument has to be carefully monitored both during and after the execution of the intervention works. Geotechnical monitoring of historic monuments is discussed in detail in the lecture given by Burland and Standing [9]

5 Concluding remarks

Geotechnical engineers have long provided their technical contribution to the preservation and restoration of monuments and old sites.
A comprehensive collection of stimulating general reports and interesting case histories can be found in the Proceedings of the International Symposium on Geotechnical Engineering for the Preservation of Monuments and Historic Sites held in Naples in 1996, and in many other relevant contributions.
A widespread use of geotechnical knowledge to face the problems related to the preservation of our architectural heritage is to be supported; to this purpose, a brief description of Geotechnical engineering has been given, and the relevant contributions offered by several authors have been presented within the framework of a methodological approach.

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