FOUNDATION PROBLEMS OF KONYA ALAEDDİN MOSQUE AND IMPLICATION OF REMEDIAL MEASURES

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ABSTRACT

Severe structural cracks in the structural system of the historical Konya Alaeddin Mosque have been investigated and a remedial design has been performed to eliminate this problem resulting from the settlements of the foundation subsoil and resulting differential settlements of column and wall foundations. Subsoil conditions have been investigated and a geotechnical model has been developed to identify the related displacements and structural damage mechanism. Micro piles have been constructed beneath the structure to transfer the loads to deeper soil layers and cement grouting has been implemented to improve the subsoil conditions. Extensive instrumentation has been implemented and the relevant parameters have been monitored during the application of the remedial measures.

1. INTRODUCTION

Konya Alaeddin Mosque was built in the twelfth century by the Seljuks, on Alaeddin Hill known to be a man-made artificial fill. The monument, has taken its final form in time with various revisions and extensions along the eastern and western sides. It is observed that remnant pieces have been used in construction and the structural system is formed of masonry arched resting on stone columns. A plan of the mosque showing the locations of the masonry walls and the stone columns is given in Figure 1.

Although the problems related to the foundation system and subsoil have been encountered long before and several attempts have been made for solution of the

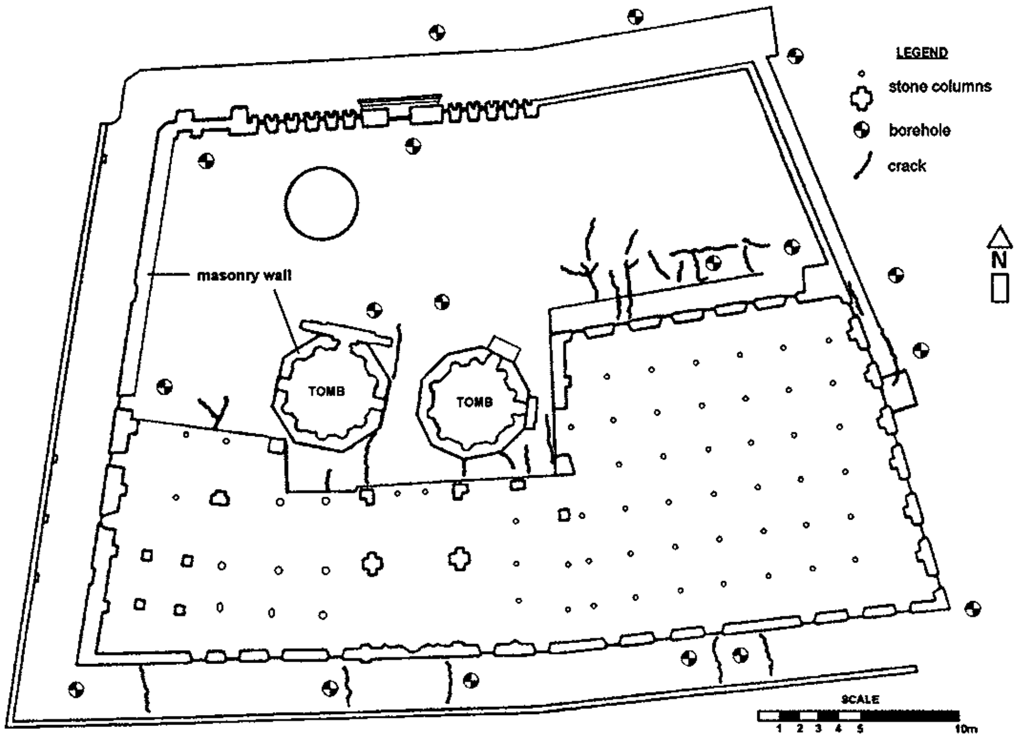

Figure 1. Konya Alaeddin Mosque, location of structural elements

problem, the situation became worse and the damage in the structural system has expanded to the other parts of the structure due to improper recognition of the cause of problem at early stages. Especially in the last 25-30 years, elements of the structural system have been subjected to severe cracks and distortions. Various investigators have agreed that this was a result of deformations and settlements in the subsoil. Although several remedial measures including structural reinforcement of the foundations and ceiling have been conducted during the period of 1967-1972, the problems related with the structural elements have not been overcome. Finally in the past with accelerating crack propagation and structural damage, to avoid any structural collapse, the structural elements have been supported with a frame system and the mosque has been closed to the public.

At this stage the governmental agency have consulted the prime author, describing the past problems and have asked to evaluate the problems towards the technical solutions. Consequently, integrated analyses have been performed in the assessment of the problem and implementation of a engineering solutions. Various studies have been made at the initial stage with the evaluation of available data. Additional investigations have been performed to determine the subsoil conditions and the assessment of the deformation pattern. The problem has been modeled using various numerical techniques with the implementation of instrumentation data. It is determined that the foundation soil is responsible for the observed structural damage as a result of leaching with water. Remedial design has involved the implementation of cement grout for subsoil improvement and micro piles beneath the structural columns and walls. The behavior of the structure has been monitored during implementation by means of instrumentation.

2. SUBSOIL PROPERTIES AND PROBLEM DEFINITION

The deformations in the subsoil are expected to be the main cause in the generation of the observed cracks. Identification of subsoil behavior and problem definition is one of the primary factors in the choice of proper remedial measures and soil improvement technique. For this purpose, detailed and integrated subsoil investigations have been initiated in 1983 and the first attempt has been made for a model test to monitor the results of remediation [1]. It has been concluded with the evaluation of the performed subsoil investigations and available data, that the cracks in the structural elements were caused by the differential settlement of the foundation. The fill material that forms the foundation subsoil is identified to be the main source of the differential settlements. Seepage as a result of leakage from a water reservoir near the mosque, piping system and seasonal precipitation have created solution cavities and channels in the foundation subsoil which ultimately caused local collapses within the structure. Therefore it has been decided that the foundation subsoil conditions have to be improved to prevent any additional deformations as a result of soil structure collapse.

Furthermore, following the identification of the problem, trial cement groutings have been performed for the choice of proper soil improvement method, and it has been observed that cement-water mixture grouting could be properly utilized for soil improvement purposes, without causing any further damage to structural members [2]. Finally the remedial project consisting of subsoil grouting and micro-pile construction beneath load carrying walls and columns has been implemented.

A monitoring system has been developed in the mosque to monitor the soil behavior and structural system performance during and after remediation. Series of pressuremeter testing has been conducted prior to and after the improvement to evaluate the achievement of the remediation with respect to mechanical properties of the subsoil.

3. STRUCTURAL AND GEOTECHNICAL MODELING

The structure and the foundation subsoil have been modeled for the identification of the deformation mechanism and evaluation of various soil improvement scenarios. In these studies, the cracking mechanism, the explicit indication of deformations has been examined and several factors contributing to the lateral and vertical deformations have been separately analyzed. Governing subsoil behavior and crack formation pattern is identified based on the results of these modeling studies.

3.1. Structural Cracks

Crack monitoring and analyses of structural behavior are important measures of control necessary during the design and application phases of the remedial project. For this purpose numerous extensometers have been installed to monitor the propagation of cracks and ground movements.

It has been determined from the evaluation of performed subsoil investigations and study of crack locations that the foundation of the structure has been subjected to differential settlements. The foundation subsoil has been observed to be highly decomposed due to leakage from the water reservoir located below the southern face and eastern corner of the mosque, which has been used for long years as municipal water storage. Finite element analysis has been performed to evaluate and model the deformation pattern expected to occur within the subsoil located below the mosque. The settlement mechanism and the resulting crack pattern along the northwest-southeast wall are shown in Figure 2.

3.2. Lateral Deformations

It has been determined from overall slope stability analyses, no stability problems or lateral deformations are expected to occur at the Alaeddin Hill where the mosque is located. However the cracks in the structural elements have revealed that the mosque has been subjected to lateral deformations. The mechanism could be explained in a way that the vertical deformations in the foundation subsoil have

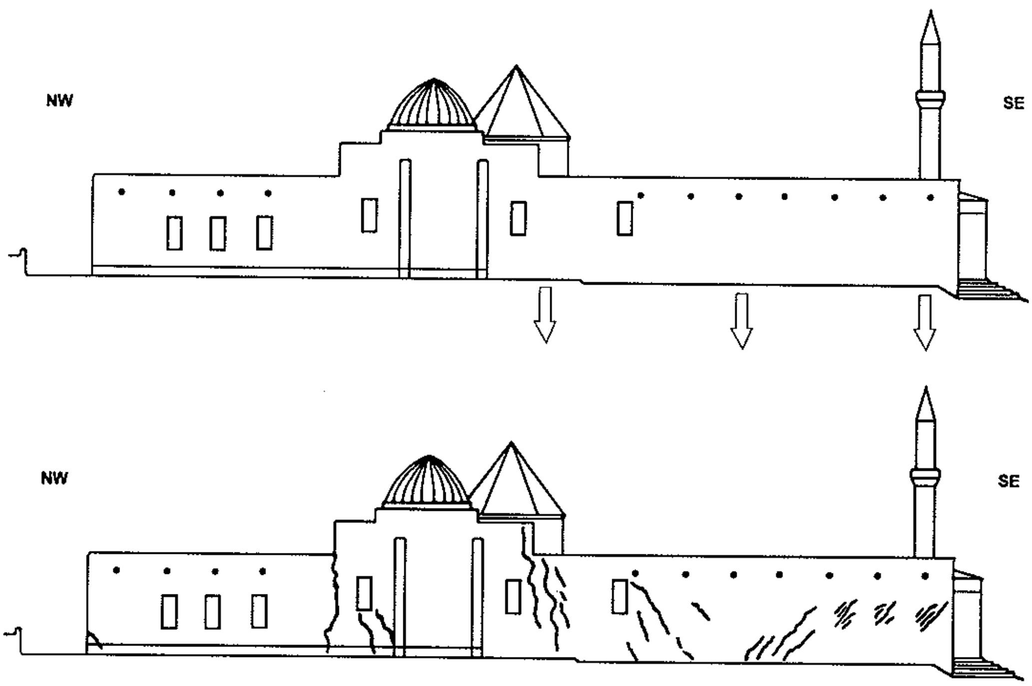

Figure 2. Settlement mechanism and resulting crack pattern along SW-NE wall

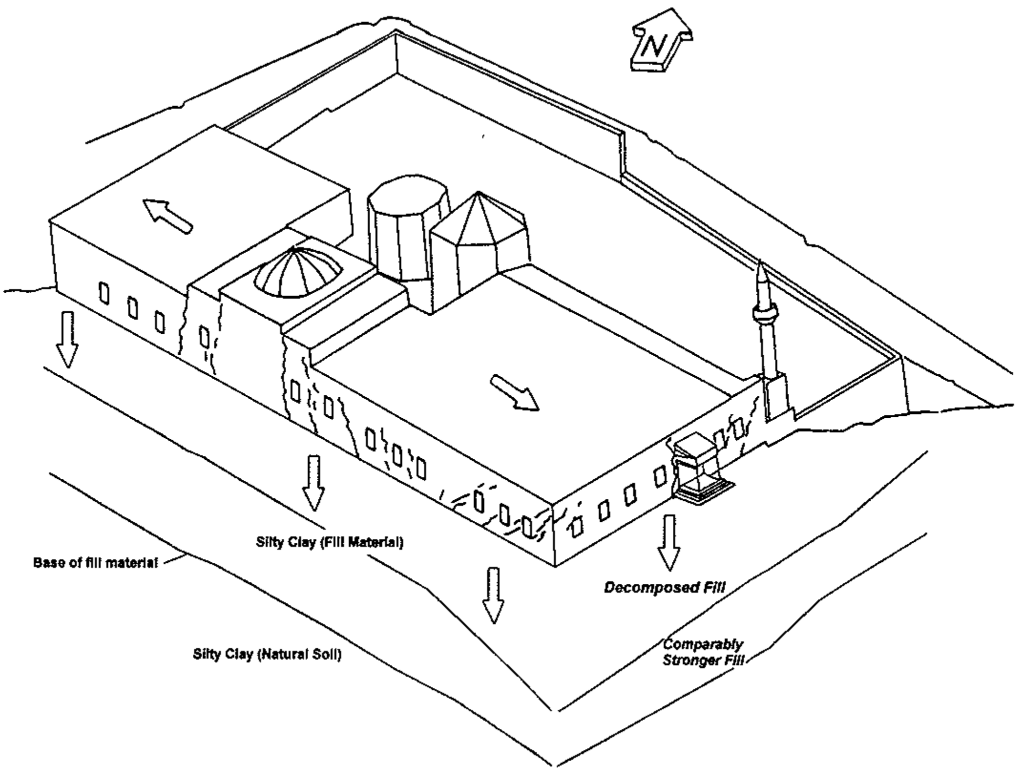

Figure 3. Schematical representation of three dimensional deformation pattern

resulted in lateral deformations in the structure due to the behavior of the structural system. In one of the remediation attempts in the past the altar has been connected with tie beams and the roof at these locations has been replaced with reinforced concrete slab. This solution has prevented a possible local failure of the structure and however at the same time it has led the problem to spread to other sections/parts of the mosque. This situation has changed the behavior of the structure drastically. Due to the connections made along structural elements differential settlements in the foundation have resulted in lateral deformations in the structure. A schematical representation of the three dimensional deformation pattern is given in Figure 3.

4. SOIL IMPROVEMENT STUDIES

The method implemented in the improvement of subsoil conditions involves pressure grouting within the fill having solution cavities and channels as a result of leaching with seepage water which is identified to be the main cause of the settlement problem and underpinning of load carrying elements with micro piles. The deformations in the subsoil and structural elements have been continuously monitored during the implementation of the project. The degree of improvement in the mechanical properties of the subsoil has been assessed with pressuremeter testing performed before and after grouting.

Two lines of cement grouting have been performed along the outer walls and these have been followed by grouts along the inner walls facing the courtyard and around the tombs. Finally the courtyard interior part of the mosque has been grouted, with grout locations forming a grid along the plan. The groutings have been produced to penetrate the nearly 25.0 m thick fill completely and socketed 2.0 m to the natural alluvial subsoil.

After the completion of the grouting application, micro piles have been constructed beneath all load carrying members including masonry walls and columns to transfer the loads to deeper soil layers. The micro piles have been drilled to penetrate the alluvial subsoil located below the fill. Upon completion of the micro piles, all structural load bearing elements, i.e. walls, stone columns, were connected to the micro piles with special elements, in order to be able to transfer any additional load from the superstructure to the newly constructed micro piles. Vertical capacity of the micro piles have been assessed by means of load tests.

5. INSTRUMENTATION AND MONITORING PROGRAM

Deformations in the subsoil and propagation of present cracks in the masonry walls and columns during grouting have been monitored with a precise instrumentation. For this purpose, crackmeters have been installed at cracks present in the load carrying members, such as masonry walls and columns. The settlements and deformations in the foundation soil during grouting have been monitored with several borehole extensometers. Additionally, the general pattern of structural movements have been monitored with extensometers installed between column spacings and exterior wall corners [3]. The safety of the remediation has been realized with the evaluation of the monitoring data.

A total of 56 crackmeters with 0.01 mm precision have been installed at crack locations and the propagation has been continuously monitored. It is seen in general that the movements in the cracks have terminated at the time just after the implementation of the remedial measures.

Additionally borehole extensometers have been installed within the subsoil to monitor the deformations and settlements in the subsoil during remediation works. Such deformations are important measures of the differential settlements that create the crack formation mechanism. The extensometers are installed at 5.0 m and 10.0 m depths from the ground surface to monitor the deformations at these locations. A total of 58 extensometers have been installed for this purpose.

A database system has been developed for the treatment of instrumentation data in the evaluation of the subsoil movements and structural behavior.

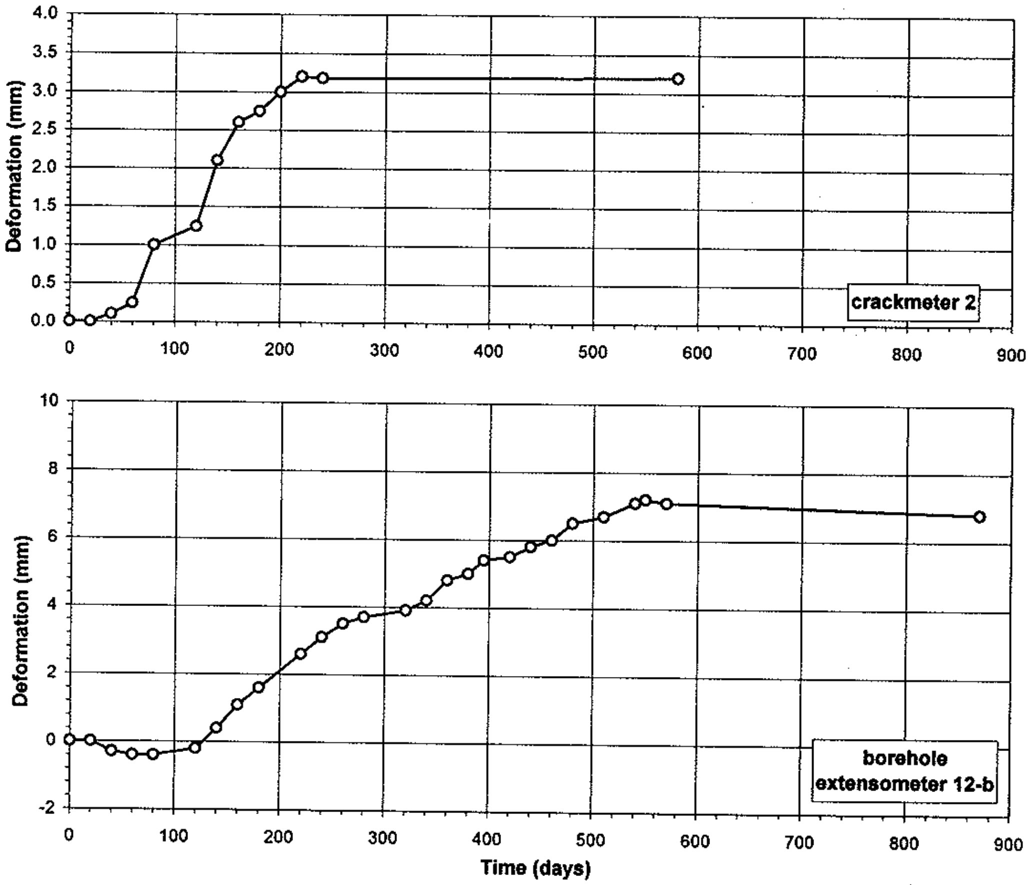

Figure 4. Deformation measurements from crackmeter and borehole extensometer

Deformation data obtained from a crackmeter and a borehole extensometer are given in Figure 4. The deformations observed both by crackmeters and extensometers are observed to diminish within time with the implementation of remediation works.

6. ASSESSMENT OF SOIL IMPROVEMENT BY MEANS OF IN-SITU TESTING

In-situ testing in the form of pressuremeter readings has been implemented to determine the degree of improvement in the mechanical properties of the subsoil. Pressuremeter testing is performed to evaluate the improvement in the bearing capacity and compressibility of the subsoil as a result of grouting. Pressuremeter testing is performed in 17 boreholes with 1.5 m intervals, extending up to 25 m depth before and after implication of soil improvement measures and therefore the degree of soil improvement has been assessed.

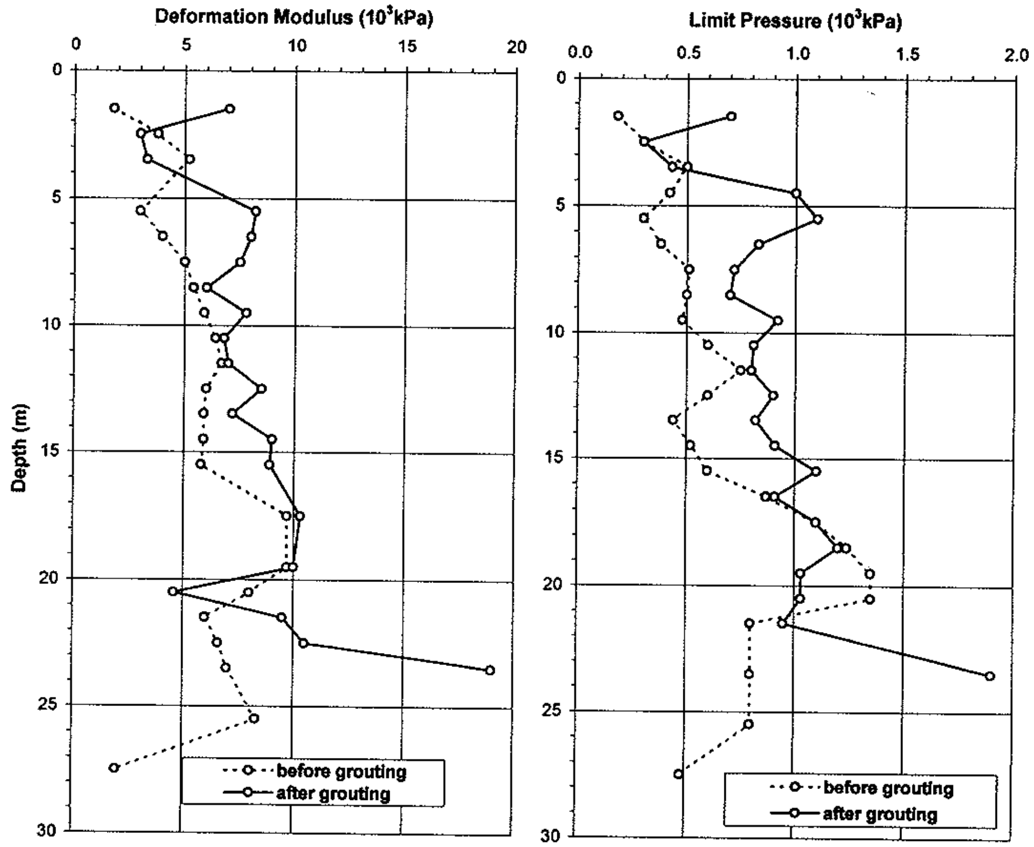

Figure 5. Assessment of degree of soil improvement from comparison of deformation modulus and limit presure obtained from pressuremeter testing.

The results of pressuremeter tests are presented in Figure 5. The change of limit pressure and deformation modulus before and after improvement are shown in the figure. The increase in limit pressure is a measure of the increase in shear strength and the bearing capacity and the increase in the deformation modulus is a measure of decrease in the subsoil compressibility.

Therefore, safety of the structure during implementation of remedial measures has been satisfied with the integrated approach of instrumentation and monitoring during application, and it has been possible to justify and implement an engineering solution by monitoring the efficiency of the soil improvement. Both the results of the displacement monitoring and pressuremeter testing indicate that the mechanism that results in structural cracks have been eliminated.

7. CONCLUSIONS

The causes of the severe structural cracks which occurred in the historical Konya Alaeddin Mosque have been investigated and a remedial design has been implemented to eliminate the problem. The remedial project consists of the improvement of the subsoil conditions and foundation systems of the structural walls and columns.

Integrated studies have been performed including subsoil investigations and geotechnical modeling to identify the related deformation and structural damage mechanism. The load carrying structural elements have been underpinned with micro piles and cement grouting is implemented to improve the subsoil conditions. Instrumentation has been conducted and the relevant parameters have been monitored with various geotechnical instruments during the implementation of the project.

As a result of this integrated remediation, the settlement mechanism that generated the problem has been eliminated and the mosque has been furnished for further structural restoration.

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