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Structural damage caused to RC buildings by tunnelling work

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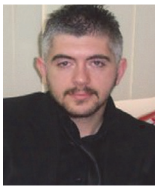

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Professional paper

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Structural damage caused to RC buildings by tunnelling work

Structural damages to RC (Reinforced concrete) buildings occasionally occur as a consequence of sudden ground movements. One of these is effect of tunnel excavation on the structures and the design process should be carried out by taking the effect into account. In this study, the structural damages caused by the impact of sudden movement emanating at the ground were investigated for a selected hospital building. Within the scope of this study, it was aimed to obtain the most accurate data by combining different engineering disciplines through a comprehensive approach.

Key words:
structural damage, ground movement, tunnel excavation, ground strengthening, georadar

Stručni rad

Baris Yildizlar, Baris Sayin, Ahmet Sertac Karakas, Cemil Akcay

Konstrukcijska oštećenja armiranobetonskih građevina uslijed gradnje tunela

Nagli pomaci u tlu mogu dovesti do oštećenja armiranobetonskih građevina. Takvi pomaci mogu između ostalog biti uzrokovani gradnjom tunela, pa se utjecaj takve gradnje treba uzeti u obzir u postupku projektiranja građevina. U ovom se radu na primjeru postojeće bolničke zgrade analiziraju konstrukcijska oštećenja armiranobetonske građevine uslijed naglih pomaka tla. Kako bi se dobili što točniji podaci za potrebe analiza, primijenjen je multidisciplinarni pristup radi povezivanja raznih inženjerskih disciplina koje su sudjelovale u ovom istraživanju.

Ključne riječi:
oštećenje konstrukcije, pomak tla, iskop tunela, pojačanje tla, georadar

Fachbericht

Baris Yildizlar, Baris Sayin, Ahmet Sertac Karakas, Cemil Akcay

Durch Tunnelbohrung verursachte Beschädigung von Stahlbetonkonstruktionen

Beschädigungen von Stahlbetonkonstruktionen werden gelegentlich durch plötzliche Bodenbewegungen verursacht, die zum Beispiel bei Tunnelbohrungen auftreten können. Daher muss dieser Effekt bei der Planung in Betracht gezogen werden. In dieser Arbeit werden durch den Einfluss plötzlicher Bodenbewegungen verursachte Konstruktionsschäden eines ausgewählten Krankenhausgebäudes untersucht. Die vorliegenden Erforschungen sind insbesondere darauf ausgesetzt, zuverlässige Resultate durch die Anwendung verschiedener Ingenieursdisziplinen und eines anschaulichen Verfahrens zu erhalten.

Schlüsselwörter:
Konstruktionsschäden, Bodenbewegung, Tunnelbohrung, Bodenverstärkung, Georadar

1. Introduction

Over the past 30 years, there has been a dramatic increase in the mechanized tunnelling activity for the construction of subway, railway, road, sewage and utilities tunnels in many big cities around the world. This has mostly resulted from the need to cope with population expansion and to improve urban and natural environments. With technological advances in the tunnel boring machine industry, more and more urban tunnel projects in soft soil environments are realized using tunnel boring machines. Because the urban tunnel construction is normally carried out in difficult and crowded city areas, one of major design and construction challenges lies in minimizing the induced ground movement, as it poses potential threats to nearby buildings and utilities along the tunnel alignment [1].
Some underground structures have experienced significant damage in recent large-scale earthquakes, including the 1995 Kobe, Japan earthquake, the 1999 Chi-Chi, Taiwan earthquake and the 1999 Kocaeli, Turkey earthquake [2]. Due to rapid urban development, more and more public facilities are being constructed under the ground surface. However, complex underground constructions may cause serious damage to existing buildings, structures, and utilities [3, 4].
The response of buildings to tunnelling-induced ground movement is a problem of soil–structure interaction, and so that the knowledge of both ground movement and structure is required. Failure to understand this interaction can lead to implementation of unnecessary protection measures, to the incurrence of unnecessary costs, and, consequently, to unsatisfactory results [5]. The influence on adjacent buildings is of major interest for tunnelling operations in urban areas, due to the high level of interaction between the tunnelling activity and existing structures [6, 7].
The construction of tunnels in soft soil generally induces soil movements, which could seriously affect the stability and integrity of existing structures. In order to reduce such movements, especially in urban areas, contractors are increasingly using tunnel boring machines (TBM) for the construction of tunnels. Indeed, thanks to the application of a face pressure and to the temporary support, the TBM aids in the reduction of soil disturbance due to tunnelling, providing enhanced safety to existing structures [8-10].
During construction of tunnels, which are planned to solve the traffic and infrastructure problems in big cities, there is always the risk of damage and collapse of buildings within the settlement zone in which the tunnel excavation is carried out (Figure 1). This is why some inspections must be done before and during tunnel construction, and the construction process should start only after the necessary precautions have been taken [7, 11-14]. This is even more important when public buildings such as hospitals, schools are concerned.

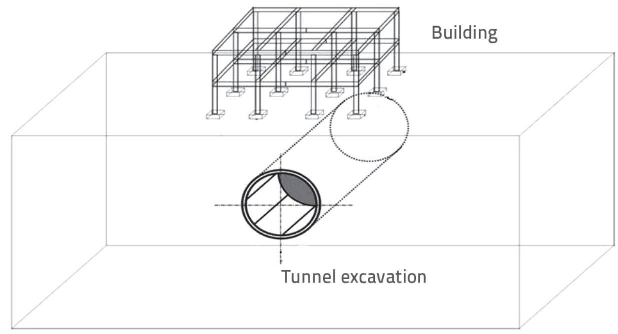

Figure 1. Tunneling–structure interaction problem (risk of damage and collapse of buildings) [15]

The Istanbul University (I.U.) Cerrahpaşa Campus is situated in the upper part of Yenikapi coast of Marmara Sea, in the region of Samatya (Figure 2). Within the campus, there are units belonging to Cerrahpaşa Medical Faculty, Faculty of Dentistry, institutes, vocational schools and two dormitories. There are many buildings, with approximately 220,000 m^2 of closed areas, within the 170,000 m^2 campus area of the Medical Faculty. These nearly 35-year old blocks serve as buildings for different departments, houses of chief physician and dean, as well as operating rooms. Some of these structures are detached and some are separated from each other by vertical joints (dilatations), with functional horizontal connections between them.

Figure 2. Satellite image of I.U. Cerrahpaşa Campus [16]

Satellite images of blocks E1, E2, E3, E4, and other blocks architecturally connected to them, are given in Figure 3. The operating-room blocks, E1, E2, E3 and E4 are qualified as being of critical importance for functioning of the I.U. Cerrahpaşa Medical Faculty. The central laboratory, operating rooms, sterilization department, departments of ophthalmology and cardiology, rooms of academic staff, polyclinic departments, and similarly used spaces, are situated in these buildings. The E1 block, which is the focus of the research, is a campus block that has to function without disturbance at all times, as it has the sterilization unit in it. In this hospital, which is one of the

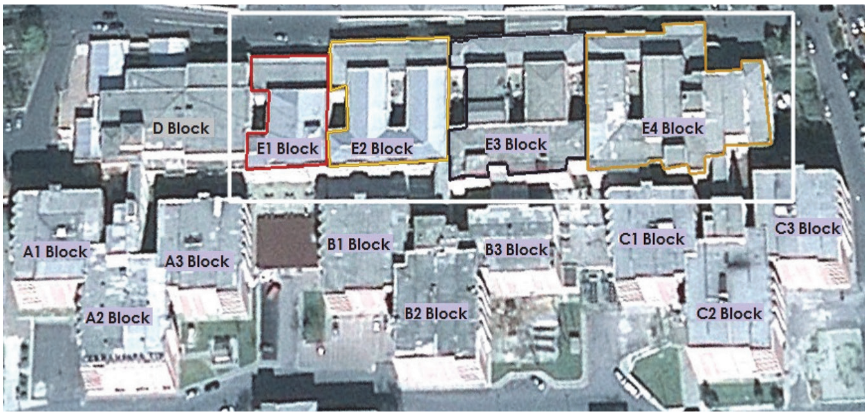

Figure 3. Satellite image of operating-room blocks and other related blocks in I.U. Cerrahpaşa Campus [17]

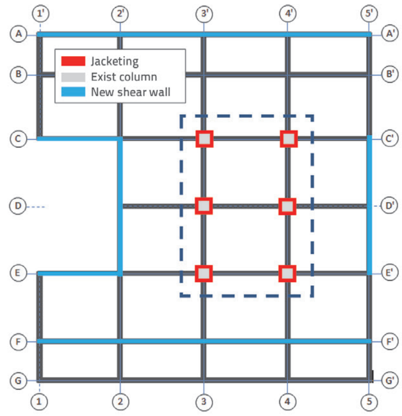

Figure 4. E-1 block basement floor plan: strengthened columns and new shear walls

most highly-respected faculties of medicine in Turkey, with many domestic and international patients, hygienic materials are supplied to the operating rooms only by the sterilization unit located in E1 building.

2. General information on building and strengthening conditions

Hospital building blocks making up the structure were examined using various equipment. The examination of these blocks revealed that the concrete of about 10MPa of compressive strength, and severe corrosion of reinforcement, are parameters presenting problems/weaknesses that are harmful to structural safety. The E1 block is the focus of this research with 696 m^2 in plan area and 2563 m^2 in usable floor area. The longest space in this block is 6.0 m in length. While the existing column dimensions are constant on the ground and first floors, they are decreasing gradually at upper levels. However, cross sections of the beams are constant throughout the height of the structure. Despite constant dimensions of the beams, the decrease in dimensions in the column cross section causes the strong beam - weak column problem for the carrier system. Before the structural strengthening, there was a RC shear wall along the x-axis only, and at four spaces along the same axis. As a result, when the cross sections and positions of the existing structural items are examined, it can be concluded that centres of gravity and rigidity are very far from each other. During previous strengthening works carried out at E1 block, a RC shear wall was constructed at five spaces along the x-axis, and at four spaces along the y-axis. The integration of reinforced concrete walls into the present structure was attempted using the minimum 0.2m thick jacketing of the columns in these spaces. The plan of the E1 block basement floor, where the strengthening work was conducted, is presented in Figure 4.

At the basement floor plan of E1 block, U-shaped structural items present at the left side of the plan, items positioned along the y-axis seen at the right side, and structural items presented along three spaces of the x-axis on F-F′ axis, are all RC shear walls added by strengthening works. The RC shear walls seen through four spaces along the x-axis on A-A′ axis are the first shear walls which existed initially [18].

The blocks under study are called the E1 and E2 blocks. They were separated from other operation blocks, E3 and E4, by dilatations while all together they were constructed in a consecutive manner. E1 and E2 blocks consist of 4 floors, i.e. one basement

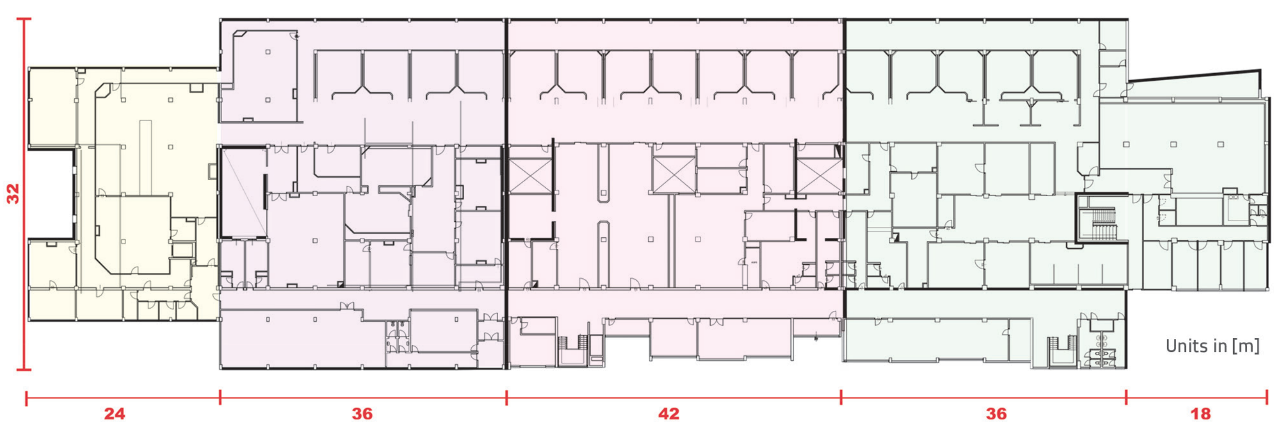

Figure 5. Floor plan of operating room blocks at I.U. Cerrahpaşa Campus

floor, one ground floor, and two upper floors, while E3 and E4 blocks consist of one basement floor, one ground floor, and three upper floors. These blocks have a RC shear wall-frame type load bearing system. The foundations of the blocks are continuous while their flooring systems are known to be girder slab. The strengthening work was carried out in operating blocks between 2005 and 2008. After this strengthening works, the blocks in question were subjected to architectural and cosmetic changes due to an increase and variations in demand. The architectural floor plan is given in Figure 5.

3. Importance of the study

With an increase in population in urban areas, infrastructural requirements are also steadily increasing and, in this perspective, new tunnels are being built, which generates the risk of damage to structures above such tunnels. It is important to minimize these risks prior to actual construction work, i.e. at the design stage, when appropriate feasibility studies should be made to prevent potential problems. This study presents possible risks before tunnel excavation, precautions which should be taken during underground excavations, and suggestions to prevent probable damage before excavation and construction of the tunnels. Operating room blocks at the Cerrahpaşa Medical Faculty of the Istanbul University are examined in this context.

The study comprises investigation of causes of structural damages, a ground-penetrating radar survey of the ground, strengthening of structures, examination of crack variations in structural elements, and proposals for the analysis of such structures. For this purpose, parameters that must be considered before and during tunnelling work are used as the basis for making suggestions aimed at preventing loss of time, increasing security and making financial savings.

4. Evaluation and precautions related to the damage

According to the personnel working at the E1 and E2 blocks, a sudden noise was heard in the building at midnight [19]. It is assumed that the cracks on the partition walls formed after this noise. It was established that the cracks are characterized by diagonal geometry. By considering the cracking geometry, it was suspected that an abnormal movement of soil beneath the structure occurred. It was also speculated that the wall cracking might have been caused by previous strengthening works on the structure and by the use of an inadequate strengthening method. This is why possible reasons for the abnormal ground movement were studied. Meanwhile, by considering diagonal cracks at partition walls, and their spreading with respect to the position of walls, it became clear that the structure was affected by settlement along the vertical axis. It was detected that cracks on the walls, especially the ones on the ground floor and the 1st floor, reached disturbing sizes. The structure was closed to the use by patients for security reasons, i.e. due to cracks of unidentified origin and concern for the personnel. Diagonal cracks 5mm in size, cracks on beam supports due to tension and bending, and shearing cracks, were identified on the walls of the sterilization unit, located at the basement floor, which is vitally important for the hospital building. Tensile cracks that formed due to bending were identified under the flooring of the basement level (Figure 6) [18].

It was observed that the relative displacement on the beams amounts to more than 1/250, and more than 1/250 of settlement was observed at the columns. Due to such relatively extreme settlement, the crushing due to bending at the upper part, and destruction of tiles, were observed at the floor level of the upper floor. All these findings point to the fact that the soil settled under the buildings in question. On the plan shown

Figure 6. Cracking observed on structural and non-structural elements

in Figure 4, the area enclosed by dashed lines represents the region where the relative settlements are concentrated within the building under study. The walls with cracks are division walls made of bricks, aerated concrete and gypsum boards.
After the decision was reached that the existing damage occurred due to ground movements, the reasons for the sudden displacement of ground were examined. Under normal conditions, the ground may move under an old building for the following reasons;

a. Sudden occurrence of water movement in the foundation soil, and drifting of foundation soil by water, i.e., occurrence of an event causing erosion under the foundations,
b. Tunnel construction or other excavation under or near the building,
c. An earthquake or a similar load.

There is no clear evidence for the mechanism described under a) above. The effect of an earthquake, presented under c) above, is impossible, as no earthquake occurred at that time. Therefore, the possible effect of tunnel construction was studied.

4.1. Investigation of causes of damage

While placing emphasis on possible causes of cracks at a specified level of the structure, and in order to observe the movement of the structure, the total of 30 mechanical crack measurement devices were placed as appropriate on the walls, beams and columns (7 items; MC-2:1-7 for the sterilization unit-E1 block, and 23 items; MC-1:1-23 for the operating rooms-E2 block). Crack variations were observed for 30 days, and data were recorded every day (Figure 7) [18].

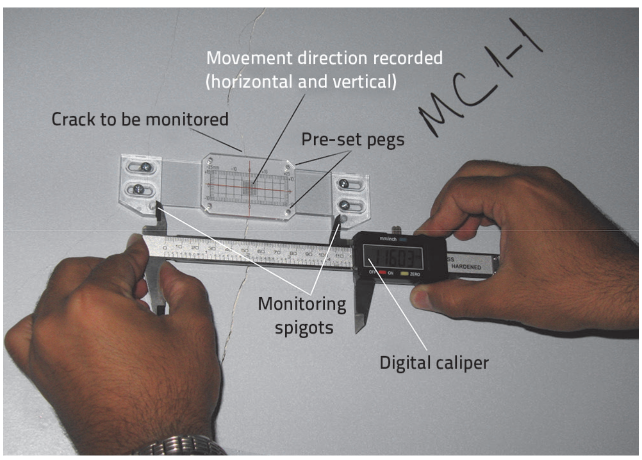

Figure 7. Mechanical crack measurement device

Additionally, external events for the formation of abnormal and sudden ground movements were investigated. Soil excavations near the hospital were scanned, and routes of the following recent excavations were studied: DLH (General Directorate for Construction of Railways, Harbours and Airways), the Marmaray Project (the Bosphorus Tube Tunnel), and ISKI (İstanbul Water and Sewage Management) European Side, 2nd part, Sewage Tunnel. Excavation processes belonging to the Marmaray Project were realized along two routes and one route, but there has been no progress for two years. The active excavation process at the other route of Marmaray Project is 1.5 km away from the building under study. The active excavation work at the other route of the Marmaray Project is nearly 1.5 km away from the structure under investigation. When the excavation route for construction of the ISKI (Sewage Tunnel) was examined, it was established that the excavation was continuing under the structure affected by the cracks, and then the study was focused on this excavation. The route for construction of the ISKI project is given in Figure 8.

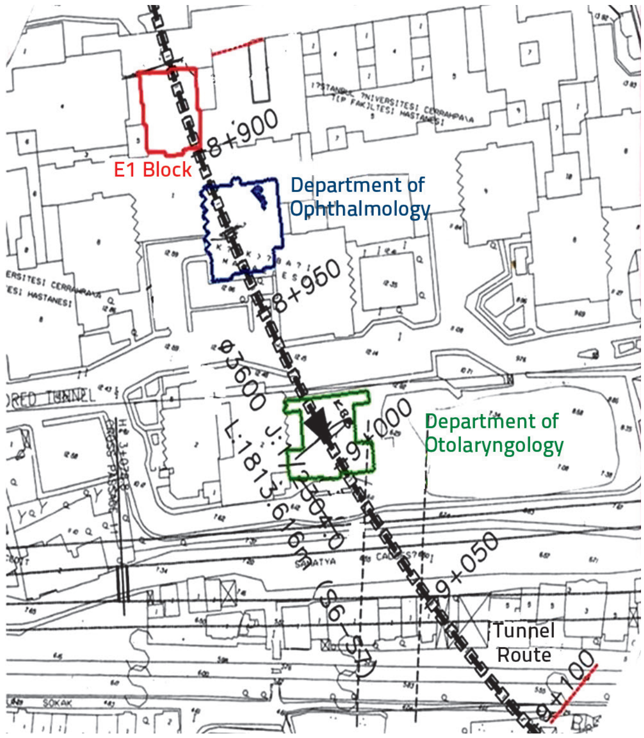

Figure 8. Route of the ISKI Project (Sewage Tunnel), and blocks of I.U. Cerrahpaşa Medical Faculty situated along the same route [20]

After various studies were conducted on the public structures and blocks in the vicinity of the faculty, it was established that cracks and different settlements occurred at some buildings almost 15 days before the damage to the monoblock. In addition, cracks were seen at the department of ophthalmology, in a different hospital block, four or five days before the event. According to interviews conducted by people residing in the public buildings, sounds were occasionally heard from the underground. The collected information suggests that there is an ongoing work under the ground. Officials stated that the excavation work for the construction of ISKI (Sewage Tunnel) has been progressing 15 m per day and, recently, the tunnel excavation work was carried out at the depth of 22 m. As can be seen in Figure 8, the position of E1 block corresponds to the KM 8+873 of the route, which passes just under a densely populated area of the building. It is emphasized in the study that the work under the privately owned buildings was carried out fifteen days ago. These public buildings, however, are at KM 9 + 100 of the route. In the light of this information, and considering relevant parameters (distance and daily rate of tunnel excavation), it can be concluded that the value of (9100-8873) (m)/15 (m/day) = 15 (day) fits the collected information quite well. The departments of ophthalmology and otolaryngology lie at KM 8 + 930 and KM 9 + 000, respectively, along the route. The collected information was confirmed by measurements subsequently conducted at these buildings, using the same parameters.

4.2. Ground-penetrating radar (georadar) study

A georadar study was conducted at the basement floor of the E1 block in order to examine possible deformations of soil in the zone where settlement of the structure was registered. The variations at the foundation level were examined by georadar measurements conducted on the parts where the damage is concentrated, on the walls and floor of the sterilization unit located at the operating room level along the parallel profiles positioned side by side for 9 m (Figure 9). For this purpose, a response was attempted down to approximately 15 m in depth, by using a 300 MHz antenna. The changes in ground level were obtained by two and three-dimensional radargram images.

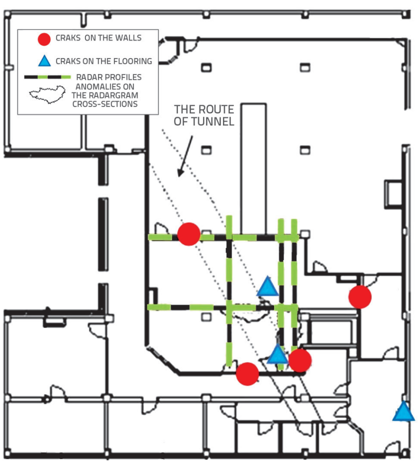

Figure 9. Georadar profiles, radargram anomalies, observed cracks / deformations, and location of tunnel route

As can be seen in Figure 9, an anomaly was also detected by georadar measurements in the region where ground movements were identified by the observed deformations. The georadar findings exactly coincide with the observation results. Interestingly, the initiation point of the anomaly, and the location of the TBM mirror, are the same.

At the operating room level of the structure under study, two dimensional radargram cross sections, obtained from the direction parallel to the x and y-axis in regions of concentrated relative settlements and ground deformations, are shown in Figure 10.

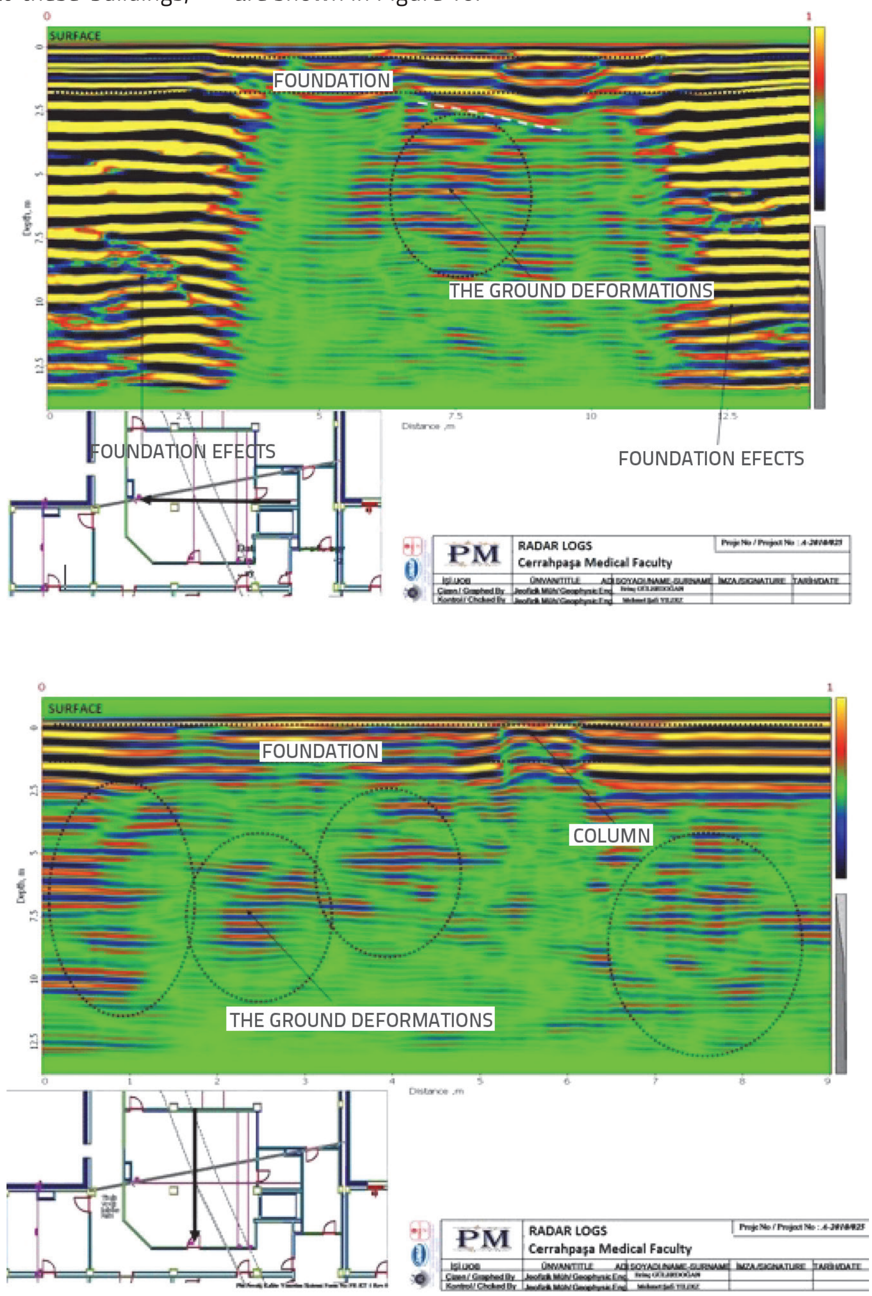

Figure 10. 2-D radargram cross-section and ground deformations [21]

4.3. Soil strengthening under the building

Studies conducted along the route show that there are two fault planes in the part of the sewerage tunnel passing through the zone of the I.U. Cerrahpaşa Medical Faculty. One of the fault planes cuts the tunnel route (Figure 9) and is located under the most heavily damaged parts of the building under study. The crushed fault zone, approximately 7-8 m in width, contains water and is known to have a disturbed porous structure. On the other hand, the other fault plane is 8-10 m in width and it widens conically from the tunnel level at a close distance from the examined structure to the upper levels, at nearly 45°, depending on the thickness of the upper layers.

The soil in the area where the examined university buildings are located is formed of the artificial fill material and alluvium layers. It is known that these soil types contain ground water and water from precipitation, and also that rapid removal of ground water, and sudden decrease in the ground water level, results in sudden collapse and settlement of ground carrying the structures [18]. The settlement started at the bottom of the block under study and caused additional damages to load-bearing elements. The settlement activity subsequently affected structural units of the neighbouring structures. This settlement and structural damage are expected to continue until the balance of geological formations is reached.

Approximately 80 tons of cement grout were injected into the ground during studies conducted under the structure damaged by sudden ground migration. In addition, nearly 80 tons of cement grout was injected into the ground of the structure located above the other fault plane. Although the addition of cement grout was performed as a "ground strengthening" activity, no studies have been made and no data exist about actual effects of this grouting. A view of the cement grouting in progress is given in Figure 11.

Figure 11. Cement grouting for ground strengthening

4.4. Assessment of crack variations in the damaged structure

Crack measurement data were obtained over 30-days via 30-mechanical measurement devices mounted in the sterilization (E1 block) and operating rooms (E2 block). The crack regression on mm scale was detected and observed by the crack measurement device in the first two weeks. After the cement grouting, at the end of the third week, the crack size increased compared to the original size. During the last 7-days, cracks reached their reference sizes, and the width of the cracks remained constant (Figure 12). This shows that ground strengthening plays a significant role in the prevention of displacement of the structure.

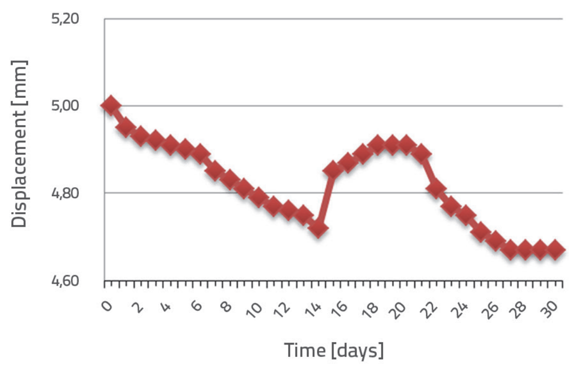

Figure 12. The sample of MC-1:13: Crack width changes along 30-days

4.5. Analysis of damage on buildings E1 and E2

The damage that occurred in the building under study can be summarized as the diagonal cracks on the walls of the basement floor, cracks formed due to bending of the basement ceiling structure, cracks on the beam braces originating from tension and bending, and shear cracks and compression cracks on some columns [18]. This damage was not considered in the design of the building, which covered damage due to earthquake, wind, dead/live load, or any combination of these. The reason for the damage is the effect of the distribution of the cross responses, prescribed in the analysis and design of the building, i.e. the variation of the balance of reaction forces in building foundations, as a result of sudden settlement. The building avoided collapse thanks to previous strengthening works. Although the cement injection slowed down ground movements, it did not repair the unbalanced condition of structural elements. Relatively high deformations on the beams show that the structure was deformed beyond the elastic limit. All these effects were not prescribed during the analysis and design of the building. For this reason, the analysis of current condition of the buildings in question must be performed, and stress variations in structural elements must be determined. The analysis should be conducted in two stages:

First stage: By determining differential settlements in the foundations of the structure, the cross responses, displacements and deformations must be calculated for these settlements only (excluding all other effects). Stress distributions existing on the floor plane and axial forces of the beams must also be included in these calculations. The extent of cross responses, originating from differential settlements only, would be observed as a result of these analyses.

Second stage: The overloading conditions described in the first step (axial stress, shear stress, torsional stress, plane stress, etc.) must be defined for structural elements. An earthquake analysis must be performed within the scope of the related codes together with these definitions. The cross responses, reaction forces, displacements and deformations calculated in the first step must be superposed (as absolute value and in the increasing direction) using the results of this analysis.

5. Results and suggestions

It was concluded that the source of damage to structural elements of the E1 and E2 blocks of the Cerrahpaşa Medical Faculty located in the Istanbul University Cerrahpaşa Campus, is the tunnel 4.6 m in diameter, which passes underneath these blocks. However, in this particular case, the disturbance and damage can partly be attributed to the actual unfavourable condition of the 35 years old building. This conclusion has been conformed by reports prepared by different institutes and experts.

The results obtained in this study can be summarized as follows:

- As a result of foundation migration, cracks formed in the load-bearing system of the structure, different settlements occurred, and the load distribution within the load-bearing system of the structure was completely changed.
- A safety level might decrease for the blocks neighbouring the structure in question, as well as for the blocks along the tunnel excavation route. The condition of such structures is the subject of another study. An appropriate evaluation, backed by additional observations and studies, must be conducted for these blocks. It is possible to that the E1 block, which is presently reasonably well balanced, may incur great danger. A similar condition may be revealed for the neighbouring building.
- The problems revealed during observation studies between 9+100km and the E1 block, which generated along the route at the rate of tunnel excavation, demonstrate that the tunnel excavation process causes problems for structures situated on the ground surface.

The study was conducted with regard to structural damage using the hospital building as an example. Suggestions on the application and research are given below:

- The loads applied on E1 and E2 blocks are determined and the analysis results showing static behaviour of these blocks could be obtained. The strengthening method and its details must be determined using the values obtained and the corresponding codes. Without considering the above mentioned points, a strengthening project and manufacturing process based on this project would not contribute to the static reliability of the building but, conversely, it is highly probable that the building will be affected by damage.
- As the structure is risky to use, it is out of usage and closed to the public. During this period, the units in the structure can not be used. The negative effect of any work to be conducted without precautions could put such a vital structure out of service.
- With the help of the data obtained, it can reasonably be concluded that similar movements could occur if the same route is followed.
- The effects of tunnel excavation on the structures positioned above the tunnel must be determined based on findings made for this study. Appropriate parameters, i.e. route, excavation diameter and depth, must be found. Necessary preliminary studies must be conducted, and appropriate precautions must be taken.
- The tunnel construction works have resulted in the loss of ground, settlement of the ground, and movements along the width. In order to prevent such occurrences, the structure-ground interactions must be considered, and the effect of the tunnel excavation process on structures positioned above the tunnel must be determined. In this respect, it would be necessary to make a numerical analysis of the ground – structure interaction, and to analyse the tensile deformation behaviour in full detail.
- In the context of the tunnel excavation processes, especially for new settlement regions, it is of crucial significance to pay proper attention, after completion of infrastructure facilities, to the construction of structures on the ground surface, with all aspects relevant to this construction, in order to prevent possible loss of lives and unnecessary financial costs.

In the light of the above conclusions, a comprehensive examination of structural safety of buildings must be made, and the impact of tunnelling work on buildings situated along the tunnel route must be evaluated. Building code provisions should be elaborated for such cases in order to avoid possible collapse of existing buildings that have not been designed for such ground disturbances.

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