Australian Journal of Basic and Applied Sciences, 1(4): 506-518, 2007
ISSN 1991-8178

Construction Risk Management of Deep Braced Excavations in Cairo

Ahmed Hosny Abdel-rahman

Associate Prof., Civil Eng. Dept., Engineering Research Division,
National Research Center of Egypt.

Abstract: Deep braced excavations are generally known to be associated with risks that become pronounced when executed below the level of groundwater table. The approach to safely design and execute deep braced excavations should follow a plan in which the project boundaries and subsurface conditions are studied and the different risk sources are identified. The risk management plan resumes with the evaluation of risk sources, setting up precautionary and contingency measures, and designing a monitoring system to watch for the red flags of the different risk sources. The balance between the economical aspects of the retaining system, along with its associated groundwater control measures, against the risk level is always the key for a successful design. The paper presents the experiences gained while adapting a risk management plan during the design and construction of a deep braced excavation in downtown Cairo. Risks associated with lateral deformation, ground settlement and effect on nearby structures, groundwater control, plug stability and integrity, as well as construction difficulties are discussed. The contingency plans as well as the monitoring systems are also presented. Conclusions and recommendations toward an integrated risk management program to be adopted in deep braced excavations are given.

Keywords: Deep Excavation, Bracing, Retaining, Risk Management, Contingency, Monitoring

INTRODUCTION

Fast development in urban areas often entails the need for deep excavations to construct a basement or a cut-and-cover tunnel to maximize the use of the underground space for car parking, transit systems, or else. Design and construction of deep excavations are associated with risks especially when performed adjacent to existing structures. The risk management program encompasses three main stages; risk identification, risk analysis and control, and contingency plans of action.

Risk Sources and Identification:

Particular attention in the design and installation of a retaining system is always given to control the lateral and vertical movements of the surrounding ground and the stability of the foundation soil if excavated under water (Gill and Lukas, 1990). Many sources of risks are associated with the construction of deep braced excavations. Ground movements, groundwater control, and improper quality of construction are always main sources of risks in executing deep braced excavations.

Unavoidable induced ground movements are always associated with the stress release from the earthwork excavation within the site. Other source of settlement could also occur due to the increases in the effective overburden pressure during lowering groundwater table in case of dewatering outside the excavation boundary. These ground movements could be predicted and controlled during the design process by adopting a finite element model by which the construction sequence is modelled and the ground movement are predicted. Empirical relationships were also presented in the literature to predict ground movements of multi-strutted excavations conducted in different types of soils (Clough and O'Rourke, 1990) as shown in Figure (1).
Prediction of ground settlement troughs along the retained side is necessary for the assessment of the differential settlement risks on the adjacent structures, especially for buildings of sensitive architectural finishes or of historical nature. Primary factors that influence the deformation of the wall and the retained ground were discussed by Abdel-Rahman and El-Sayed (2002), and Cowland and Thorley (1985) as follows:

Corresponding Author: Ahmed Hosny Abdel-rahman, Associate Prof., Civil Eng. Dept., Engineering Research Division, National Research Center of Egypt.
E-mail: ahosny66@hotmail.com Fax: +202-2275-7417

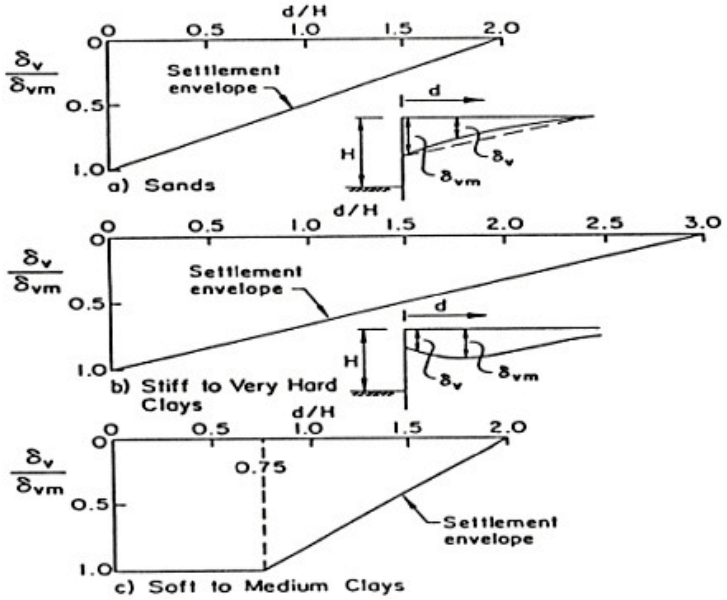

Fig. 1: Settlement distribution due to braced excavation in different types of soils (After Clough and O'Rourke, 1990)

- Nature of subsurface soil condition;
- Variation in groundwater level;
- Depth and width of excavation;
- Stability of the bottom of excavation;
- Stiffness of the support system;
- Rigidity of the wall;
- Construction technique (e.g. pre-stressed anchors, struts, top-down excavation, etc).
- Quality control adopted during construction

However, other causes of settlement are associated with the stability of the excavation base in clayey soils (Mana and Clough, 1984) as shown in Figure (2).

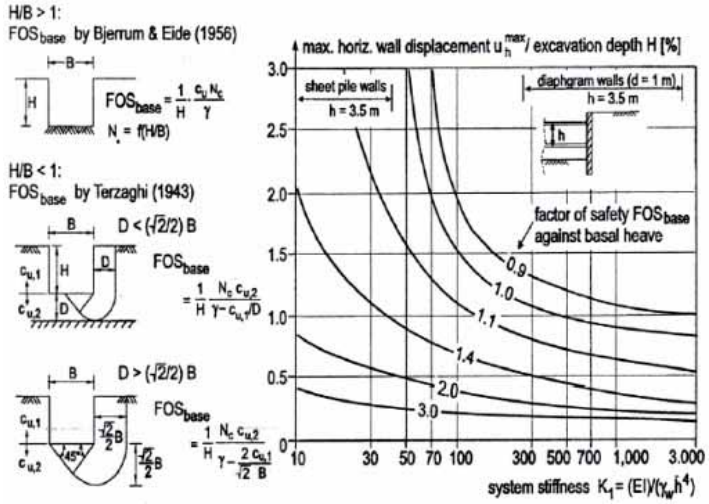

Fig. 2: Effect of the base stability of braced excavations in clay on the induced lateral displacement (After Mana and Clough, 1984)

Severe ground movements could also occur during the process of groundwater control. Flow of water in and around an excavation can occur through the following mechanisms (refer to Figure (3)):

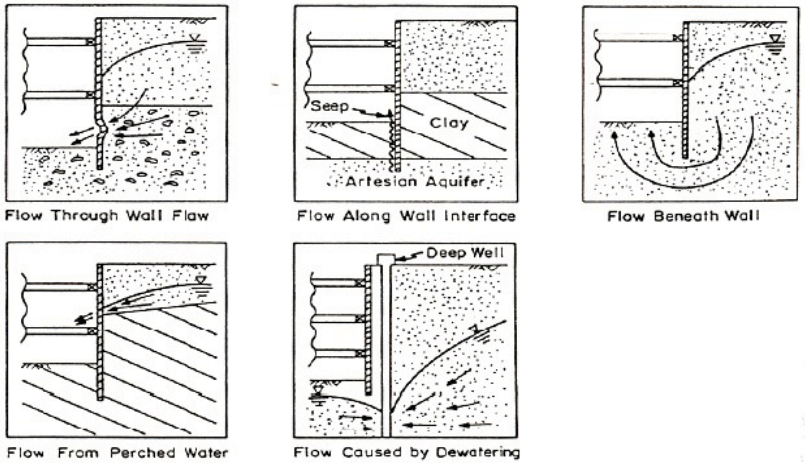

Fig. 3: Sources of groundwater-related risks during construction of deep braced excavations (After Clough and O'Rourke, 1990)

- Flaws in the walls (e.g. cracks, joints between pile wall, etc)
- Flow along wall-soil interface
- Flow beneath wall (e.g. insufficient penetration depth of the wall)
- Flow due to dewatering

Risk Analysis and Control:

By identifying the different risk sources, risk analyses could be performed according to the following procedure (Ahuja, 1994):

- Estimating the probability of occurrence of the undesirable event;
- Estimating the magnitude of consequences;
- Identifying options to accommodate the risks, including:
  - reducing the probability of the cause;
  - mitigating the consequence; and
  - reducing the escalation from cause to consequence.
- Prioritise risk management efforts based on:
  - level of risk (probability and consequence);
  - status of risk control and risk management activities; and
  - optimum timescale for risk control action.

Risk control could be always ensured through the following:

- Incorporating a design with adequate safety factor and reasonable ground movements that could be safely tolerated by the surrounding structures.
- Incorporating an inclusive quality control program during construction.
- Performing a pre-construction dilapidation survey to verify the conditions of the surrounding structures and their safety conditions when subjected to the predicted ground movements.
- Adopting an elaborate monitoring system that suit the risk sources associated with the execution of the deep excavation.

Contingency Plans of Action:

Contingency plans are used in the event of emergency response, back-up operations, and disaster recovery for construction projects which carry a large element of risk. The contingency plan shall therefore focus upon

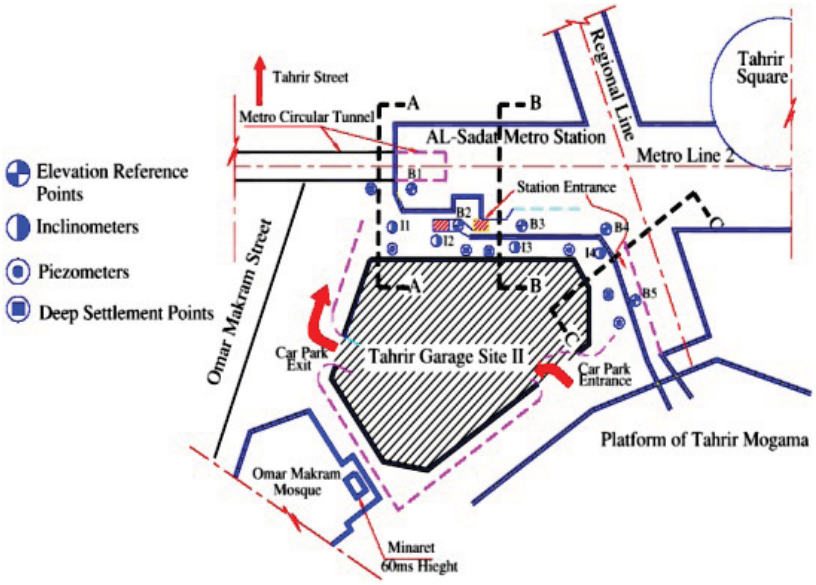

Fig. 4: Location of Al-Tahrir garage and its surrounding existing structures

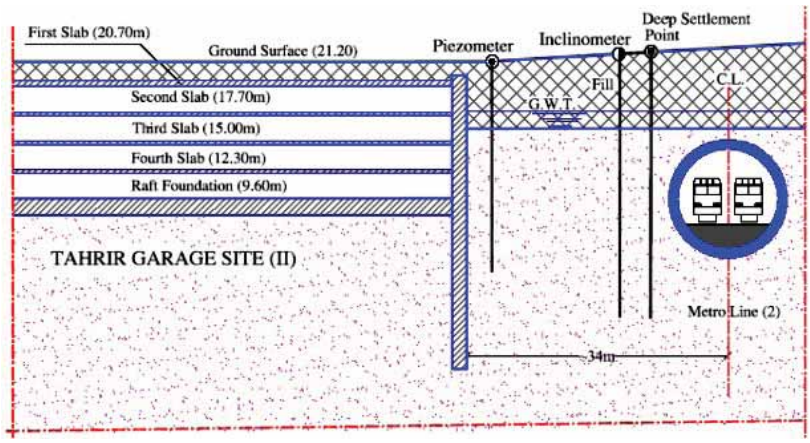

Fig. 5: Section A-A presents the location of the garage boundary relevant to the tunnel tube of the Urban Cairo Metro Line

ways in which certain events identified through completion of project risk assessments can be militated against using a set of pre-identified procedures. The plan shall be fit-for-purpose and undergo the following key tests prior to its release:

- Is the plan achievable in reality, should this be required?
- Are the trigger mechanisms for actual activation of the plan clear and realistic?
- Does the plan address anticipated situations in a timely, affordable, effective, consistent manner?

Construction of Al-tahrir Underground Garage in Downtown Cairo:

The project is the construction of a multi-story underground garage in Al-Tahrir square, Cairo, Egypt. Figure (4) presents the location of the site and indicates its surrounding structures. The garage consists of 4 underground stories that required 13.60 m of excavation to reach the foundation level. Figures (5, 6, and 7) present cross sections A-A, B-B, and C-C, which also illustrate the location of the garage structure relevant to existing underground structures. The crossing of the Regional and Urban Cairo Underground Metro lines

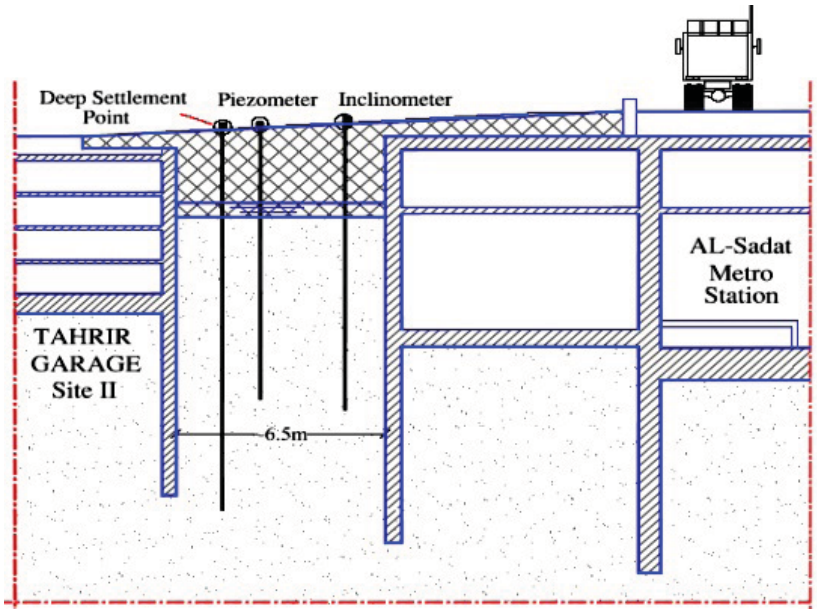

Fig. 6: Section B-B presents the location of the garage boundary relevant to Al-Sadat Station of the Regional Line of Cairo Metro.

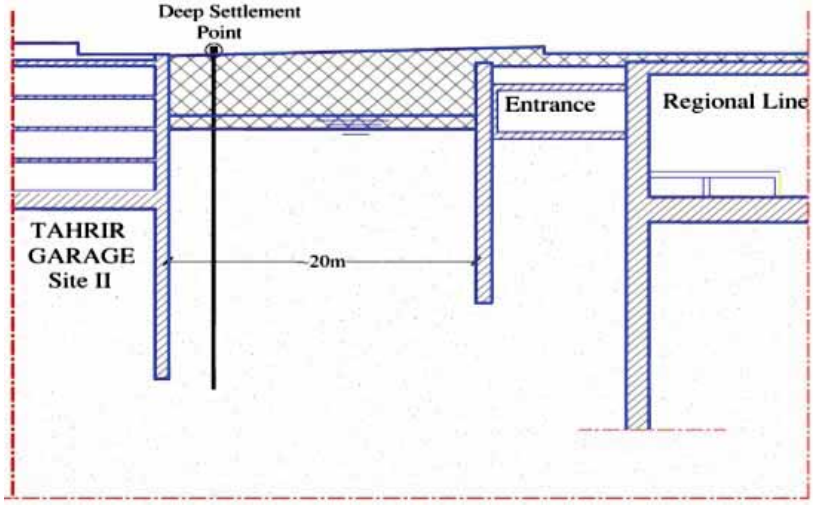

Fig. 7: Section C-C presents the location of the garage boundary with respect to Al-Sadat Station of the Regional Line of Cairo Metro.

at Al-Sadat station is close to the garage excavation boundaries by distances vary from 6.0 m to 34 m as can be seen from Figures (5, 6, and 7). On the other side, the historical Omar Makram mosque and its 50 m height minaret is located 6.0 m away from the excavation boundary of the garage, as can be seen from Figure (8).

Subsurface Soil Condition:

The subsurface soil condition at the subject site consists of a top fill layer of a thickness varying between 4.50 m and 6.0 m, followed by a dense to very dense sand layer which extended to the end of the boreholes at 48 m depth. Interlayers of hard clay appeared at depths vary between 30 m and 45 m with thicknesses range between 3 m and 6 m. The groundwater table appeared at a depth from ground surface ranging between 3.0 m and 3.50 m, which corresponds to levels (17.50 m) to (18.00 m).

Identification of Risk Sources:

A top-down system was adopted in executing the excavation to the foundation level of the garage. Diaphragm walls of 0.80 m width and 27 m deep were used. The slabs were partly cast and connected to the diaphragm wall during the excavation toward the foundation level to provide lateral supports to the diaphragm wall. A grout plug of about 2.50 thick was installed throughout the site to form with the diaphragm wall a tanking system to prevent the inflow of water toward the excavation pit.

Risk situations developed during the excavation of the diaphragm wall trenches, especially at the panels that were close to Omar Makram minaret (6.0 m away). Further risks developed from the effect of anticipated ground settlement and lateral deformations on the structure of Al-Sadat station (Figures 5 and 6).

Risks on the Structure of Al-Sadat Underground Metro Station:

The close proximity of parts of Al-Sadat station to the Southern side of Al-Tahrir garge, as can be seen from Figures 5 to 7, induced risks on the safety and stability of Al-Sadat station due to the following:

- Possible instability of the diaphragm wall trenches during excavation as a result of an improper quality of excavation, or a particular ground anomaly.
- Effect of the induced ground movements due to trenching and strutted excavation on the structural safety of the metro station as well as its shallow-founded entrance.
- Possible instability/dis-functioning of the base grout plug might affect the safety of the metro station.
- Possible ground loss due to migration of soils, if water leakage between the diaphragm wall panels occurred during water pumping from within the construction pit.

Risks on Omar Makram Mosque and Minaret:

- Figure (8) indicates that the location of the minaret of the historic Omar Markram mosque is about 6.0 m from the boundary of the site, while most of the mosque structure itself is about 10 m to 11 m away. The effect of the induced ground movements on the mosque structure and the minaret imposed a potential risk on their structural safety or their aesthetic appearance.

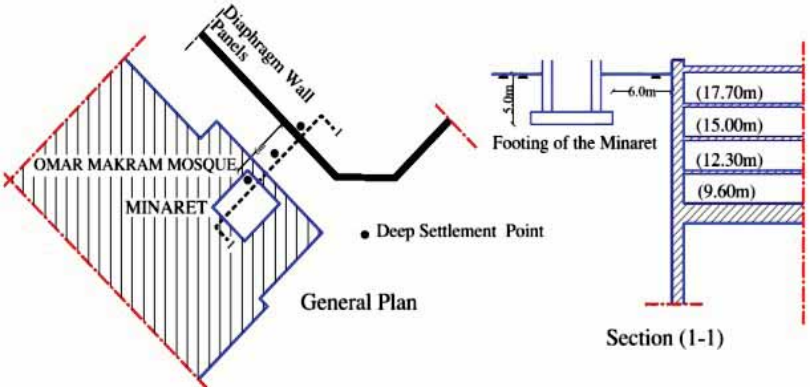

Fig. 8: Location of the Minaret of Omar Makram Mosque with respect to the diaphragm wall line

- Figure (8) indicates that Omar Makram minaret is supported on an isolated footing at a depth of about 5.0 m from ground surface. Structural calculations indicated that the contact stress at the foundation level is about 200 kN/m^2. The minaret footing is about 5 m x 5 m in plan. Therefore, the minaret was considered to be in a high risk condition due to the following reasons:
  - Any failure to one of the diaphragm wall panels would cause a collapse to the minaret due to its proximity to the diaphragm wall trench. The footing width (5.0 m) is very comparable to the length of the diaphragm wall panels (2.80 m). Also, the relatively high contact stress (about 200 kN/m^2) elevates the risk as well.
  - The effect of any tilting that might develop due to the excavation process would result in an obvious tilt to the minaret because of its height (50 m).

Risk Analysis and Control:

Quantifying the degree of risk after its identification is essential in setting out acceptance criteria for the excavation and groundwater control systems. Outlines of the methodologies followed in assessing and controlling the risks during the design and construction of Al-Tahrir garage are discussed in the following sections:

Risk Analysis:

After mapping out the site boundary conditions and identifying the risk sources, technical assessments of the risk levels are addressed according to the following approach:

Mapping out the Structural Conditions of the nearby Buildings:

A pre-construction dilapidation survey was carried out for all surrounding structures in order to locate any structural anomaly, i.e.; cracks, opening of structural joints, steel/concrete degradation, water leakage…etc. This survey is aimed at recording the existing conditions of the surrounding structures so that any updates occur due to the construction process could be observed. Meanwhile, elevation reference points (ERP) were installed in order to monitor the settlement of the structures. Crack indicators are also installed where cracks or structural joints exist.

Dilapidation surveys and installation of ERP's and crack indicators were thoroughly performed for Omar Makram Mosque and Minaret as well as Al-Sadat station and its entrance corridor, which is founded on a shallow foundation system. Figure (9) presents the installation of Elevation Reference Points (ERP's) at parts of Omar Makram Mosque and the entrance of Al-Sadat station.

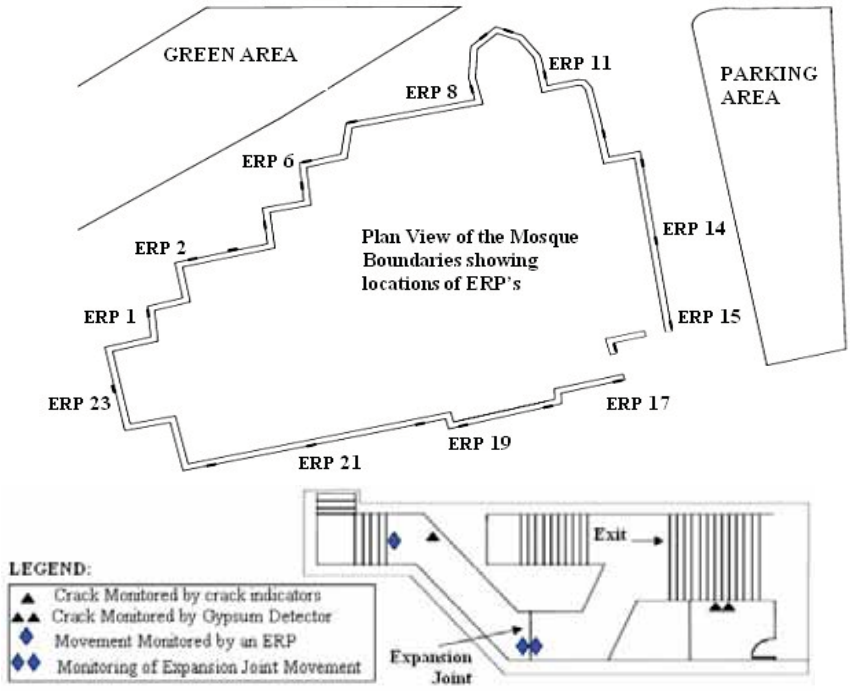

Fig. 9: Elevation Reference Points (ERP's) and crack indicators on Omar Makram Mosque and the shallow-founded parts of Al-Sadat Station.

The effect of wind on the tilting of Omar Makram minaret (50 m height) was also recorded prior to construction for a period of two months at two points (T & B), as shown in Figure (10). The Minaret tilted during this period about 1.3 cm at point "T" due to wind effect, which was extrapolated using data at point "B" to a value of nearly 2.0 cm a the minaret top. It is worth noting that this value represented the minaret response only to the wind speed at the time of measurements, and not at the maximum wind speed that the minaret has experienced throughout the years. However, the measured values indicated the range in which normal tilting of the minaret occurs.

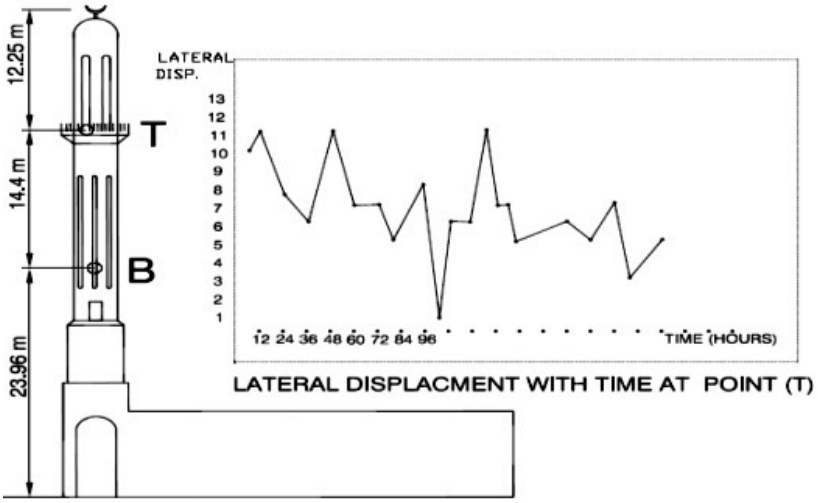

Fig. 10: Sketches for the Mosque Minaret and the records of the lateral displacement at Point "T" under normal conditions.

Setting out the Serviceability Criterion:

Safety limits, up to which deformation could occur, were set for the different structures. These limits depended on the statical systems of the structures as follows:

Al-Sadat Station:

Being a multistory, multi-bay structure, its undetermined statical system was found to be safe, through structural analyses, if the support that is close to the excavation pit settled by a maximum of 0.50 cm.

Omar Makram Mosque:

Based on reported values of acceptable distortion angles for different structure types in many codes and standards a limit of 1/700 was considered for Omar Makram Mosque to avoid any distresses in its structure.

Omar Makram Minaret:

Since the minaret is a special structure, because of its height and proximity to the boundary of the excavation pit, consequent settlement to its foundation was predicted from a finite element analysis. Subsequent structural analyses were performed to check the effect of the predicted settlement on the safety of the minaret. The maximum predicted tilting along the height of the minaret from the analyses was 1/1500, which was found to be within the acceptable limits for the minaret structure.

Geotechnical Analyses:

A nonlinear finite element analysis was performed to model the subsurface geotechnical conditions along with the stages of construction of the garage. The construction sequence followed a top-down excavation system; i.e., sequentially casting the slabs during advancing excavation toward the raft foundation. In this system, the lateral support of the wall is considered to be the roof slabs. After initial installation of the diaphragm wall, a grout plug was formed across the site to prevent infiltration of water to the site. The site was designed to be divided into compartments, as shown in Figure (11) for architectural and geotechnical purposes. The geotechnical benefit was to limit the areas of the plugs and so any defect in the plug construction could be located and controlled.

A two-dimensional plane-strain finite element analysis was performed using the program SOILSTRUCT (Filz *et al.,* 1990) implementing the nonlinear modified hyperbolic model to represent the soil behavior (Duncan *et al.,* 1984), the hyperbolic model (Filz *et al.,* 1990) to model the interface behavior, and the linear elastic material model to represent the diaphragm wall and the struts material models.

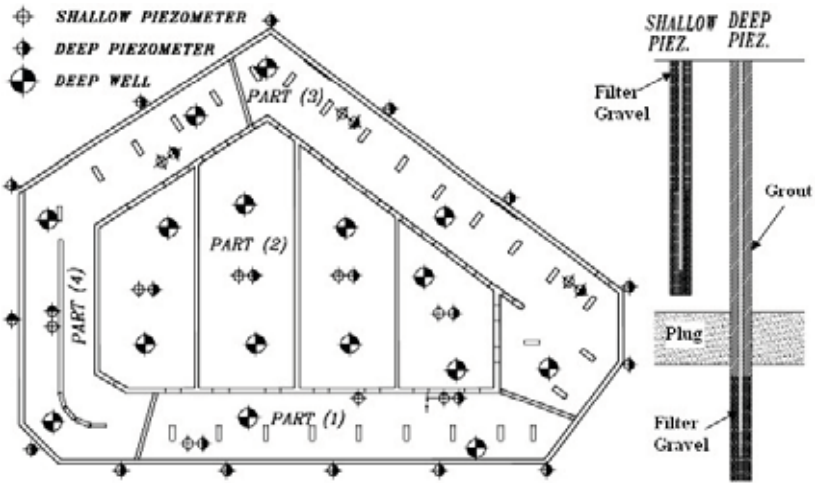

Fig. 11: The implemented dewatering system and the locations of the piezometers to monitor the groundwater Table.

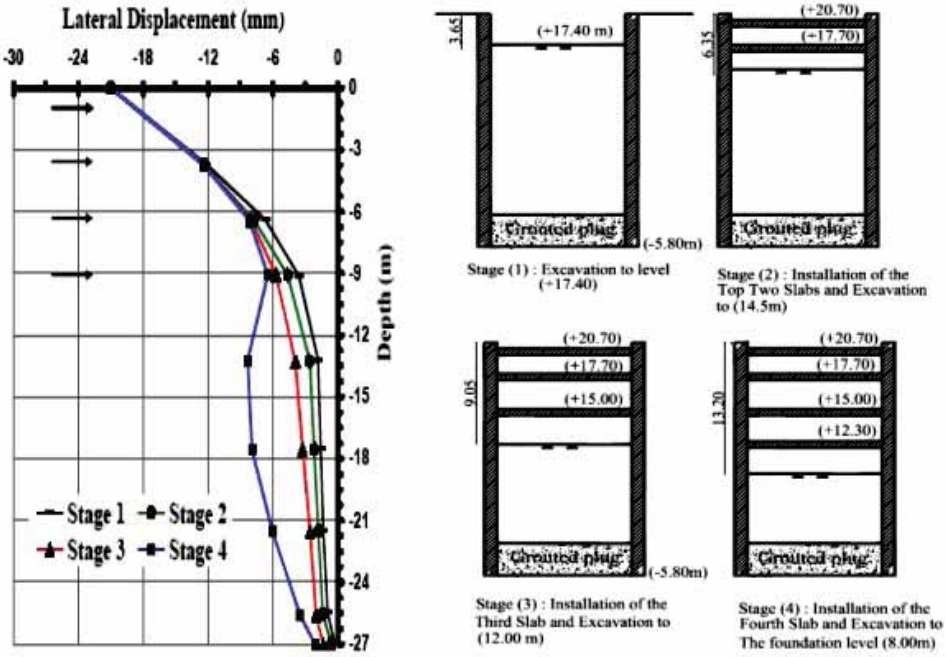

Fig. 12: Predicted lateral displacement of the diaphragm wall while advancing the construction stages.

Figure (12) presents the stages of construction modeled in the analysis and the corresponding predicted lateral deformation induced while advancing the construction stages. The maximum predicted lateral displacement was 20 mm, while the maximum predicted settlement at the location of Al-Sadat station at the tip of its diaphragm wall is 2 mm, which is less than the limit allowed in the serviceability criterion.

Installations of Monitoring Systems:

The locations and the types of the monitoring devices installed to measure the induced changes in the ground movements and groundwater table around and inside the construction site are shown in figures (4 to 7). These devices included standpipe piezometers to monitor the levels of the ground water table within

and outside the site, inclinometers to monitor the lateral displacement of ground and the diaphragm wall facing Al-Sadat station, deep settlement points to monitor vertical settlement at the tip of the diaphragm wall of Al-Sadat station, and elevation reference points to monitor the settlement of the pedestrian entrance to the station.

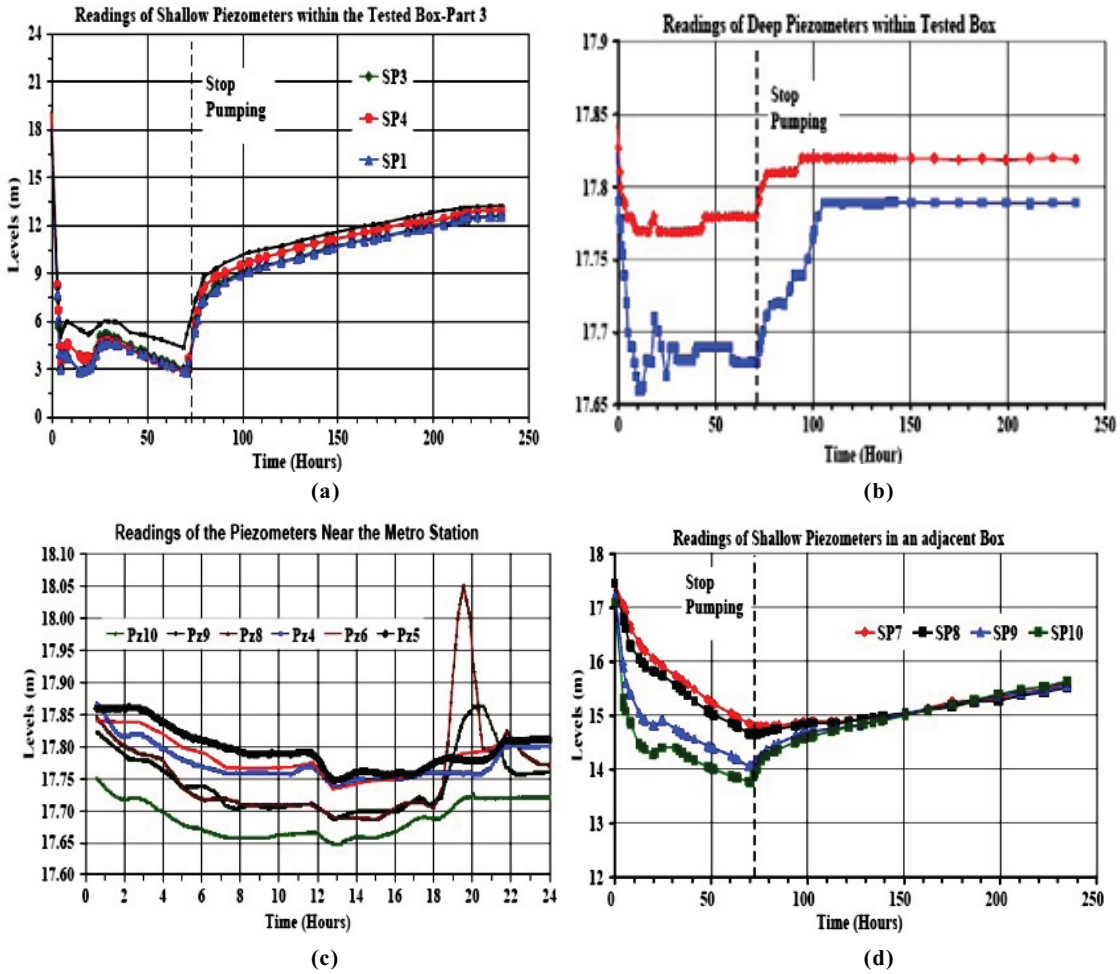

Fig. 13: Results of the pumping test performed in one of the compartments

Perform and analyze Large Scale Field Tests:

In order to confirm the analytical prediction of the different variables and ensure the effect of the construction sequence, large scale field tests were performed before developing the excavation within the entire site in order to detect un-foreseen sources of risks encountered due to construction problems such as leaking within the tanking system. Figure (13) presents the results of pumping water from one of the compartments and the relative drawdown within the deep piezometers installed below the horizontal grout plug, the shallow piezometers in the adjacent compartment, and the piezometers installed beside Al-Sadat station and the metro lines. Figure (13-a) presents the drawdown throughout the duration of the pumping test (during and after pumping) which reached up to 5.5 m from the static levels. The test duration lasted for about 10 days. Figures (13-b and 13-c) present minor and acceptable fluctuation (6 cm to 20 cm) within the water levels at the deep piezometers installed below the grout plug at the same tested compartment, and the piezometers installed near the metro station. However, figure (13-d) indicated higher variations in the water table enclosed within the adjacent compartment that reached to a maximum drawdown of about 3.75 m. That indicates construction problems in the cut-off between the two compartments, which reflects the presence of a major opening that allowed water seepage between the two compartments during pumping. This location was traced through the piezometers readings and sealed by injecting jet-grout columns.

Risk Control:

Risk control during the construction stages is insured by periodically reviewing the monitoring reports of the different variables (surface and deep settlement, lateral movements, drawdown,….etc). The readings are to be compared with the limits set during the design stage. A green light to advance the construction is only given when the monitored values are less or equal to the predicted values. Whenever the monitored values exceed the predicted limits, re-evaluation for the entire situation and probable contingency measures are normally considered.

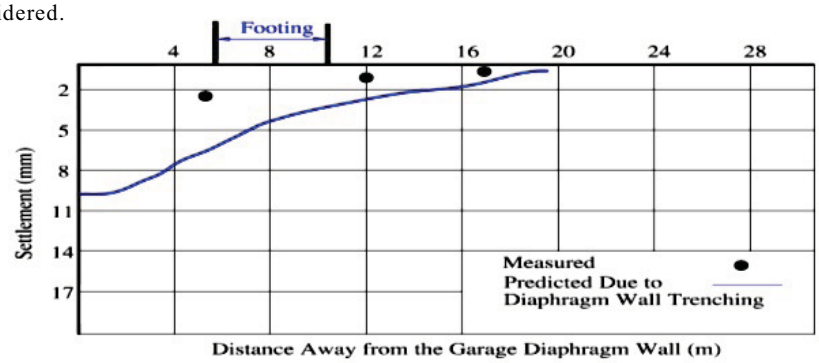

Fig. 14: Predicted versus measured settlement values at the minaret due to diaphragm wall installation

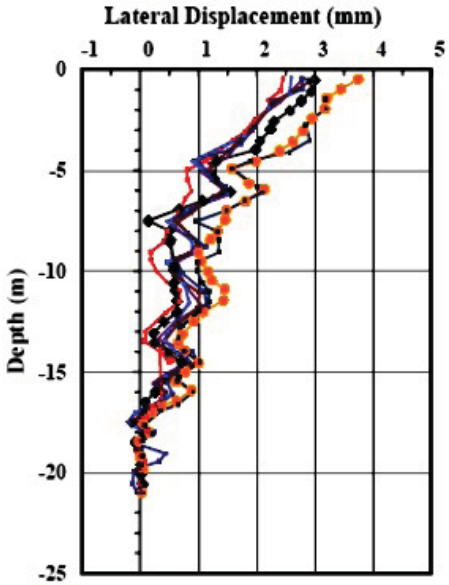

Fig. 15: Measured lateral displacement during advancing the excavation for the diaphragm wall side facing Al-Sadat Metro Station

Figures (13 to 16) implied control of risks during the construction stages. The different plots presented in Figure (13) indicated control of risks that might arise from a defected plug condition, Figure (14) presents control of risks during the construction in the vicinity of Omar Makram Minaret, Figure (15) presents values for the lateral deformation of the diaphragm wall that are less than those predicted and presented in Figure (12), and Figure (16) presents no movements for the readings of the Elevation Reference Points (ERP's) and the deep settlement points at Al-Sadat station.

Contingency Plans of Action:

Parallel to the risk assessment and control, contingency plans of actions should be set. The main problems that are normally associated with deep braced excavation are related to high values of lateral movement and hence settlement, stability problems to the grout plug, insufficient water drawdown below excavation level, and possible leaking from the sides of the side support system. Table (1) summarizes the contingency plans considered for the project.

Table 1: Contingency Plans of Actions Implemented in the Project

Risk Source	Contingency Plan of Action
Excessive lateral movement of the wall and ground settlement	Increase the number of lateral supports
Instability of the grout plug	Refill the excavation pit with water up to the level that adequately re-stabilize the situation, or perform heavy dewatering to lower the water table as needed.
Insufficient drawdown to the water below excavation level	Increase the number of wells
Lateral leaking from the side-support system	Inject grout columns behind the leaking location.

Monitoring of Elevation Reference Points (ERPs) from 12/10/02 to 17/10/02

Points	Initial Reading	Date 12/10/02		Date 13/10/02		Date 14/10/02		Date 15/10/02		Date 16/10/02		Date 17/10/02	
		Elev.	Sett.	Elev.	Sett.	Elev.	Sett.	Elev.	Sett.	Elev.	Sett.	Elev.	Sett.
B1	22.910	22.910	0.000	22.910	0.000	22.910	0.000	22.910	0.000	22.910	0.000	22.910	0.000
B2	22.278	22.278	0.000	22.278	0.000	22.278	0.000	22.278	0.000	22.278	0.000	22.278	0.000
B3	20.838	20.838	0.000	20.838	0.000	20.838	0.000	20.838	0.000	20.838	0.000	20.838	0.000
B4	17.030	17.030	0.000	17.030	0.000	17.030	0.000	17.030	0.000	17.030	0.000	17.030	0.000
B5	19.3575	19.3575	0.000	19.358	0.000	19.3575	0.000	19.358	0.000	19.358	0.000	19.358	0.000
B6	20.051	20.051	0.000	20.051	0.000	20.051	0.000	20.051	0.000	20.051	0.000	20.051	0.000
B7	8.615	8.615	0.000	8.615	0.000	8.615	0.000	8.615	0.000	8.615	0.000	8.615	0.000
B8	10.607	10.607	0.000	10.607	0.000	10.607	0.000	10.607	0.000	10.607	0.000	10.607	0.000

Monitoring of Deep Settlement Points from 1/12/02 to 6/12/2002

Points	Initial Reading	Date 01/12/02		Date 02/12/02		Date 03/12/02		Date 04/12/02		Date 05/12/02		Date 06/12/02	
		Elev.	Sett.	Elev.	Sett.	Elev.	Sett.	Elev.	Sett.	Elev.	Sett.	Elev.	Sett.
S1	23.1830	23.183	0.000	23.183	0.000	23.183	0.000	23.183	0.000	23.183	0.000	23.183	0.000
S2	22.6270	22.627	0.000	22.627	0.000	22.627	0.000	22.627	0.000	22.627	0.000	22.627	0.000
S3	22.2560	22.256	0.000	22.256	0.000	22.256	0.000	22.256	0.000	22.256	0.000	22.256	0.000

Fig. 16: Readings of the Elevation Reference Points and the deep settlement points indicating zero movement during excavation

Conclusions:

- Sources of risk concurrent with deep braced excavations are not only limited to the stability of the excavation pit, but also extended to the safety and stability of the surrounding structures.
- Structural surveys and setting serviceability criteria of the surrounding structures are necessary to identify risk sources
- Proper evaluation of ground settlement using suitable numerical models is necessary to identify risk sources.
- Risk control during construction is mainly performed by periodical review to the monitoring reports of the different monitoring devices and comparing the measurements with the predicted safe limits.
- Performances of local large-scale field tests such as pumping tests are necessary to limit and control risk during construction.

REFERENCES

Abdel-Rahman, A.H. and S.M. El-Sayed, 2002. "Settlement Trough Associated with Diaphragm Wall Construction in Greater Cairo", the Journal of the Egyptian Geotechnical Society, accepted for publications.

Abdel-Rahman, A.H. and S.M. El-Sayed, 2002, “Building Subsidence Associated with Cut-and-Cover Excavations in Alluvial Soils", Journal of the Scientific Bulletin, Faculty of Engineering, Ain Shams Univ., 37(4): 55-71.

Ahuja, H., 1994. “Project Management-Techniques in Planning and Controlling Construction Projects”, J. Wiley & Sons, USA.

Clough, G. and T. O'Rourke, 1990. "Construction Induced Movements of Insitu Walls", Design and Performance of Earth Retaining Structures, ASCE Geotechnical Special Publications, 25: 439-470.

Cowland, J.W. and C.B.B. Thorley, 1985. “Ground and Building Settlement Associated with Adjacent Slurry Trench Excavation.” Ground Movements and Structures – Proc., Third Int. Conf., University of Wales Institute of Science and Technology, J. D. Geddes, ed., Pentech Press, London, England, 723-738.

Duncan, J.M., R.B. Seed, K.S. Wong and Y. Ozawa, 1984. "FEADAM84: A Computer Program for Finite Element Analysis of Dams", Geotech. Eng. Research Report No. SU/GT/84-03, Stanford Univ., Stanford, CA, USA.

El-Sayed, S. and A.H. Abdel-Rahman, 2002. "Spatial Stress-Deformation Analysis for Installation of A Diaphragm Wall". Civil Eng. Jrl, Ain Shams University.

Filz, G., G. Clough and J. Duncan, 1990, "SOILSTRUCT: A Computer Program for Plane Strain Analyses," Virginia Tech., Blacksburg, VA.

Gill, S. and R. Lukas, 1990, "Ground Movement Adjacent to Braced Cuts", Design and Performance of Earth Retaining Structures, ASCE Geotechnical Special Publications, 25.

Mana, A. and G. Clough, 1984. "Prediction of movement for Braced Cuts in Clay", ASCE Jrl, 107(GT6): 759-777.