Excavation-caused Extra Deformation of Existing Masonry Structures

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Abstract**—Growing need for construction of infrastructures and buildings in fast urbanization process creates challenges of interaction between buildings under construction and adjacent existing buildings. This paper presents the mitigation of contradiction between two parties, who are involved the interaction, using civil engineering techniques. Through the in-depth analysis of the results of monitoring surveys and enhanced accuracy and reliability of surveys, a better understanding of the behavior of deformable buildings will be achieved. Combination with the original construction documents, the two parties agree that both of them are responsible for building damages and a better understanding for the rehabilitation of the existing buildings is focused on. Three case of studies are used to demonstrate and describe the importance of better understanding of the behavior of existing buildings and their rehabilitations. Two cases were analyzed, in specific approach, in Shanghai. And one can compare oneself to a successful case in London. Therefore, the objective of this study is to employ the mechanisms of soil-structure interaction for buildings adjacent to deep excavations. Finally, both parties are able to achieve a common ground, whereby, excavation safety, economic, and enough serviceability of adjacent building in urban area with soft soil conditions.**

Index Terms**—masonry structure, inclination, settlement, crack, excavation**

I. INTRODUCTION

Design and construction of deep excavation is a challenging task for both geotechnical and structural engineers. This may be attributed to the lack of understanding of site-specific properties of soils and the mechanics of the interaction between the soil and the structure. In order to ensure safety in excavation works and protect the surrounding facilities, field monitoring becomes necessary. It can monitor potential dangerous situations during the excavation process, measured data can check the design and guide construction [1].

In many cities in densely populated areas around the world, like the metropolis, the application of deep excavations for the realization of underground spaces or infrastructure, near to existing building, is becoming common practice. It is common that some of the existing buildings affected by new construction lack serviceability when excavation is happening nearby. For example, in metropolis like China, where there has been high speed development of urbanization in the past three decades. The distances between new building constructions, infrastructures, and their adjacent existing buildings are decreasing inevitably. In addition, the evaluation of adverse effect caused by adjacent new construction, construction period, budget, and housing privatization do not match the speedy development of urbanization[2-3]. These issues creates conflicts between new construction and adjacent existing buildings, especially in soft soil region. Soft soils typically cause large displacements due to the compressibility of the soil stratum and are usually combined with the structural integrity of adjacent existing buildings. The interaction between new underground construction and adjacent buildings exhibits that: the soil displacements cause an effect in the building in the form of deformations, strain and sometimes cracks or other types of damage and that the existence of the building, alters the soil displacements immediately beneath it. The main range of

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excavation-caused deformation to adjacent buildings is sketched in Fig. 1[4] .

This paper focuses on the elaboration of the interaction between a new construction and adjacent existing buildings, from views of geotechnical engineering, structural engineering, geodesy monitoring, and evaluation methods. Then the effect of new construction on the existing buildings could be described reasonably and quantitatively. The conflicts between the new construction's party and existing buildings' party are mitigated by the reliable evaluations. Then, the two parties would concentrate on rehabilitations or strengthening for the existing buildings if it is necessary rather than having conflicting each other. Furthermore, the party of new constructions will take effective measures to compensate the party of existing buildings based on the field monitoring and analysis, as well as strategies for maintenance. Finally, the existing building serviceability is controlled within the allowable condition.

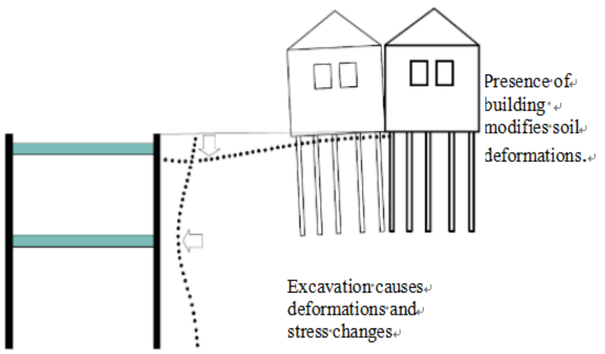


Figure 1. Interaction between excavation and adjacent buildings

Three case of studies are presented in this paper. Two from Shanghai are negative cases which show the excessive additional deformation of adjacent buildings created by deep excavation. One from London, where the civil engineering technical knowledge and the application of the technique minimized the damage during the construction of the Jubilee Line Extension Station at Westminster. Some protective techniques was applied/implemented while working the Big Ben Clock Tower.

II. Techniques to Evaluate the Deformation and Cracks

The protection of adjacent buildings and the environment is obligatory during excavation, and can be divided into the following procedures: (a) before-excavation plan (b) monitoring and prevention during the construction, and (c) compensation after damages. Monitoring the whole system consisted of adjacent buildings and new construction with excavation have to be scientific so that it has a good control of total construction and excavation condition. This can save cost of the future intervention.

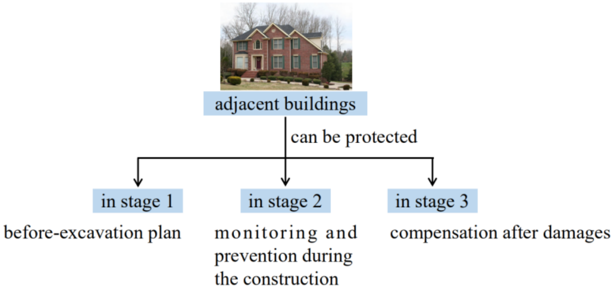


Figure 2. The procedures to protect the adjacent buildings

A. Monitoring Deformation

Geotechnical monitoring deformation during construction may provide large benefits; there are two principal theories, the first related to Dunnicliff [5] and the second by Bles and Korff [6] and Bles et al., as Fig. 3 shows.

Dunnicliff approach includes 12 steps to implement instrumentation, starting with definition of the project conditions and purpose of the instrumentation, via assignment of tasks and responsibilities to selection, preparation and installation instruments. His main conclusion is that monitoring without reason serves no purpose but a good instrumentation program may save lives, money and reduce risks. Bles, Korff and Bles described a structured scheme to design an adequate monitoring plan based on risks from a risk analysis for deep excavation. Their main conclusion is following steps are introduced and obtain an adequate monitoring plan.

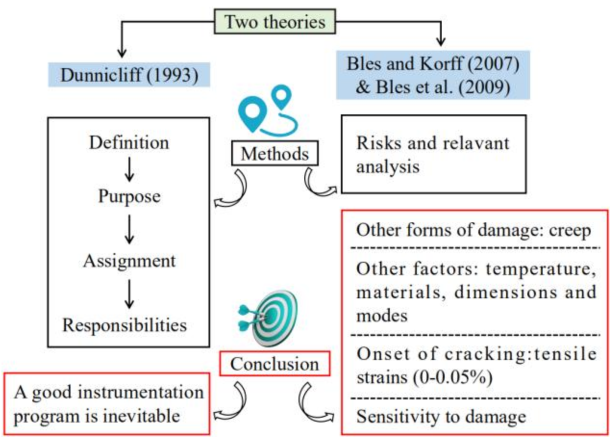


Figure 3. Two principal theories for monitoring deformation

Building deformation and damage in structures is not only related to construction, but also temperature and creep which are major attributes in soft soil region. The deformation results in new cracks and crack width increment. The cracks in a building depends on material details, building dimensions and deformation modes. Usually, low values of tensile strains (0-0.05%) are used as the onset of cracking. In general, buildings that experience more curvature, show more damage than buildings that rotate rather than bend or shear [7].

The damage of buildings due to excavation-induced deformations, accordingly, it is important to good monitoring plan.

B. Creep Deformation

Creep usually occurs in clay soils. The softer soils are, the more obvious the creep is. Creep relates to time and stress level. It increases with the increase of the stress level and time and covers a long period of time. The deformation of adjacent buildings increases continually after excavation of new construction [8-9].

C. Relationship between Excavation Displacement and Additional Inclination of Adjacent Buildings

Ground movements, displacements and inclination of buildings are related to deep excavation that have multiple sources or causes, as Figure 4 shows. They can be predicted either for all stages overall or per stage of the construction.

Several methods exist to determine these ground movements. Some of these methods include all construction activities, whereas others only describe a specific aspect, so that the different contributions have to be added to a total. The empirical methods from the present state of the art, one should expect for a deep excavation in soft-stiff clay:

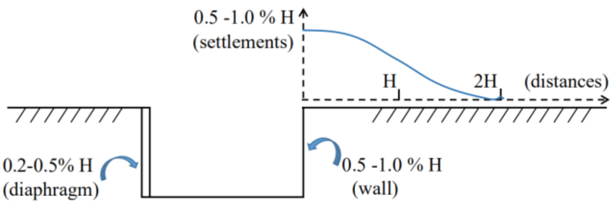


Figure 4. Excavation-related deformation

Wall deflection 0.5 – 1.0% (for an average system stiffness and sufficient basal stability);

Better results are possible (0.2-0.5%H) for diaphragm wall with good supports, as long as the excavation effect is the main cause and installation and other effects are controlled sufficiently;

Settlements behind the wall are about the same as wall deflections and may reach over a distance of 0.75H from the wall and decrease to 0 at 2-3H away from the wall.

Stability is assured when settlements due to installation of diaphragm wall can be limited to 5-10 mm.

50%-100% margins should be expected around the values presented [7].

In conclusion the empirical methods have shown that displacement and additional inclination to be predicted are conditioned on the type of construction, excavation, and soil. Other important aspects are the differences of use in wall type, depth, workmanship, ground water, etc. One can be conclude that trough wide ranges of settlements can be derived for design purpose from empirical relationships .

D. Crack Interpretation

Buildings under specific loading can move, create buildings' deformation, tilt, crack or be damaged under way depending on their construction type, stiffness, openings and joints. New construction surroundings cause further buildings deform under their self-weights. Cracking in buildings can have several, also non-construction related causes (Figure 5). It is most likely triggered by changes in the size of the building and by foundation movement (it is more common specifically in the case of excavations). Size changes are caused by temperature, moisture content or several other possible causes, such as chemical reactions within the building's material itself [7].

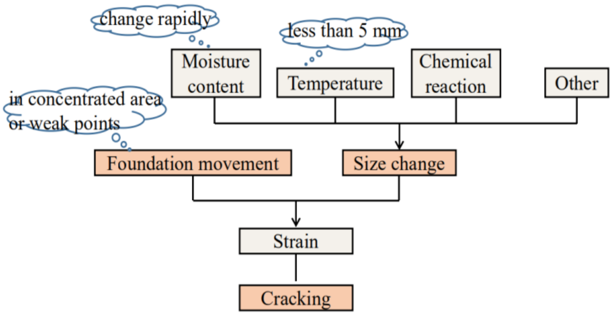


Figure 5. Several causes of cracking

There are different factors that can create cracks, such as temperature, chemical reaction, moisture or deformation of the building. Bonshor [10] distinguishes between several types of cracks shown in Figure 3. Cracks that are of uniform width throughout their length are usually temperature or moisture related and unlikely to progress in time. Temperature-caused cracks usually are not larger than 5 mm. Cracks due to changes in moisture content of the soil (e.g. when a tree is removed) will be caused by reversion of the soil to its original volume, thereby leading to a relatively rapid change. Fast changes are usually more dangerous than slower changes [2]. The cracks are produced by foundation movement that are concentrated in areas where maximum structural distortion occurs, or at one of the weak points in the structure. there are cracks, due to deformation of the building, continuous below and above ground level, which are often inside and outside of the building. Cracks are usually tapered small at one end and wider at the other. The location and direction of the crack depends on the deformation mode.

III. Case Studies

A. Introduction of Soil and Buildings

In soft soil region, for instance Shanghai and London, the conflict is more obvious than other regions due to geological reasons.

Out of the three case studies, two are from residences in Shanghai, and the third is from London. The two residents' buildings are of concrete raft foundation with 2.0 m embedded below ground surface. The residences are masonry structure with concrete ring beams on the floor elevations and concrete columns in the cross points of brick walls. The floors are of precast hollow slabs, but concrete cast-in-place slabs for kitchens and washrooms. The cracks are noticeable on the ground surface around them. The crack widths on bearing brick walls and self-weighted walls are over the limitation (GB/T 50344-2004, DG/TJ 108-79-2008, and DG/TJ 08-804-2005)[11-13]. In diagonal direction, irregular cracks exhibit on the ceramic tiles attached on the decorated layer in the kitchen and washroom. Also excessive deformations are visible on the frame of windows and doors.

In London, the construction of the Jubilee Line Extension Station at Westminster, consisted of the excavation of two tunnels and a station escalator box. The box is located 34 m north of the foundations of the Big Ben Clock Tower. The Clock Tower was constructed in 1858, and consists of load-bearing brick work with stone cladding approximately 11 m2 in height of 61 m. Supporting a cast iron framed belfry and spire to a total height of 92 m. The Tower founded is on a mass concrete raft, 15 m2 and 3 m thick within Terrace Gravels overlying London Clay. The construction of the New Westminster Station on London Underground Jubilee Line Extension (JLE) project was predicted to cause significant movements of the Clock Tower and the adjoining Place of Westminster [14].

B. Field Monitoring

1) Building 1

The residence 1 (Photo.1) built in 1995 is located in the center of Shanghai in China (latitude 310 16’ 51.58”, longitude 1210 25’24.22”). The minimum net distance away from the new construction is 10 m. The maximum depth of excavation of new construction is 9.8 m. The new construction began from December, 2014. The field monitoring conducted by Tongji University started from January 22, 2016 and ended on April 15, 2016. The layout of work site is shown in Fig. 6, and the layout of measure points are shown in Fig. 7.

Figure 6. Layout of work site (from google earth, July 2016)

The points of the connecting transverse are easy to design when we follow the previous reference point about 50 m in south east of the building. The measurement points follow the previous monitoring team who conducted settlement measurement from the end of December, 2014 to January 19, 2016. The settlements in different periods (Fig. 8) are listed in Table 1.

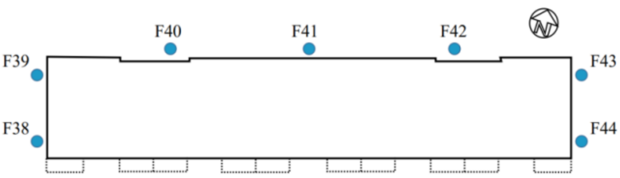


Figure 7. Measure points of the residence building

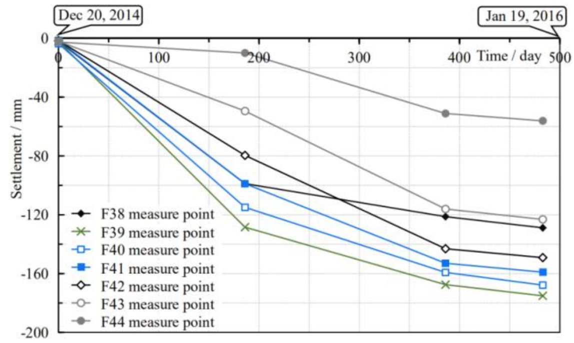


Figure 8. Excavation-caused settlement

TABLE I. ACCUMULATED SETTLEMENT IN DIFFERENT PERIODS SINCE NEW CONSTRUCTION BEGINNING (MM)

Measure points	**S1 / mm** (by previous team, from Dec 20, 2014 to Jan 19, 2016)	**S2 / mm** (by Tongji team, from Jan 22, 2016 to Apr 15, 2016)	**TS / mm** (total settlement)
F38	-120.7	-8.4	-129.1
F39	-166.2	-9.3	-175.5
F40	-158.6	-7.5	-166.1
F41	-152.2	-6.7	-158.9
F42	-143.6	-6.0	-149.6
F43	-116.3	-6.5	-122.8
F44	-48.7	-5.9	-54.6

Drawing the data in Table I as shown in Fig. 9.

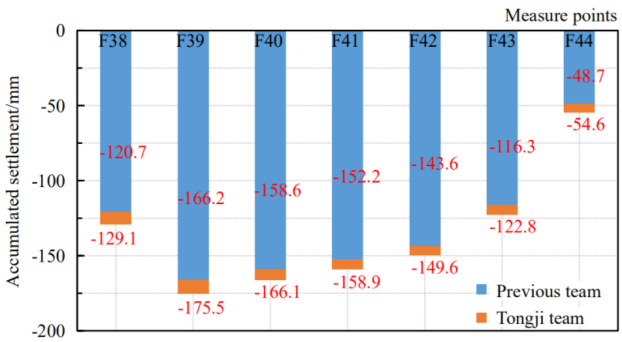


Figure 9. Accumulated settlement in different periods

It is noted that the Tongji University checked the previous system before monitoring to ensure that the results are reliable.

Assume the building is a rigid body despite of moment deformation, combined with settlement data in different periods, we can deduce the initial building’s inclination before new construction begins. During excavation of adjacent new buildings, and after excavation. The results analyzed are listed in Table II.

TABLE II. THE RESIDENCE INCLINATION IN DIFFERENT PERIODS (‰)

Position	**Before new construction**	**Dec. 2014 - Feb, 2016**	**Feb, 2016 - April, 2016**
North west	1.8	7.60	1.57
North east	5.2	4.39	2.82

Consider that the inclination of building 1 is approaching the criteria of 10 ‰ (JGJ 125-99,2004)[15], we calibrated the Total station (RTS112SR5L) made by Germany and we monitored 10 setup lines. Each line had been monitored three times. Each time we read three coordinates. This technical measure can mitigate the errors from measurement system and limited data. The building's inclination on April 15, 2016 is shown in Fig. 10.

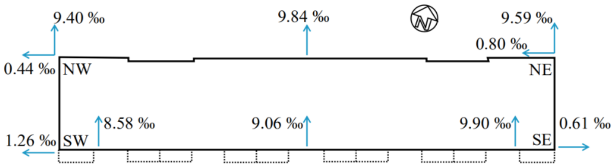
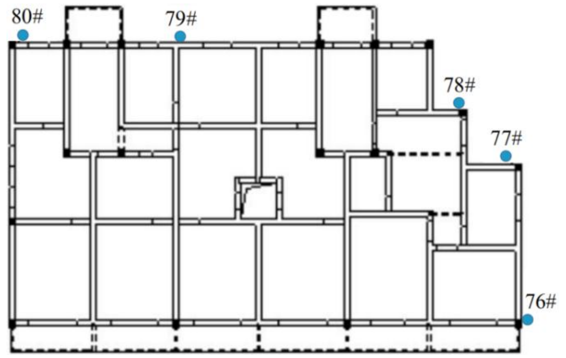


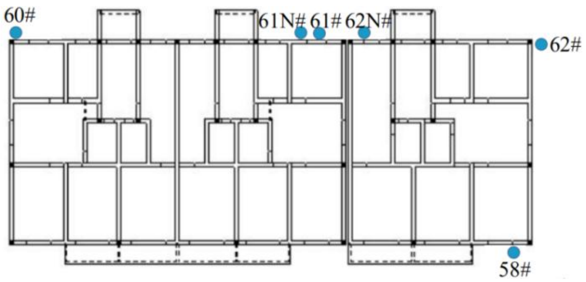
Figure 10. Residence inclination in representative positions

2) *Building 2*

The building 2 is located in the south of Shanghai in China (latitude 310 12' 18.34", longitude 1210 22'50.37"). They were built in 1993 and 1994. The construction of the tunnel nearby began from November, 2003. The field monitoring conducted by Tongji University started from May 24, 2006 and ended on July 28, 2006.The measure points are shown in Fig. 11. The size of the building and initial condition is listed in Table III. The minimum net distance away from the tunnel is 9 m. The maximum depth of excavation of the tunnel is 6 m.



(a) 1# residence



(b) 4# residence

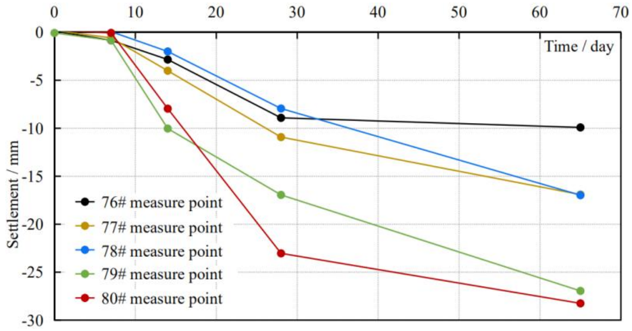
Figure 11. Layout of measurement points

TABLE III. SIZE AND INITIAL CONDITION OF THE BUILDINGS

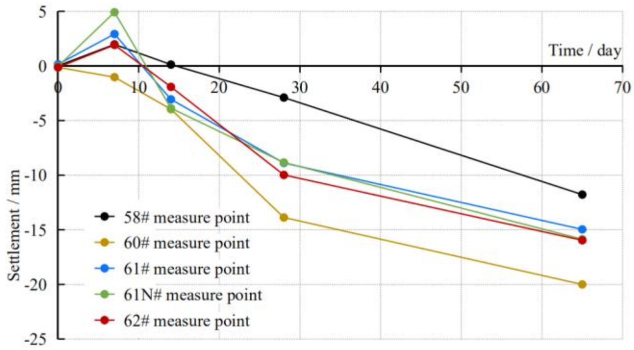
No. of residence	Height of story(m)	Width(m)	Length(m)	Initial condition
1#	2.8	12.3	22.0	Note 1
2#	2.8	12.3	40.2	Normal
3#	2.8	12.3	53.7	Normal
4#	2.8	12.3	31.5	Note 2
5#	2.8	12.3	43.0	Normal
6#	2.8	12.3	34.0	Normal

*Note 1: 60 square meters located on the dark creek processed. Note 2: It includes two parts which are not built at the same time. The settlement joint between two parts is 280 mm width.

Combining the deformation measurements from three periods (August to September in 1994, October in 2004 to February in 2006, and May to July in 2006), the building's settlement is shown in Fig. 12, and the inclinations (Tang, 2010)[16], are listed in Table IV.



(a) 1# of residence 2



(b) 1# of residence 2

*Time 0 denotes May Dec.20,2004.

Figure 12. Settlement caused by new construction nearby

TABLE IV. THE RESIDENCE INCLINATION IN DIFFERENT PERIODS (‰)

No. of residence	Before new construction beginning	Duration of new construction	July 28,2006
1# West	5.00	3.76	10.238(11.720)
4# West	5.00	2.66	7.705(7.590)

*The values in brackets are from settlement monitoring data.
*Monitoring duration of new construction from Oct, 2014 to Feb,2006.

3) *The big ben clock tower*

The Big Ben Clock Tower (St Stephen's Tower) (photo 3) is in the Elizabeth Tower at the north end of The Houses of Parliament in Westminster, Central London, next to the river Thames (latitude 51° 51' 03.57'', longitude -0° 11' 67,73''). The weight of the Tower is about 8400 t and given an average foundation bearing pressure of approximately 400 kPa (Harris, 2013)[14]. The construction of new Westminster Station on London Underground Jubilee Line Extension (JLE) project was predicted to cause significant movements of the Clock Tower and the adjoining Palace of Westminster. The JLE platforms are contained with 7.4 m outside diameter bored tunnels in a vertically stacked. in order to increase the distance to the Clock Tower, and a 39 m deep station escalator "box" for access purposes, the measure points near the Clock Tower was set as Fig. 13. The minimum distance is 36 m between the Westminster and the Clock Tower. Protective measures, primarily in the form of compensation grouting beneath the Clock Tower, were implemented during the construction period to control the settlement and tilt of the monument (Harris, 2013)[14].

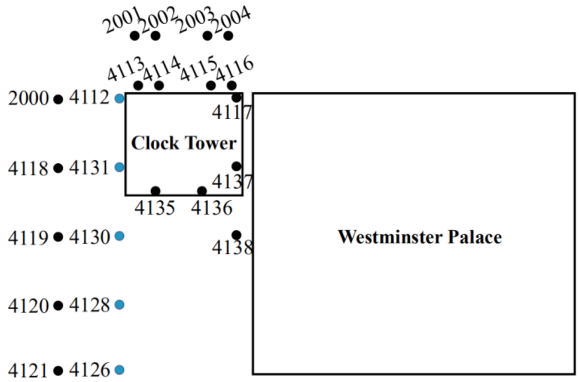


Figure 13. The measure points near the Clock Tower

The excavation was carried out using the well known ‘top-down’ technique (Crawley and Stones, 1996)[17]. Fig. 14 shows the settlements with time for a selection of the points (4112#, 4131#, 4130#, 4128#, 4126#) along the western facade of the main structure of the Palace of Westminster.

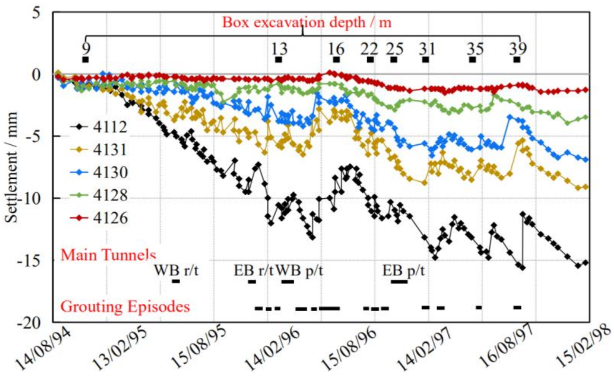


Figure 14. Settlement near the clock tower during compensation grouting

Fig. 15 shows the measured settlements along the west facade of the Palace of Westminster at various stages. immediately before and after each of the four main tunnel drives and from the end of construction at the September 1997. The settlement extends southwards to a distance of 30 m form the north face of the Clock Tower (form point 4112).

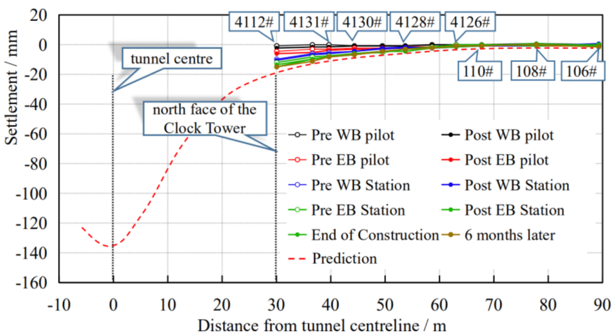


Figure 15. Measured settlements at various stages along west face of Westminster Palace

Fig. 16 shows the results obtained from the optical plum measurement over the period of time since they were initiated in the early 1970s for the construction of the underground car park (Burland and Hancock, 1977)[18]. As reported by these authors, the construction of the car park caused the tower to tilt about 2.5 mm to the south at a height of 55 m. The fluctuations around this trend line of about +/- 2.5 mm are due to the seasonal and daily thermal effects. Fig. 16 also summarizes the changes in north-south tilt of the Clock Tower during and subsequent to the construction of the new JLE station (Harris, 2013)[14].

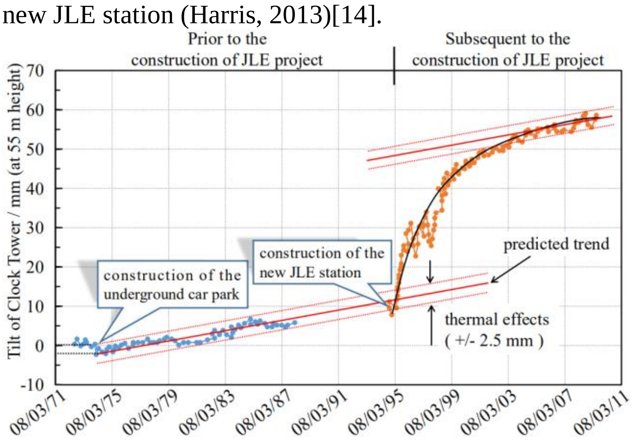


Figure 16. Tilt of the clock tower prior to and subsequent to the construction of JLE project

The formation on the new cracks is taken across significant pre-existing cracks. The cracks were monitored by extensor, showing that the horizontal movements were evenly distributed with no obvious concentrations of strain. The maximum tensile and compression horizontal strains recoded in any single span were 0.005 % and 0.0085 % respectively. The monitoring systems shown that the range of +0.5 mm opening and -1.5 mm closing. The cracks following an annual cycle with the maximum widths begins recorded in January/February and the minimum in August. The influence of the temperature that indicated variations is more significant for Big Ben Clock Tower than any change in crack width induced by construction operations.

IV. Result Analysis and Strategies for Rehabilitation

A. Result Analysis Buildings

Building 1 and 1# of Building 2 have 5‰ initial inclinations (Table 2 and 4). Compared with other monitored buildings, they have more increments of inclination. Maximum inclination rates are calculated to 2.82‰ and 1.9‰, respectively.

Maximum settlement rates from Feb. to March and from March to April, field monitoring by Tongji University are 0.090 and 0.043 mm/d, respectively. From the slope of settlement rate, they are not stable. Tang and Zhao (2012, 2016)[19] found that the soft layer under rafts of residences is not convergent due to constant slope of deformation based on laboratory triaxle tests.

Assume the residence has 10‰ inclination (the maximum allowable inclination, JGJ 125-99), so building 1 has 100 mm differential settlement going northward, building 2 has 210 mm going westward, and the Big Ben Clock Tower has 25 mm going northward. According to elastic theory, we can deduce the differential stress on the rafts according to Equation (1).

$$S = \frac{P}{E} H \tag{1}$$

where S is settlement,

P is average stress on the raft based on the loads of superstructure and self-weight of foundation, usually take 100 kPa,

E is soil elastic modulus,

H is thickness of compressive layers.

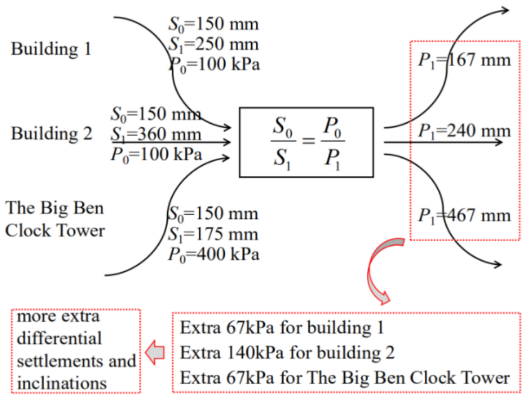


Figure 17. Calculation process of extra pressure

Assume the residences have 150 mm average settlements (based on local experiences) after two decade service, then the settlements for residences 1 and 2 and the Big Ben Clock Tower after adjacent new constructions are 250 mm, 360 mm and 175 mm, respectively. S0 = 150 mm, S1 = 250 mm for residence 1, S1 = 360 mm for residence 2, and S1 = 25 mm for the Big Ben Clock Tower, P0 = 100 kPa for two residences and 400 kPa for the Big Ben Clock Tower.

$$S_0 = \frac{P_0}{E} H, S_1 = \frac{P_1}{E} H,$$

Then

$$\frac{S_0}{S_1} = \frac{P_0}{P_1},$$

Thus, P_1 = 167 kPa, 240 kPa and 467 kPa for residences 1 and 2 and the Big Ben Clock Tower, respectively, figure 17 shows the calculation process of the extra pressure.

Estimated stress increments due to inclinations are 67 kPa ,140 kPa, and 67 kPa for residences 1 and 2 and the Big Ben Clock Tower, respectively. These stress increments will lead to more extra differential settlements and inclinations.

Three cases exhibit creep deformation after excavation of new construction. The two buildings in Shanghai had 0.36 mm / day settlement. The Big Ben Clock Tower had tilt of 0.015‰ / month.

On the basis of the settlement rate, inclination rate vs. initial condition, as well as the deformation caused by different period conducted by scientific analysis, we can better understand the results of monitoring surveys and two parties realize their responsibilities for the present condition of the residences. Then both parties will concentrate on how to improve the serviceability of the residences.

We also employed the finite element software to evaluate the bearing capacity and seismic performance of the residences (the process is omitted here). The result is almost satisfied with the requirements (GB 50009-2012, GB 50011-2010, and GB 50007-2011)[20-22].

B. Strategies for Rehabilitation

In urban areas, there are many situations where new construction or underground excavation such tunnels are proposed to be constructed adjacent to old buildings. Moreover, new construction work can be influencial the economical, political and technical aspects of the building project. The important parts of risk management for excavation work are to the understand and to predict the ground movement and the corresponding level of damage. Excavation of basement, especially to adjacent buildings, indices movements as a consequence of stress-release from earthwork and an increase in overburden pressure in the retained ground. At the end the results shown that there are numerous sources of risk associated with performing deep excavations in urban areas, because during the deep excavation projects are the potentially large ground deformations in and around the excavation, which might cause damage to the adjacent buildings and utilities.

It is important to understand how the ground movements due to excavations influence nearby structures. The response of buildings to excavation-related ground movements is dependent on the source and pattern of the ground movements, type and condition of the structure, and mitigation measures employed to protect the buildings (Korff, 2009). Most methods to assess the impact on the buildings are originally derived for tunneling projects, which is not always problematic, but could be improved by specifically looking at deep excavations. Furthermore, there are various measures to avoid existing buildings adjacent new constructions from excessive deformation. For instance, underpin under existing shallow foundations, install diaphragms around existing foundation to isolate existing buildings and new constructions, mitigate excavation deformation itself, and mitigate existing building settlements by effective methods.

V. Summary and Conclusion

In soft soil region, brick masonry buildings with shallow foundations are very sensitive to adjacent new constructions which are with deep foundations accompany with deep excavations. Two case studies in Shanghai show that extra 5~7‰ inclination happens frequently if they have initial defects, such as initial inclination. One case study in London show that inclination and settlement of historic masonry tower could be controlled in required range by hybrid measures of dynamic monitoring, grouting, top-down construction. Evaluation of extra deformation and structure safety should be done before the new construction begins. It is recommended to protect existing buildings or mitigate deformation of excavation of new construction if the evaluation exhibits that the existing building is vulnerable.

Damage in structures is not only related to construction, also temperature, creep which are that major attributions. Three cases in this paper exhibit the creep behavior. It is essential to monitor the movements as they develop and thereby progressively refine understanding of both the ground movements and the response of the nearby structures impacted by them.

For historic masonry buildings, the level of damage and the mitigation methods used to control should be in accordance with the principles of conservation as far as practicable. Protection of ground movements and the corresponding level of building damage of adjacent structures forms an important part of risk management for excavation works.

Prediction methods can be used at design stage of the project. Five main points are listed as follows:

1) Sensitive damage can be originating during excavation with a result of settlements and inclination in the buildings. it is important to understand the settlements of the building due to nearby excavation works. The settlements in general caused horizontal and vertical differential buildings deformation.

2) Another important factor is to study the geometric information, and the geotechnical condition for the soil (physical and mechanical) in order to foresee and mitigate the settlement and the inclination during the works.

3) It is important to consider the interpretation of the numerical modelling in order to drawing an interaction between the buildings and ground with geotechnical and structural aspects, before and after the excavation.

4) The formation of the new cracks is likely near the significant persisting cracks, which were very sensitive to temperature. Crack-width changes from seasonal temperature effects were comparable in magnitude to those associated with the ground movements due to deep excavation.

5) Monitoring and mitigation measures can effetely contribute to reduce the risk management if it is used proactively during and after the excavation work. In order to reduce the deformation, it is better creating a monitoring plan, which can be used for the construction process. Moreover, some external factors due to environmental conditions (water, subsidence, porous material, creep) can be derivate while using mitigation measurements to manage the buildings.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

We thank each author's effort to this paper. Zhi-Yuan Chen conducted the research; Yong-Jing Tang collected and analyzed the data; Haiyang Qin wrote the paper; all authors had approved the final version.

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