Computer Intelligent Response Evaluation Model of Building Adjacent to Deep Excavation and the Automatic Monitoring System

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Abstract. Due to the high density of buildings in urban areas, a major concern when making deep excavations is the impact of construction-related ground movements on adjacent buildings. The real-time monitoring is required to minimize damage to adjacent structures before, during, and after construction. This paper presents such a case study. During excavation, a variety of instruments are used to monitor the response of adjacent structures. The automatic monitoring system successfully monitored the settlement, tilt and cracks of adjacent structures near the excavation of the new office building in real time. Measurements made throughout the project indicated that the excavation-related deformations were slight in the adjacent buildings. These deformations did not cause actual structural damage. To sum up, careful evaluation and sufficient instrumentation are both required to ensure structural safety during construction.

Keywords: Excavation, adjacent building, deformation, cracking, settlement.

1. Introduction

With the rapid development of urban construction in metropolitan areas, building land is becoming more and more scarce, and high-rise and super high-rise buildings are increasing. Infrastructure construction and subway projects often require deep excavations. Due to the high density of buildings, most of the construction sites are inevitably surrounded by buildings at close proximity. Therefore, the process of excavating for a new building foundation, especially in urban settings, can often result in damage to adjacent buildings. Much of the damage to existing buildings resulting from new construction could be avoided if the relevant buildings had been fully monitored and the possible consequences of the foundation works had been predicted based on the monitoring data.

Over the last decade, structural health monitoring has become a useful tool for the construction, management and damage identification of bridges, super high-rise buildings and other civil structures. The monitoring of static and dynamic parameters about the structural behavior such as strains, deformations, tilts and displacements can provide real-time feed-back during construction. The quantitative data helps the engineers to evaluate the real current condition of the structure and take informed decisions to plan maintenance or repair actions to minimize the risk of damage. This paper
describes the process used to monitor the response of buildings adjacent to deep excavations. Combined with the monitoring data, the potential for damaging these structures was estimated.

2. Project description
Located at the tip of the alluvial Yangtze River Delta, Shanghai has variable soil conditions with thick layers of soft alluvial clay. Complex geological conditions bring challenges to excavation projects. The new office building is a 14-story structure with a two-level basement. The basement is used mainly for parking. This new project occupies a plan area of about 5,404 m² (68 m × 80 m). The general excavation of the basement is 9.70 m in depth, the main building is 9.90 m in depth, and the local depth of the elevator shaft and water collecting well is 1.40-2.85 m, which were carried out in relatively soft alluvial deposits.

According to the Shanghai standard "Technical Code for Excavation Engineering" (DG/TJ08-61-2018), the safety level of the excavation project is Grade 2, and the environmental protection level is Grade 2. The excavation support system consisted of a secant pile wall with two levels of support. The wall was constructed with overlapping 850-mm-diameter cast-in-situ bored piles and triaxial cement-soil mixing piles. Excavation support was provided by a combination of cross-lot strut, knee bracing and side truss.

3. Adjacent structures
The general plan of the surrounding site is shown in Fig. 1. According to the site survey, there are four buildings located within two times the maximum depths of excavation of 9.9 m, including the 14-storey Customs Building on the north side, the 3-storey New Trade Building on the northeast side, and the single-storey distribution substation and water pump house on the south side.

Figure 1. Plan view of case study excavation.
The Customs Building situated to the north of the construction site is founded on precast reinforced concrete square pile foundation. The cross-section of the square pile is 450mm×450mm, and the pile length is 28m. It was built in 2000, and is a reinforced concrete frame - shear wall structure with a basement. The distance between south side of Customs Building and the edge of the excavation is 15.5 m.

New Trade Building is a reinforced concrete frame - shear wall structure without basements. It is founded on shallow strip footings with a depth of 1.9 m. It was originally built in 1994 and renovated in 2007. The distance between the southwest corner of New Trade Building and the edge of the excavation is 14.7 m.

The substation and water pump house were built of load-bearing brick on shallow spread and strip footings in bricks. The depth of the foundation is 2.1 m below ground surface. It was built in 2002. The north side of the water pump house and the substation are about 7.9 m and 6.5m away from the edge of the excavation, respectively.

4. Comprehensive monitoring methods

In the case of excavation project, the monitoring system is used to increase the safety of the adjacent structures and provide early warning of an acceleration of the building damage that are being monitored. Therefore, 24h automatic monitoring is carried out to obtain the real-time monitoring data and monitor the progression of the building damage throughout the duration of the excavation activities. Based on periodic damage surveys, the designer, the construction party and the supervisor can take corresponding measures according to the monitoring results in time. Measurement goals mainly included settlements, inclining and cracks in the surrounding buildings. In order to prevent impact on the construction monitoring and judgment caused by large deviations in the data, comprehensive monitoring methods is adopted.

4.1. Tilt monitoring

The lateral ground movements associated with the excavation were monitored with inclinometers placed around the structures. The biaxial inclinometers are installed on the exterior walls of the buildings to automatically monitor the tilt of structure 24 hours a day. In addition to the above methods, manual monitoring is also used at some monitoring points to monitor the overall tilt of the building and to check each other.

4.2. Settlement monitoring

According to the site conditions, the static leveling system is selected to carry out 24 hours automatic relative settlement monitoring. Fig. 2 shows the locations of the instrumentation used to monitor the responses of the Customs Building, including tilt, settlement, and crack monitoring. Settlements were monitored using monitoring points established on exterior walls. According to the requirements of relevant codes, two groups of fixed monitoring leveling points should be designed in the area more than 100m away from the deep excavation. Then, the actual height difference of the four points can be measured by high-precision measuring instruments, and these four points are determined as the reference points of deformation and settlement.
4.3. Crack monitoring
The most common measure used to assess excavation-related building damage is the onset and growth of cracks in walls of adjacent structures. The changes in crack widths are measured with crack sensors to assess the structural safety of critical components near construction.

4.4. Monitoring alarm value
The above monitoring points were monitored before and after the construction every day in principle. In general, the settlement monitoring accuracy of the automatic monitoring system could reach 0.1mm and the automatic inclining accuracy could reach 0.2‰. The alarm value for settlement monitoring is that the cumulative deformation is greater than ±30mm or the daily deformation is greater than ±2.0mm for two consecutive days. For tilt monitoring, the increment of tilt rate reaches 1‰ is regarded as the alarm value. For crack monitoring, the alarm value is set as the crack width increase of the concrete member reaches 0.3mm, the load-bearing brick wall reaches 1.0mm, and the enclosure and outdoor ground reaches 10.0mm. When the monitoring data exceeds the limit, the alarm is sent and the emergency plan is activated.

5. Adjacent building responses to excavation
After more than one year of monitoring, a large number of monitoring data have been obtained.

5.1. Tilt monitoring results
The monitoring results of tilt deformation show that the Customs Building tilts slightly to the southeast on the whole, with the maximum tilt of all monitoring points in the east-west direction of 0.65‰ to the east (no significant change compared with the initial value), and the maximum tilt of all monitoring points in the north-south direction of 0.74‰ to the south (no significant change compared with the initial value).
New Trade Building tilts slightly to the southwest on the whole, with the maximum tilt of all monitoring points in the east-west direction of 0.93‰ to the west (no significant change compared with the initial value), and the maximum tilt of all monitoring points in the north-south direction of 0.80‰ to the south (no significant change compared with the initial value).

Both the water pump house and the distribution substation are inclined slightly to the northwest on the whole (the tilting directions have changed compared with the original detections). The maximum tilt rate of east-west monitoring points to the west is 1.22‰ and 0.82‰, respectively (no significant change compared with the original detection). The maximum tilt rate of north-south monitoring points to the north is 1.95‰ and 2.24‰, respectively (2.08‰ and 1.73‰ more than the original detections).

5.2. Settlement monitoring results
The cumulative deformation of settlement monitoring points in the Customs Building ranges from -20.9 mm to 2.6mm, and the additional settlement is greater on the south side of the building. The cumulative deformation of settlement monitoring points in the New Trade Building ranges from -16.4 mm to 0.4mm, and the additional settlement is greater on the southwest side of the building. The cumulative deformation of settlement monitoring points in the water pump house ranges from -43.0 mm to -26.5mm, and the additional settlement is greater on the northwest side of the building. The cumulative deformation of settlement monitoring points in the distribution substation ranges from -38.2 mm to -24.2mm, and the additional settlement is greater on the northeast side of the building. According to the results, the additional settlement of a few measuring points in the water pump house and the distribution substation reaches the alarm value.

5.3. Crack monitoring results
The facade of the Customs Building is basically intact. The outdoor ground in the south side is partially cracked, and some outdoor steps in the southeast corner have a settlement of 27 mm. The maximum east-west crack is approximately 800 mm long and had a maximum width of about 1.5–2 mm. The cracks in the other three buildings are similar to those in the Customs Building. Cracks are mainly found in the outdoor ground. Some hairline cracking was also reported in these buildings before construction. Before and after construction, except that the width of a few crack monitoring points increased slightly, the width of most crack monitoring points around the building basically did not change. The change of crack width at each crack monitoring point did not reach the alarm value.

6. Comprehensive analysis of monitoring data
According to the monitoring results, the excavation has caused different degrees of impact on the surrounding four buildings. The following defects of the four buildings developed consequent to the excavation were observed: (1) cracks on outdoor ground and walls; (2) a certain degree of additional settlement; (3) localized settlement of outdoor steps ;(4) tilting of the buildings toward the deep excavation site. The aforementioned defects were caused by the ground movements associated with the deep excavation.

Additional settlement was concentrated around the excavation and was larger on the side near the excavation and smaller on the side away from it. Due to the relatively close distance to the excavation, the additional settlement of the water pump house and the distribution substation is relatively large (-43.0 ~ -24.2mm). The overall tilt towards the excavation has increased. The excavation-induced damage within the four buildings was primarily in the form of architectural cracking (i.e., nonstructural) of outdoor ground and exterior walls. Throughout subsequent construction, most cracks lengthened, but widened only slightly. It was mainly the general aging damage caused by temperature variation and material shrinkage. There was no further extension of damage in the building after construction. The observed damage is characterized as “negligible” to “slight” according to the damage severity classification proposed by Burland et al. (1977). Measurements made throughout the project indicated that the excavation-related deformations were slight in the adjacent buildings. To sum up, the construction did not change the structural safety of the surrounding buildings.
7. Conclusions
Experience has shown that the adjacent structure is vulnerable to damage as a consequence of differential settlement unless preventive measures are undertaken prior to excavation in soft clay. Damage to a building resulting from excavation-induced ground movements depends on the condition of the structure before excavation begins, excavation support system, the structural system of the affected building and distance from the excavation. Because of the complexity of the problem, it is difficult to estimate the response of a building to excavation-related deformations by a purely theoretical method. Consequently, building response must be evaluated primarily based on empirical observations and real-time monitoring. Adjacent buildings must be monitored 24 hours a day to verify that the building response is kept within tolerance during excavation and foundation construction. Furthermore, faced with so much monitoring data, it is very important to make a comprehensive judgment on the response of the adjacent buildings and give timely advice.

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