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Real-time monitoring on diaphragm wall inclination by using WSN

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This paper introduces a real-time monitoring system by using wireless sensor network (WSN). And this is a real application on inclination monitoring on the diaphragm wall of an excavation engineering project, which is adjacent to a metro line in Shanghai. According to Shanghai local regulation, the maximum lateral displacement of retaining wall should be less than 0.14%H (i.e. excavation depth). As for the monitoring of wall deformation, buried inclinometer with manual measurement is widely used. However, it is hard to obtain continual data for the timely warning by the conventional method, especially under a critical condition such as rainy or hazy days. Besides, measurement data of different monitoring points can't be acquired simultaneously. The applied WSN system on the diaphragm wall consists of 48 tilt nodes and a gateway. A project cloud platform allows all interested parties to access the data, and it helps to recognize an early damage signal quickly and analyze the diaphragm wall in a spatial manner. The monitoring system the paper introduces might be helpful for those excavations that require real-time monitoring under severe ground conditions, or those adjacent to tunnels as in this case.

Keywords: deep excavation, real-time monitoring, wireless sensor network, wall inclination.

1 Introduction

Field monitoring is an effective way to sense the variation of surrounding environment and the real response of a supporting system. Many factors need to be monitored, including displacement of soil, pore pressure of water, displacement and inner force of a supporting system. Among them, lateral deformation of the retaining wall is a vital one which can comprehensively reflect the soil and structural response caused by excavation.

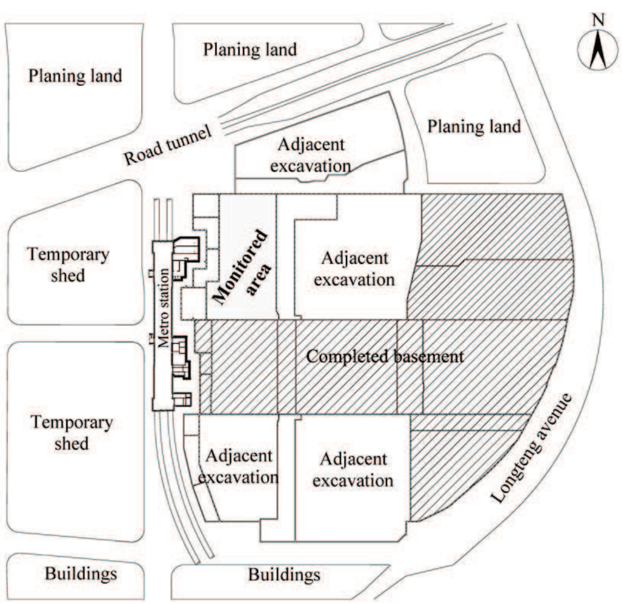
As for the monitoring of wall deformation, buried inclinometer with manual measurement is widely used. The features of low-efficient data acquiring and processing with long monitoring internal are prominent. Additionally, there might be no sign when a sudden accident occurs, such as a collapse or a trouble of large structural deformation. To solve these problems, a real-time monitoring system is needed. These continual measurements can provide early detection of large deformation to avoid potential damage happened to the nearby structures.

WSN is a self-organized wireless network composed of a number of sensor nodes that interact with the physical world (Akyildiz et al. 2002). Due to the technology of Micro-Electric-Mechanical-System (MEMS) and wireless communication, sensors are becoming smarter, characterized by automatic and real-time sensing, wireless transmission, no external power, large scale distribution, and ease of installation. Because of these advantages, the research of its deployment at real construction sites has been carried out in some countries (Chi and Hong 2009, Nawaz et al. 2015, Wilkins et al. 2015, Xu et al. 2016). However, few of current investigations have given a detailed monitoring data analysis for its application on real projects.

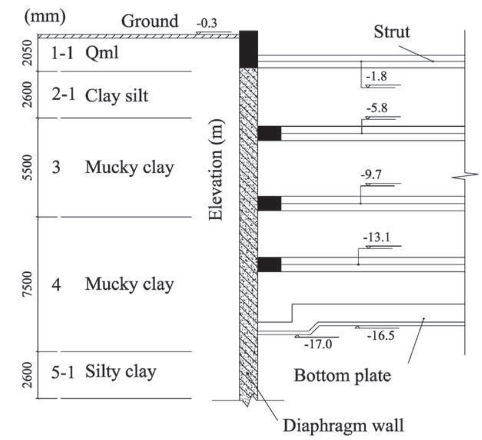
This paper introduces a WSN system consisting of 48 tilt nodes and a gateway to remotely monitor the inclination of the diaphragm wall at an excavation site adjacent to a metro line in Shanghai. Section 2 describes the surrounding environment, the excavation area, the supporting system, and soil conditions. Section 3 presents the WSN system and its field deployment. Section 4 analyzes the monitoring results with construction progress to show the temporal and spatial advantages of the WSN system.

2 Site description

As shown in Fig 1 (a), the monitored area takes the planform of an inverted L shape, which is 147m long, 68 to 86m wide, and 16.2m deep. It is located at the northwest corner of the whole construction site in Xuhui district, Shanghai, and the metro line, closely at the west. In addition, some temporal sheds, planning land, road tunnel, buildings, avenues and adjacent excavations are near the monitored area. As shown in Fig 1 (b), the excavated soil is mainly consisted of mucky clay. This kind of soft soil has a feature of fluidal plasticity and high compressibility, which requires a robust supporting system. The supporting system is made up of a diaphragm wall and four levels of reinforced concrete struts, and the excavation work started from 9th May and was due by the end of 2017 after finishing the underground structure.



(a)



(b)

Figure 1. (a) Surrounding environment; (b) Supporting system and soil conditions

3 WSN system and deployment

3.1 *Tilt node and gateway*

As the left picture shown in Fig 2, the tilt node is installed on a pre-mounted metal holder on the wall. The device has a MEMS-based inclinometer in the internal, which can automatically sense the dual-axis angular variation (range from -30° to 30° with 0.01° accuracy), and the A-axis represents the inclined direction. A piece of 2.4GHz wireless transceiver is assembled inside the tilt node, to make sure the data are received and transmitted in real time. The right picture of Fig 2 shows the gateway tied on a railing. It acts as the root node and the border router. Data packet received from tilt nodes can be transmitted by a 3G wireless module, and it links with a box of standby battery for longer power supply.

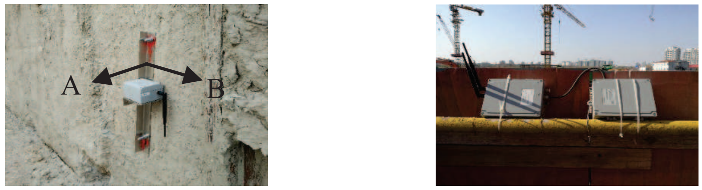


Figure 2. Site installation: Tilt node (left); Gateway (right)

3.2 *Field deployment*

Fig. 3 shows the 3D model of the excavation and the WSN system deployment. Eight monitored sections were chosen (namely I-1 to I-8). Tilt nodes suggested by blue cubes, which were intended to be installed on these monitored sections at six different elevations (namely -3.7m, -4.9m, -7.7m, -8.9m, -10.9m, and -12.1m), as the excavation moved on. The gateway denoted by a red ball was to be fixed on a tower crane for better signal strength and coverage. To balance the engineering requirement and power consumption, the sampling time internal of 15 minutes was set, and monitoring period was from 26th May to 22th Aug when bottom plate was casted.

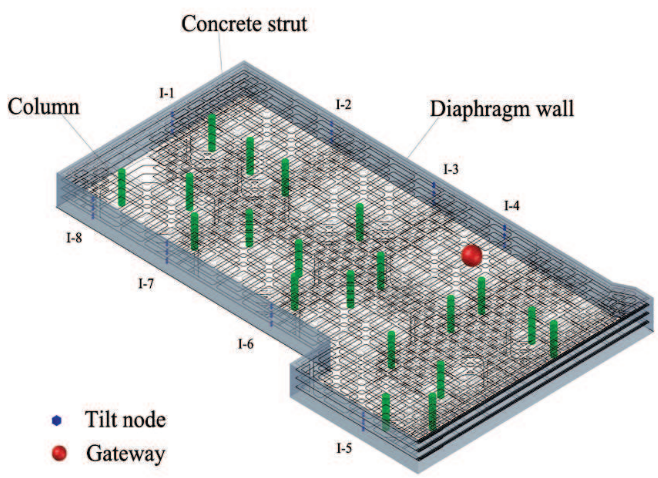


Figure 3. 3D model of excavation and WSN system deployment

3.3 *Network system*

Fig 4 shows the mode of sensing data transmission based on multi-hop routing.

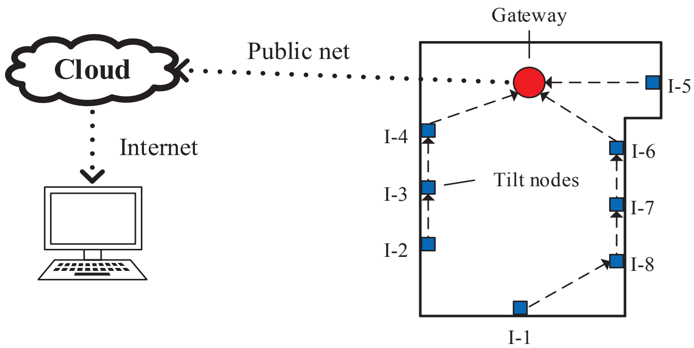


Figure 4. Network system

Each tilt node takes its own sensing data and relays them to other nodes, and all the data will converge to the gateway. Data packet is then transferred from the gateway to the cloud, which can be viewed directly through a browser or downloaded to a local computer via FTP for further processing.

4 Monitoring results and analysis

4.1 *Single tilt node monitor continually*

Dense data were obtained for capturing any response in a short time. As shown in Fig 5, take monitoring results of the tilt node where its install elevation was -4.9m at I-8 as an example, a rapid increment appeared at 11:30 on 31th May, which was caused by the soil excavation nearby, and inclination increased up to 0.03° till the 3rd level strut braced at 14:30 on 4th June.

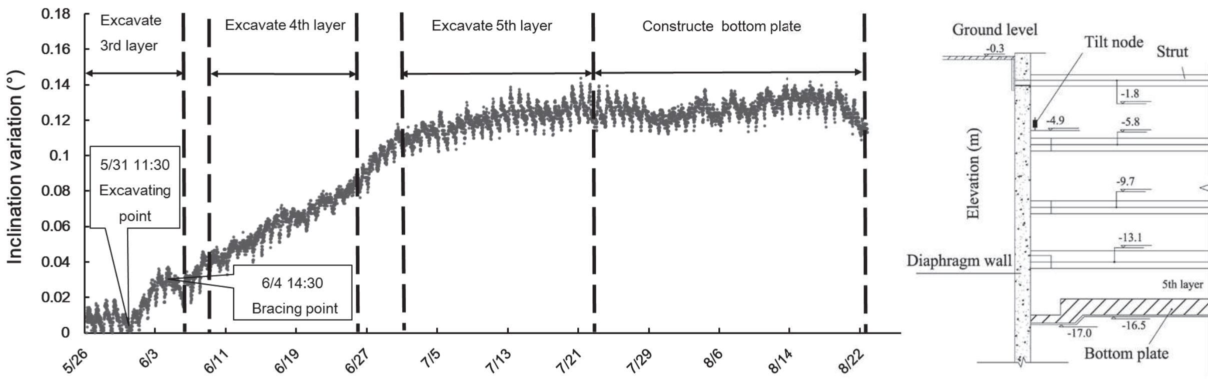


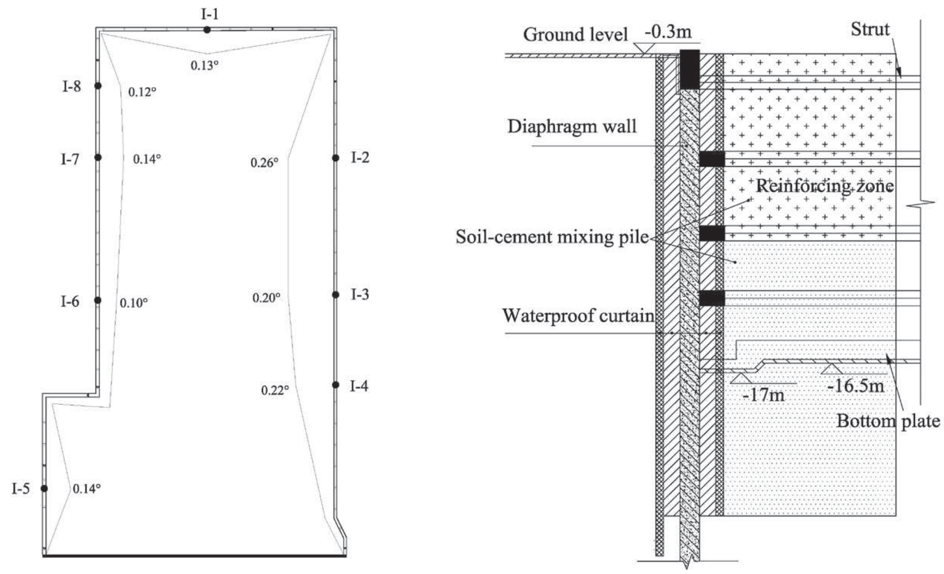
Figure 5. (a) Monitoring results; (b) Location of the analyzed tilt node

Whole construction process was continually monitored. For example, the 3rd layer was excavated from 26th May to 6th June, ultimately causing 0.02° inclination increment in 12 days. The 4th layer was excavated from 9th June to 26th June, causing 0.05° inclination increment in 18 days. The 5th layer was excavated from 1st July to 23th July, causing 0.02° inclination increment in 22 days. There was no big inclination variation during bottom plate construction. It could be concluded that the highest average inclination rate happened during the 4th layer excavation. The reason for the results was that the 4th layer had the poorest condition, in which the friction angle of this soil layer was 11.5°, causing the lateral pressure coefficient to increase up to 0.83 based on the Rankine's theory. In addition, temporal effect of the soft clay could be clearly seen from the continuing development of the wall inclination in the days without any excavation.

4.2 *Multiple tilt nodes monitor corporately*

Connecting the multi-sensor data is aiming to study the spatial effect of the excavation. Fig 6 (a) sketches a rough planar inclination profile of diaphragm wall by connecting all the sensing data of -4.9m elevation on 22th Aug. It was observed that the maximum inclination occurred was close to the middle part, which was caused by conducing the basin excavation method, and the maximum inclination of the west wall, the east wall, and the north wall was 0.14°, 0.26°, and 0.13° respectively.

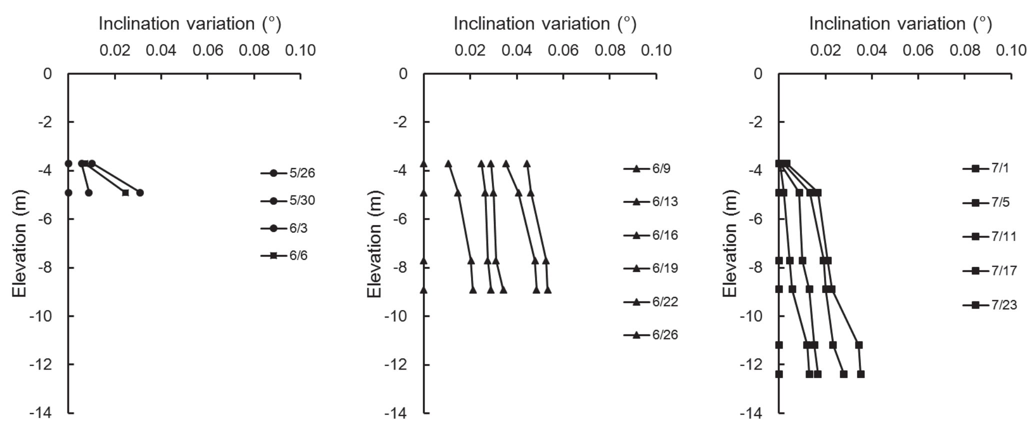
It was clear to see that the maximum inclination of the west wall was much smaller than that of the east wall. This distinction should be attributed to some protection on the west wall, which was near the metro line, as Fig 6 (b) shows. Soil-cement mixing pile reinforcing the passive zone was prior to excavation. During the excavation process, earth berms for west wall were required to remain to provide a certain resistance for the wall and increase the vertical pressure of soil below the excavation level so that the resisting rigidity of the reinforced passive zone was enhanced further.



(a) (b)

Figure 6. (a) Planar inclination profile of diaphragm wall (b) Reinforcement at west wall

To explore the spatial effect at different excavation stages, Fig 7 displays the monitoring results of I-8, the nearest section adjacent to metro tunnel. And the other sections are similar too.



(a) (b) (c)

Figure 7. Inclination monitoring at different stages: (a) two tilt nodes monitor the 3rd layer excavation; (b) four tilt nodes monitor the 4th layer excavation; (c) six tilt nodes monitor the 5th layer excavation

Multi-strut effect was clearly seen from the fact that both the minimum and the maximum inclination variation occurred at places close to the top and the excavation level, and the inclination pattern presented was nearly linear, no matter what excavation stage was. And the maximum inclination variation of the 3rd layer excavation, the 4th layer excavation, and the 5th layer excavation was 0.03°, 0.05°, and 0.04° respectively. It is crystal to see that the wall inclined most in the 4th layer excavation stage caused by the poorest soil condition of the 4th layer, which was also mentioned in 4.1 section.

5 Conclusion

The deployed WSN system was consisted of 48 tilt nodes distributed on eight wall sections at six levels, with a gateway fixed on a tower crane. With the key technology of communication module, network protocol and time synchronization, a robust connectivity of tilt nodes was established, so the inclination information of all the locations where tilt nodes were installed could be received timely, simultaneously and remotely.

At the 15-min sampling time internal, small responses were captured in time, such as at the excavating and bracing moment. These continual measurements not only indicated that the highest inclination rate occurred at the 4th layer excavation, but also recorded the inclination in the days without any excavation. They represented the temporal advantage of the WSN system.

Multiple tilt nodes can work as monitors in a corporate way. A planar inclination profile of the diaphragm wall was obtained, and the maximum inclination occurred close to the middle part was caused by using the basin excavation method. The inclination of the west wall was much smaller than that of the east wall, verifying the effectiveness of the soil-cement mixing pile reinforcement and the remained earth berm for the west wall. Besides, even at different excavation stages, the place where the maximum inclination occurred was close to the excavation level, with the most prominent inclination happened at the 4th layer excavation. This represented the spatial advantage of WSN.

For the safety assessment and early warning of the diaphragm wall, the parameter of maximum displacement and variation daily rate as the evaluation index are required to use, according to the existing regulations in China. Therefore, inclination data can't be used directly. In order to solve the problem, the following task of this paper will be around how to integrate the multiple inclination data to analyze the uncertain parameters of ground by using Bayes method. Then it is necessary to evaluate the current situation and predict the variation for the next construction stage based on the upgraded parameters.

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