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A WIRELESS RAILWAY MONITORING SYSTEM OF PROBLEMATIC SUBSTRUCTURE IN TUNNEL

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ABSTRACT

The railway substructure needs to be monitored to determine whether the substructure is stable. In the paper, the damages to the substructure of the heavy-haul railway in the tunnel were recognized and the grouting technology and water pipes were used to avoid further damages. To monitor the state of the substructure in the tunnel, a wireless monitoring system was developed. The accelerometers, laser rangefinders, water level gauges, and cameras were used in the sensor module, the fiber optics and mobile telephony were used in data transferring module, and a data managing system was developed in the control center. To examine the measured date by the monitoring system, the measured vertical displacement and horizontal displacement, the settlement, and the water levels at the site were presented. The measured data showed that the underground voids still existed after the grouting technology and water pipes of installation were applied. The horizontal and vertical displacement and settlement were induced by the underground voids and the loading of the train. The water level varied at the three locations, and the change of the water level beneath the surface showed that the flowing water was drained due to the water pipes. The wireless monitoring system was successfully developed to monitor the real-time data of the substructure and determine if the substructures was stable.

KEYWORDS

Railway substructure, Monitoring system, Wireless, Sensors

INTRODUCTION

China heavy-haul railway is experiencing the growing demand for traffic and capacity. Due to the increasing number of cargo and passengers, the heavy-haul railway is playing an important role in the transportation system. The railway track [1], consisting of the superstructures and railway substructure, is governing the smooth rides of the train. One of the important factors needs to be considered during the operation of the heavy-haul railway is the health state of the railway track.

The performance of the railway track may be weakened by problematic railway substructure. The problematic railway substructure could be caused by various factors, such as repeat loading, high water content, loose soils, temperature and so on [1]. The railway track of heavy-haul railway is under large axle loading frequently, which results in the increasing vibration on the railway track and permanent deformation [2], so there is a high probability that the problematic railway substructure would occur in the railway track of heavy-haul railway.

To avoid further damages to the railway track, the status of railway track needs to be analysed for the heavy-haul railway. Several methods are available to monitor and analyse the railway track, including field monitoring method [3, 4] and numerical method [5, 6]. Some investigations [7,8] had been conducted on the dynamic response of the heavy-haul rail substructure using numerical simulation method. The dynamic response of the railway substructure varies with the site condition [9,10]. Although the numerical analysis was proved to be more accurate in the calculation of dynamic response of the substructure, detailed material properties and non-linear analysis of soil behaviors had to be taken into consideration. In engineering practice, the field monitoring gains a better understanding regarding the dynamic response of substructure with various instruments, such as inclinometers, acceleration sensors, and other measuring devices. The field monitoring could be used in the railway track, and various monitoring system [11, 12, 13, 14, 15, 16, 17] were developed for different purposes.

One of the challenges for the field monitoring of the railway substructure in the tunnel of the heavy-haul railway is that the field monitoring is limited to the space of the tunnel, and the conventional monitoring is difficult to be instrumented without the interruption of the train operation. Furthermore, the intense freight of the heavy-haul railway decreases the maintenance time. In such a situation, a stable, efficient and accurate system that monitors the railway track. As a result, a real-time, long-time monitoring system consisting of sensors, data station, and control center connected by wireless network [18,19] needs to be developed to monitor the structure health of the railway substructure and overcome the shortcomings of the conventional field monitoring.

The problematic substructure was identified in the railway tunnel of Jundushan, which was part of the Daqin heavy-haul line in China. To guarantee the further safety of the tunnel after the initial treatment, a monitoring system was proposed, which aimed to monitor the problematic substructure and evaluate the safety of the tunnel. In the paper, the monitoring system based on wireless transmission technology was developed for a long-term monitoring to monitor the state of railway substructure in the tunnel and provide real-time surveillance of the railway substructure. The framework of the monitoring system was introduced as well as the sensors used in the monitoring system. The monitored data such as displacement of railway substructure, settlement, and water levels were presented to illustrate the monitoring system and evaluate the safety of the substructure.

SITE CONDITION

The railway from Datong to Qinhuangdao, known as Daqing line, was heavy-haul transportation, which was the first double-lane and electrified line in China. The tunnel was located at the Southeast of County Yanqing and the total length of the tunnel was 8460m, which was the longest tunnel among the 52 tunnels of the line.

The geology condition of the site mainly consisted of magmatic rock, which was classified as hard rock. However, the weak surrounding rock for the section of the tunnel from the entrance extending to the length of 670 m was composed of loess sandy clay, and the weak surrounding rock for the section accounting for 500 m of the tunnel to the exit of the tunnel was composed of weathered granite. The concrete board sleeper and wall lining were used during the construction of the tunnel. The section of tunnel was designed as horseshoe shape for the hard-surrounding rock and egg shape for the weak-surrounding rock with the inverted arch. The underground water was found at the site and fissure water was recognized at the bedrock, so the drainage ditches were designed locating at two sides and the center of the tracks.

IN-SITU SURVEY

The tunnel was completed and opened in the year 1988. The tunnel included double tracks, one of the two tracks was used as heavy-haul, and the other one track was used as light-haul transportation. As one track was used as a heavy-haul track, the heavy freights caused serve damages to the track. A preliminary in-situ investigation was conducted by observation, measurement and referring to the design sketch.

Severe damages were identified at the section K279+902-K279+962 (where K stands for kilometre). The damages to the railway substructure and tunnel lining were investigated and shown in Figure 1, and the damages were categorized into 4 different types.

Type 1is settlement of the substructure: the settlement of the railway substructure was observed at the center and side of the track close to the drainage ditch, which was the heavy-haul track out of the two tracks in the tunnel. The vibration of the sleeper and roadbed of the heavy-haul track were observed when the vehicle ran on the rails. The observation of settlement was shown in Figure 1 (a). The settlement of the substructure was identified along the heavy-haul track at the section K279+917-K279+947. The value of settlement was not measured during the in-situ survey due to the limited condition.

Type 2 is water pooling: water pooling was observed at the side drainage ditch close to the heavy-haul track. Figure 1 (b) showed the water pooling at the drainage ditch close to the heavy-haul track. The depth of water pooling was measured as 0.3m at the Section K279+927. The cracks of the concrete beneath the drainage ditch were observed at the side and center drainage ditch. At section K279+935-K279+937, the width of the cracks was as much as 200 mm. Flowing water was identified at the center drainage ditch in the tunnel. The road bed was stroked by the flowing water at the center drainage ditch, due to the vibration of the vehicle. Water wave was observed at the side drainage ditch and the amplitude of the water vibration was as much as 10 cm.

Type 3 is underground void: beneath the base of the substructure, the underground voids were observed. The height of the voids was ranging from 0.03 m to 0.15 m at the section K 279+907-K279+947. The vibration of the sleeper was observed when the vehicle was running on the trail. Figure 1 (c) showed the measurement of underground voids by steel scale.

Type 4 is water seepage and cracks: water seepage and cracks were observed along the tunnel lining. Figure 1 (d) showed the cracks observed along the tunnel lining.

(a) Settlement of substructure

Fig. 1 - Damages of the railway substructure and tunnel

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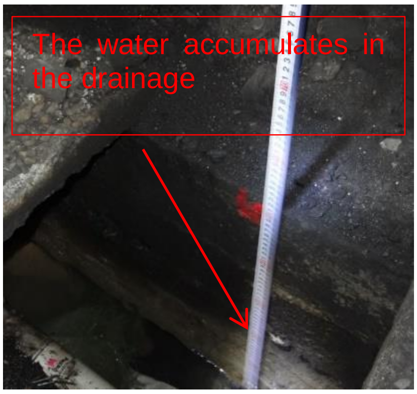
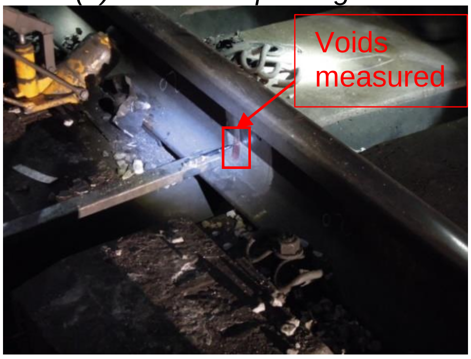
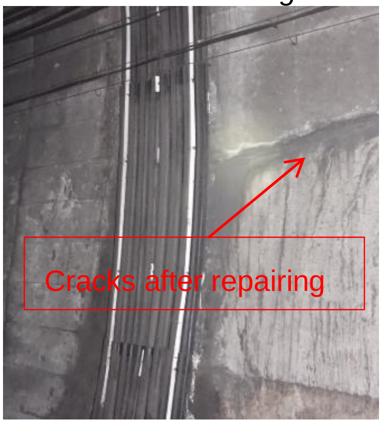


(b) Water pooling



(c) Measurement of the underground voids



(d) Cracks of the lining

Fig. 1 - Damages of the railway substructure and tunnel: (a) Settlement of substructure; (b) Water pooling; (c) Measurement of the underground voids; (d) Cracks of the lining

COUNTERMEASURES TO FURTHER DAMAGES

For the heavy-haul track, the skylight time of the railway (the time interval between the two trains coming to the same location) was short and the traffic flow rate was high. The railway was undergoing the heavy axel loading frequently, so the cyclic loading resulted in rapid stress change vertically, which induced damages to the substructure. At the base of the substructure, the grouting technology was used to prevent the further occurrence of settlement and underground voids. While the grouting technology was limited to the site condition and due to its uncertain distribution beneath the ground surface, the damage may occur due to the existence of unfilled voids, thus the

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monitoring would be conducted to decide if more grouts were required. As the water was found in the tunnel, water pipes were installed to drain water and prevent the flowing water from the adjacent sections.

The high performance of the railway required high safety levels, which could be achieved if the maintenance was scheduled correctly. A solution to a timely maintenance process was the application of monitoring system to monitor the health state of the substructure and avoided the damages to it.

The monitoring system needed to be developed based on the in-situ conditions. The substructure in the tunnel was located far from the control center of the line, the in-situ monitoring system was the alternative method if the real-time and long-term monitoring were required. The remote monitoring system integrated the monitoring data and video monitoring and recognized the damages remotely, in this way, the remote monitoring system would reduce the risk that the substructure would be damaged due to the heavy loading effectively. More measures could be taken for further treatment of the railway substructure based on the monitoring data if the damages occurred.

WIRELESS SENSOR NETWORK FRAMEWORK

The wireless sensor network required the sensors, data acquisition, data transferring, data processing and data management. A wireless sensor network, shown in Figure 2, was proposed to monitor the structural health of the substructure. The system included three major modules:

1. The sensor module, which attached the sensors to the substructure of the railway to measure the data and preliminary data processing;
2. The wireless transferring module which transferred the data from the sensor module to the control module;
3. The remote-control module, which consisted of data receivers, data management system.

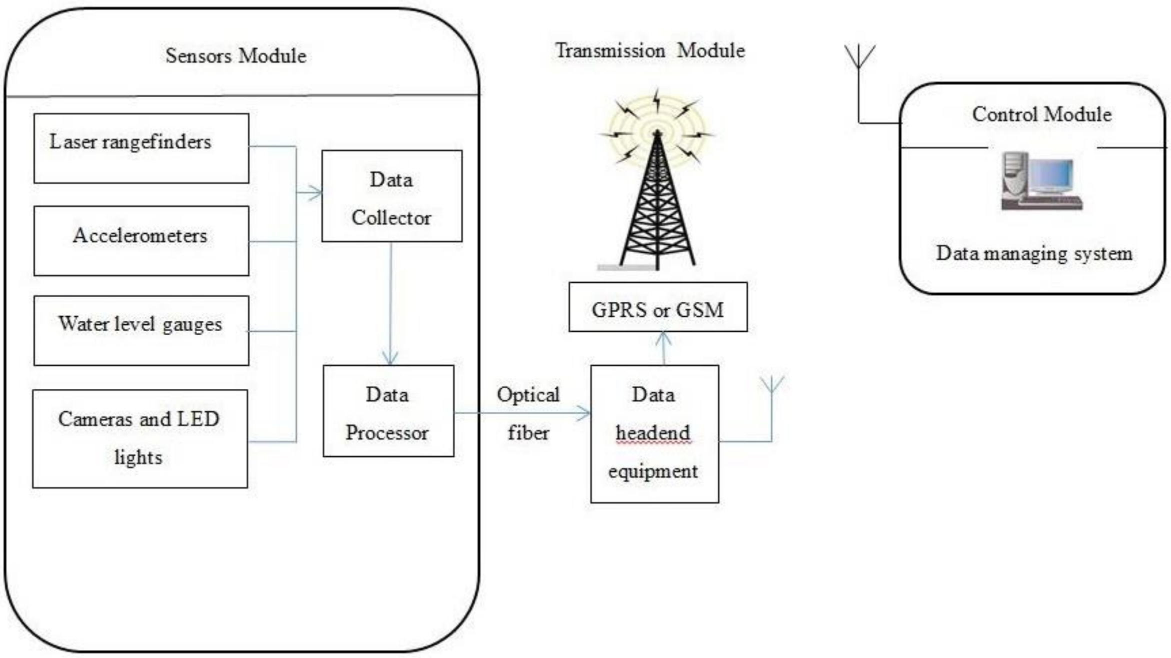

Fig. 2 - The wireless sensor network

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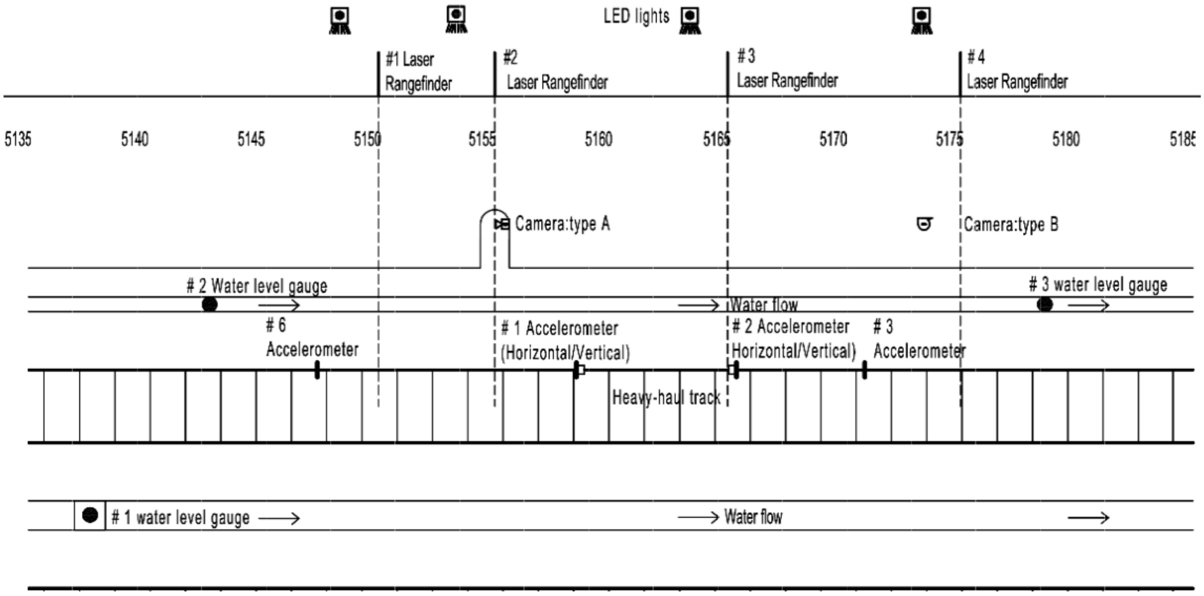
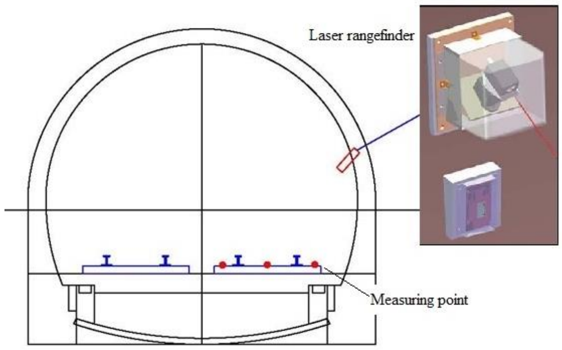
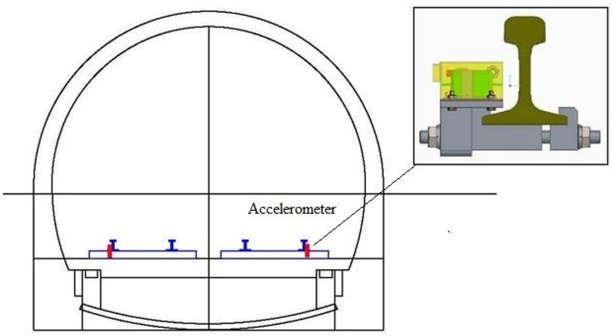


Fig. 3 - Layout of sensors



(a) Sectional view of the laser rangefinder



(b) Installations of accelerometers

Fig. 4 - Sectional views of the sensor module in the tunnel

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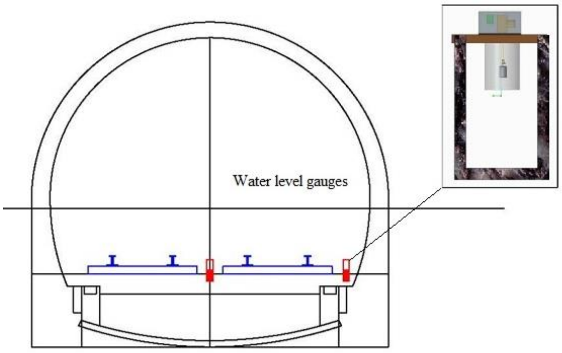
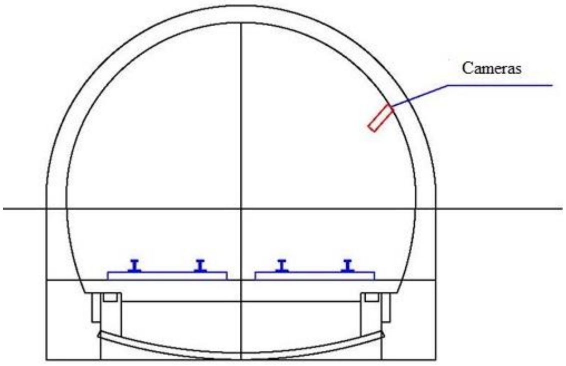


(c) Installations of water level gauges



(d) Installations of cameras

Fig. 4 - Sectional views of the sensor module in the tunnel: (a) Sectional view of laser rangefinder; (b) Installations of accelerometers; (c) Installations of water level gauges; (d) Installations of cameras

In-place instruments located at the railway substructure and tunnel were used to determine the damage of the railway substructure, and various types of sensors were needed to develop the sensor module. The sensor module was aiming for the measurement of the condition that the train passes through the specific section. In the sensor module, several key parameters, such as settlement, dynamic displacement, and water levels needed to be monitored periodically. In addition, to realize the purpose of real-time monitoring, cameras were used to capture the images in the tunnel.

In Figure 3, the layout of the sensors was shown. Accelerometers were installed at the sleeper for vertical displacement and horizontal displacement monitoring. The vibration data monitored by the accelerometer were converted into displacement corresponding with various speeds of the heavy-haul train. The accelerometers were calibrated before the installation to reduce the stochastic error induced by the double integration. As the data was acquired frequently by the accelerometers, a data processor was used to filter the mass of data and obtain the vibration data every 4 seconds, and the data was regarded as the vibration data, the maximum displacement was used as the representative data for each day. Laser rangefinders were installed along the wall of the tunnel for settlement monitoring of the railway substructure. The distance between the laser rangefinder and the center of the sleeper was measured and the settlement was calculated based on the distance difference of two phases: before the train passage on the rails and when the train is passing through the section. The inclination angle between the height of the laser rangefinder and the measured distance was used to determine the settlement of the sleeper. Water level gauges installed at the drainage ditches were used to measure the water level during the period that train passed on the rails. Cameras and Led lights were installed along the wall of the tunnel to capture the real-time image of the railway substructure. There were two types of cameras used in the system: the type-A camera was a dome camera and type-B camera was the outdoor camera. The video system could be switched on or off based on the demand of the user in the control module. Figure 4 (a) showed the sectional view of the laser rangefinder, and Figure 4 (b) showed the accelerometers installed at the sleeper of the rails. In Figure 4 (c), the water level gauges installation was shown, and in Figure 4 (d), the camera installation was shown. Before the data was transferred to the data management system, the measured data were collected and processed in the data collector and data processor, as shown in Figure 5.

Fig. 5 - Data collector and processor

In the wireless transferring module, as the distance between the monitoring system and control center was long, a two-stage data transferring was proposed: the data needed to be transferred through the tunnel to the entrance of the tunnel, and the data needed to be transferred from the tunnel entrance to the control module. In the module, the data were collected from the sensors and transmitted to the station at the entrance of the tunnel via optical fiber and then to the control center via GPRS or GSM. The fiber optics networks along the tunnel were used for data transmission inside the tunnel as well as for video transmission, and the mobile telephony was used for transmitting the signals outside the tunnel. In Figure 6, the data forwarder and antenna for data forwarding at the tunnel exit were shown in Figure 6 (a) and Figure 6 (b), respectively.

(a) Data forwarder at the tunnel exit

Fig. 6 - Transferring module

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(b) Antenna for data forwarding at the tunnel exit

Fig. 6 - Transferring module: (a) Data forwarder at the tunnel exit; (b) Antenna for data forwarding at the tunnel exit

In the control module, the data was transferred and stored, and the data was accessible to the user. A data managing system was developed, which consisted of several functions: an introduction to the system, real-time monitoring and analysis, data inquiry, parameters setting and data managing. The introduction to the system provided the basic information of the data managing system. The real-time monitoring and analysis showed the measured data in the format of numbers and the curves. When the measured data was greater than the criteria value, the system sent alerts to the user. Data inquiry allowed the user to extract the history data in the format of numbers or curves. The parameter setting set the basic information of the project, the type of monitored data, the criteria value of the measured data, the receiver of the alert and the accessibility of the data. Data managing was aiming to collect and store the data. In Figure 7, the screenshot of the data managing system was shown.

Fig. 7 - Screenshot of data managing system

APPLICATION OF THE MONITORING SYSTEM

To study the capability of the remote monitoring system, the measured data at the site for a period were presented. A general analysis of the monitored data was presented. The measured data consisted of the horizontal displacement of a sleeper, the vertical displacement of the sleeper, the settlement of the substructure and the variation of the water level.

Video surveillance

The cameras were used to capture the real-time image in the tunnel. The measured data was shown and analysed in the control module, once the irregular data was shown in the data managing system, the health state of the substructure needed to be examined by the real-time surveillance, and the video surveillance captured the image and video of the substructure for determining if an in-situ investigation was needed. Figure 8 showed a real-time image in the tunnel.

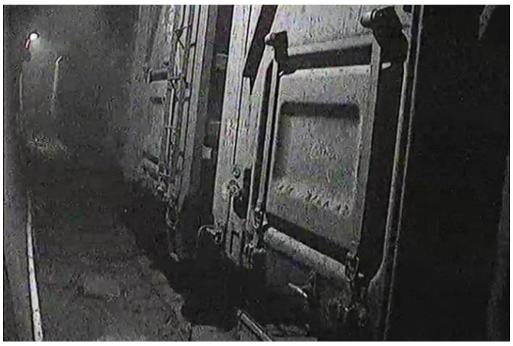

Fig. 8 - A real-time image in the tunnel

Vertical displacement

The dynamic displacements of the sleeper were recorded by the sensors installed at the sleeper. Along the heavy-haul track, the displacements by four sensors were recorded. The measured maximum displacements of each day by four sensors were shown in Figure 9 for 100 days from the beginning of the installation of the remote monitoring system. The magnitude of the displacement was affected by the heavy axel loading.

The displacement variations of the four sensors were different, and No.3 had less fluctuation compared to the other three sensors: for No.1 and No.6 sensors, the displacement varied from 6 mm to 8 mm; for No.3 sensor, the displacement varied from 2.32 mm to 4.0 mm; for No.2 sensor, the displacement varied from 4.4 mm to 5.5 mm. The greatest displacement was recorded by No.1 accelerometer. The maximum displacement was 8 mm on the day of 8. The smallest displacement was recorded by No.3 accelerometer, and the smallest displacement was 2.32 mm on the day of 21. The displacement varied with the time but within a certain range, and the integrity of the substructure was reflected by the trend of the dynamic displacements. The occurrence of the displacement was due to the existence of the underground voids and heavy axel loading on the substructure. When axel loading was acting on the sleeper, downward movements occurred and a maximum displacement was monitored. The variation of displacement of each day depended on the loading acted on the sleeper and the occurrence of underground voids. More underground voids existed under the location where the No.1 sensor was installed compared to No. 3 based upon the fluctuation of dynamic displacements.

Horizontal displacement

The curves of maximum horizontal displacements varying with time were shown in Figure 10. Two accelerometers were installed at different locations of a sleeper. As the axel loading and the horizontal displacement were orthogonal, the less fluctuation of the horizontal displacement was observed. During the monitoring period, the horizontal displacement recorded by the two accelerometers slightly changed within a certain range. The displacement varied at the range from 0.54 mm to 0.61 mm during 88 days. The maximum horizontal displacement was 0.61 mm on the day of 23, and the minimum horizontal displacement was 0.54 mm on the day of 35. The underground voids had less influence on the horizontal displacement of the sleeper. No.2 accelerometer was more influenced by the underground voids comparing to No.1 accelerometer. In general, the horizontal dynamic displacements could be ignored as the maximum displacement was less than 1 mm. The axle loading of the heavy-haul train and the underground voids had less influence on the horizontal displacement of the sleeper.

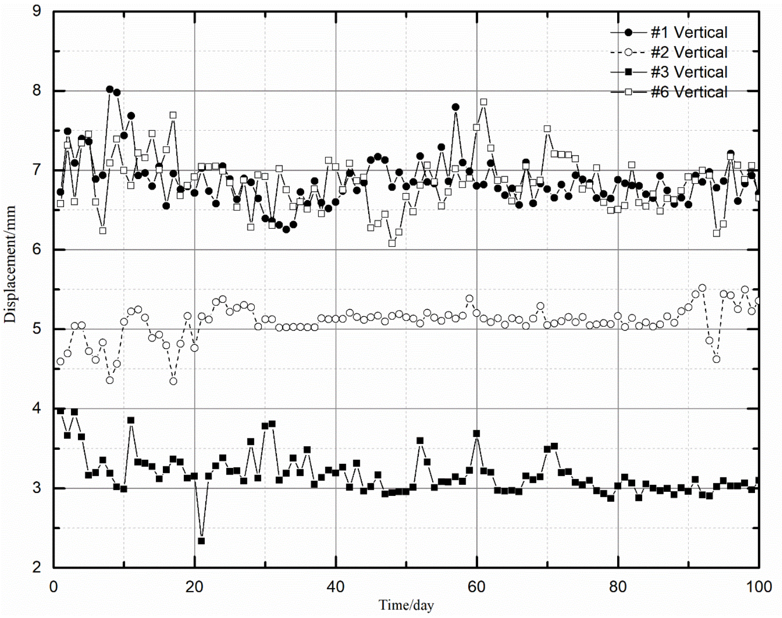

Fig. 9 - The maximum vertical displacement versus time

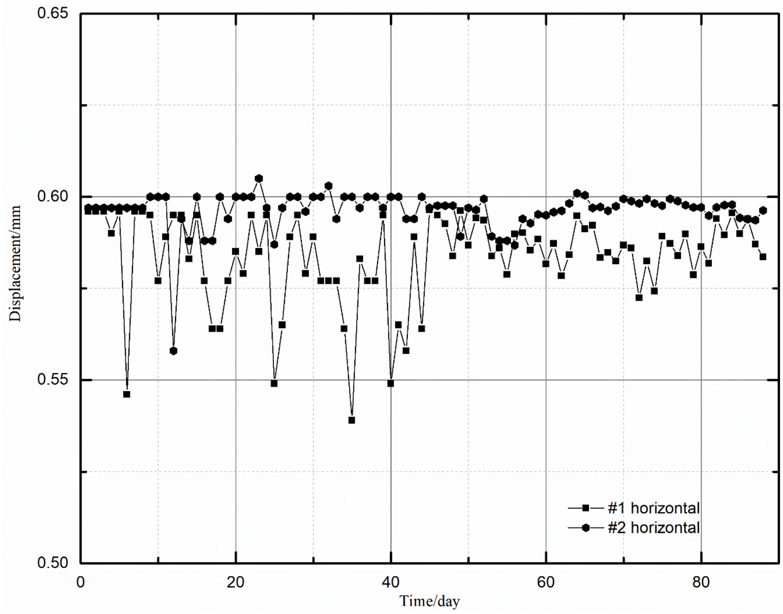

Fig. 10 – Maximum horizontal displacement versus time

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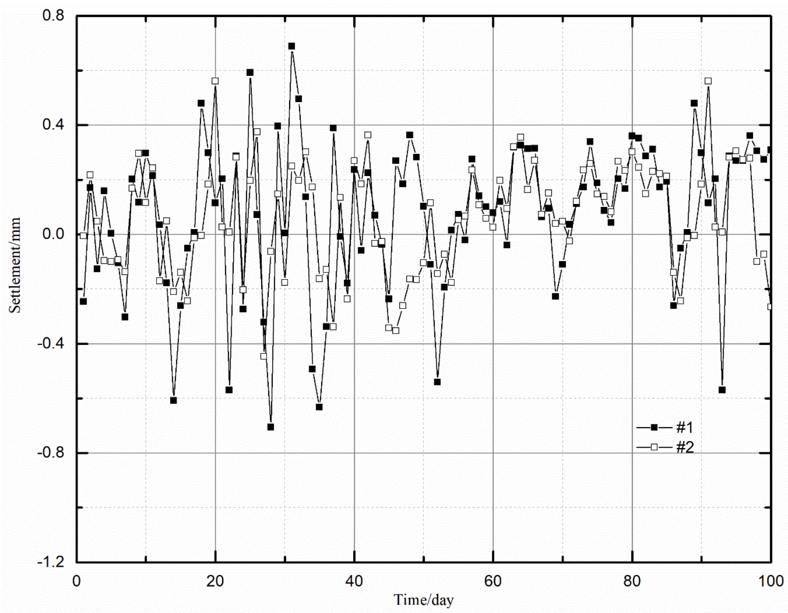
Settlement of railway substructure

The settlements of the railway substructure were recorded by the laser rangefinders, and the curves of the settlement versus time were plotted in Figure 11. Figure 11 (a) showed the settlements by No.1 and No.2 laser rangefinders, and Figure 11 (b) showed the settlement by No.3 and No.4 laser rangefinders. If the settlement occurred during the monitoring, more measures to treat the substructure were needed.

The accuracy of the laser measurement was affected by many factors, such as temperature, atmosphere, and the environment. In the tunnel, the measurement of the laser rangefinder depended on the surface roughness of the measured object and the measuring vibration. The noisy or unstable measurement induced by the surface roughness, train vibration and the particles in the tunnel air would bring the uncertainty to the measurement of the settlement. In Figure 11, the measured settlement was induced by the underground voids under the loading of the train and the fluctuation may be attributed to the uncertainty of the measurement. The four laser rangefinders measured the different amplitude of displacements, and the amplitude for the four laser rangefinders were 1.40 mm, 1.05 mm, 1.56 mm and 1.29 mm, respectively. The settlement by different rangefinder showed the influence of the underground voids and loading of the train. During the 100 days of monitoring, the measuring error of the laser rangefinder was 1mm, and the settlement changed with the time but within a certain small range, so the railway substructure could be regarded as being stable. While before the grouting technology was applied, the settlement was observed at section K279+917-K279+947.



(a) Settlement by No.1 and No.2 laser rangefinder

Fig. 11- Settlement of the railway substructure

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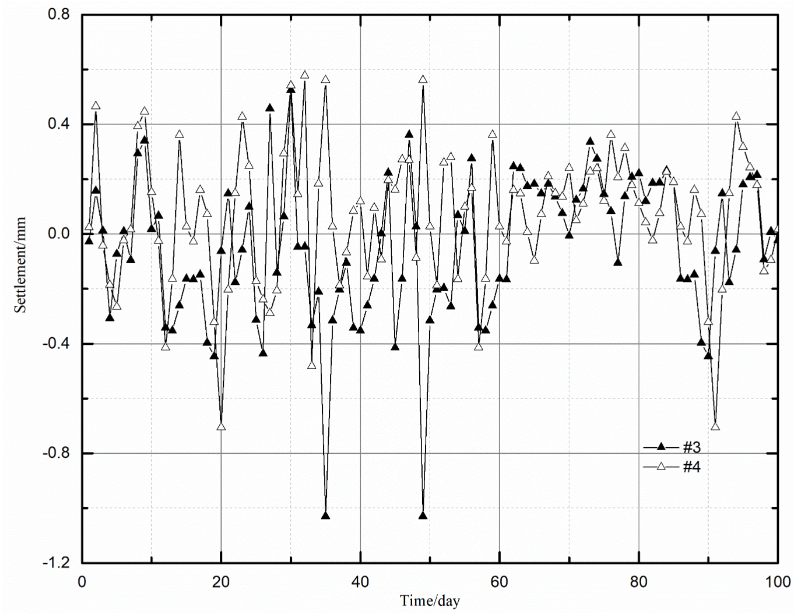

(b) Settlement by No.3 and No. 4 laser rangefinders

Fig. 11- Settlement of the railway substructure: (a) Settlement by No.1 and No.2 laser rangefinder; (b) Settlement by No.3 and No. 4 laser rangefinders

Water level

The amplitude was defined as the difference between the maximum water level and the minimum water level in the section. The amplitudes of water levels for each day were plotted in Figure 12. The variation of the water level was induced by the flowing water from the surroundings and the train. For the amplitude of No.1 and No.2 water level gauges, the amplitude decreased with time. The water level amplitude of water gauge No. 2 changed from 24 cm to 18 cm at the day of 100, while the water level amplitude of water gauge No. 1 decreased from 17.5 cm to lowest water level amplitude of 11.0 cm and then increased to 16 cm. For the No.3 water level gauge, the amplitude changed slightly. The water level amplitude varied at the range between 6 cm to 11 cm. The measured water levels were smaller than the measured maximum water level of 30 cm at section K279+927. It was noted that the underground voids were affecting the water levels measured by the water level gauges. The decreasing water level amplitudes indicated that although the water pipe was working for drainage, the water in the underground voids came out when the train was passing through the section. The influence of the underground voids could be determined by the amplitude of the water levels. As water level amplitude change recorded by No.2 was greater than the other two gauges, more underground voids close to No.2 water level gauge were assumed. The installation location of the water levels was influencing the variation of water level amplitude: the location of No.2 water level gauge was close to the drainage ditch and water pipe, so more water was drained comparing to the other two locations where the water level gauges were installed.

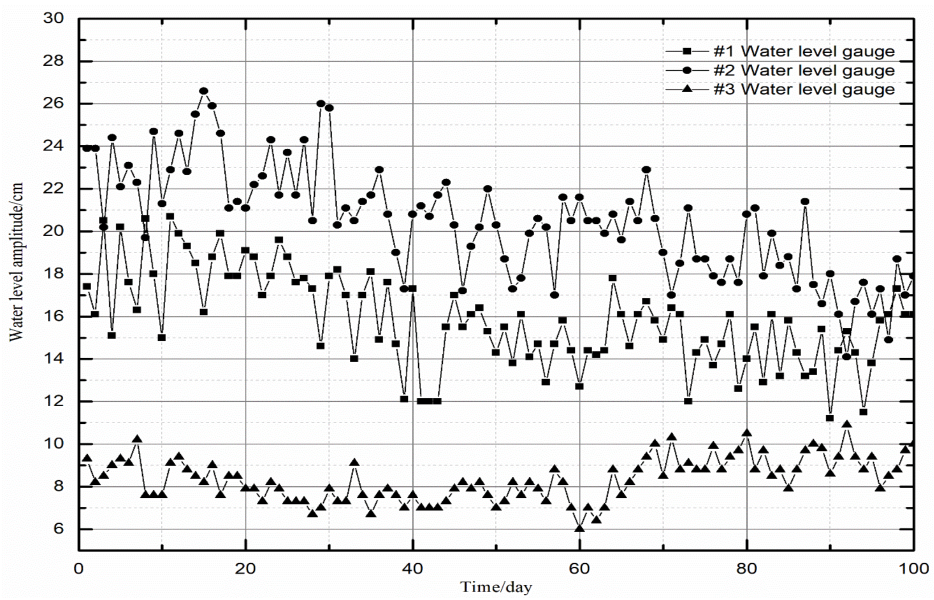

Fig. 12 - Water level amplitude versus time

CONCLUSION

In the paper, the damages to the substructure of the railway in the tunnel were investigated. The grouting technology and water pipes were used to mitigate the damages identified in the substructure. To monitor the further state of the substructure, a wireless monitoring system was proposed. The system has proved to be effective in monitoring the state of the substructure in the tunnel.

The wireless remote monitoring system was installed with three modules, the sensor module, the transferring module, and control module. The measured displacement, settlement, water level, and real-time image were transferred from the site to the control center.

The monitored results showed that the vertical displacement was more influenced by the underground voids comparing to the horizontal displacement, the fluctuation of the measured settlement was attributed to the vibration of the train, the particles in the tunnel air as well as the underground voids. The water level at the site was influenced by the flowing water and the drainage ditches locations. By applying the grouting technology and installing the water pipes, the settlement of the substructure was stable and the water was drained continuously to lower the water level.

According to the analysis of the measured curves, the existence of underground voids was affecting the measured displacement and settlement, so more measures were needed based on a long-term monitoring to eliminate the underground voids, and a further application of the monitoring system needs to be examined in the similar sites.

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