Development and Application of a Remote Monitoring and Analysis System for a High Speed Railway Subgrade Structure in Mountainous Areas

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Abstract

Remote monitoring and analysis system for high speed railway subgrade structure in mountainous areas is one of most effective method to ensure the safety operation, which as a strong practical significance. Diagnosis technology scheme for the monitoring of high speed railway subgrade health status in soft mountainous area was developed in this paper. To ensure the reliability of this technology, the use of a combination of intelligent sensor, fast data acquisition, signal processing and wireless communication technologies were adopted. This was done by establishing a point-line-surface, multi-level and multi-objective remote monitoring system for high speed railway subgrade. The monitoring parameters including dynamic soil pressure, settlement deformation, inclination and rainfall information are determined using data acquisition card. Data acquisition and wireless communication were obtained through an industrial computer and a 3G/GPRS technology. Client/server for the controlling of remote monitoring system was developed based on the Visual C++ network programming technology and the Access 2010 database platform. The server controlling software also analyze data for the provision of technical support for realizing the target of early warning forecast for high speed railway structure.

INTRODUCTION

The high speed railway has become the most powerful transportation means in the world. Increase in train speed will not only increase train dynamic load and vibration frequency, but will also increase the subgrade vibration acceleration, intensify the train and line vibration, thereby increasing the depth of dynamic load effects on subgrade, expedite the accumulation of permanent deformation, which directly affect high speed railway use and maintenance, as a result raised new challenges on subgrade deformation and post-construction settlement control, especially for the high speed railway built in the mountainous area which is influenced by the complicated geological and environmental conditions. Currently, the safety assessment for high speed railway of the relevant standards (relevant standards of china, 2007 & 2009; relevant standards of German, 2002 & 2008) in home and abroad is mainly done through monitoring the settlement of the railway in resting period and then calculating the post-construction settlement to judge the stability. But the facts proved that although the projects are judged safe from the settlement level in resting period, the disasters in operation period continually occur due to the ignorance of judgment of the dynamic properties (Bian et al., 2015; Ferreira, 2002). As a result, constantly monitoring and judgment of the project stability is necessary.

The commonly used safety monitoring methods for high speed railway consist of vehicle mounted radar method(Lohmeier et al., 2002; Al-Nuaimy et al., 2004), wave velocity method(Li et al., 2008; Zhang et al., 2006), artificial survey and so on. All these methods can only be used under specific engineering environment and geological conditions to obtain specific stability level, which cannot reflect the structural health state of the railway in essence. Considerable part of these methods rely on manual measurement or record. The efficiency of these methods are low, time consuming and cannot realize the automatic and remote monitoring.

However, several researchers developed some new methods without carrying out actual operation i.e., Roveri et al.(Roveri et al., 2015) presented a real time monitoring method by using FBG sensors for monitoring the structural health of the railway track; Ribeiro et al.(Ribeiro et al., 2014) developed a non-contract dynamic displacement measurement system for railway bridges based on video technology; Yang et al.(Yang et al., 2013) proposed a novel method to automatically measure the subgrade settlement by using a linear CCD to detect the position change of the point light's image; Aw(Aw, 2004 & 2007) described a novel monitoring system to diagnose rail track foundation problems. From all these new monitoring methods, we can know that they have improved the monitoring efficiency due to automatic measurement without much operation of people, but although there are advantages compared with the old methods, their main problem is they haven't realize remote monitoring which makes their application greatly limited because the operation of high speed railway is very strictly and anyone is not allowed to near the railway during the high speed train operation.

Inspite of the few available remote monitoring technologies used in railway engineering, the remote monitoring system have been fully developed and successfully applied on other engineering such as slope and tunnel engineering (Zhang et al., 2011; Intrieri et al., 2012; Zhang et al., 2009;). Few scholars have tried to build their own remote monitoring system for high speed railway.i.e. YANG and FENG (Yang et al., 2012) have developed a wireless data acquisition and transmission network by applying local wireless communication module and DTU-GPRS module to realize automatic monitoring of railway subgrade static variables; Feng et al.(Feng et al., 2011) developed a system for monitoring the additional expansion and contraction force of the high speed railway long bridge seamless line, which can do remote and real time monitoring. After the analysis, it was observed that the developed system can also monitor the static parameters of the railway, which which can be applied on slope or tunnel engineering but not suitable for detecting the variation of dynamic parameters reflecting dynamic stability of the railway. Therefore, a research on remote and unmanned monitoring system suitable for the monitoring of high speed railway static and dynamic parameter is of significance.

The developed diagnosis technology scheme for the monitoring of high speed railway subgrade health status in soft mountainous area is characterized by:

①Stability, reliability, adaptability, accuracy and low power consumption; ② Ability to acquire datum static and dynamic sensors automatically stabilise and transmit them to the controlling center; ③ Ability to display the dynamic data wave precisely and preprocess the dynamic datum to reduce the amount of wireless transmission data which satisfies the requirement of the subgrade status.

DESIGN AND LAYOUT FOR REMOTE MONITORING AND ANALYSIS SYSTEM

Goal and design of remote monitoring system. A diagnosis technology scheme for the monitoring of high speed railway subgrade health status in soft mountainous area was developed to ensure safety and stability of high speed train railway with complicated geological conditions. Through the combination of the intelligent sensor, signal processing and wireless communication technologies. A point-line-surface, multi-level and multi-objective remote monitoring system for high speed railway subgrade is established. The specific objectives and design conceptions are as follows:

1. In view of the multiple types of sensors, the corresponding network communication measurement is researched and then formulated, which makes all the sensors in the same area connected together. According to the type of monitoring parameters, network quantity and real environmental condition, the corresponding signal acquisition strategies (static and dynamic parameter acquisition) are studied and then determined, which includes the acquisition and storage method, the acquisition instruction control method and so on.
2. Through the application of the multi-channel data acquisition technology, integration of monitoring parameters in different sections, effective automatic real time, economic and unmanned monitoring sub-station is formed. The field power supply system (line power supply, solar panel or battery etc.) for the monitoring of frequency and in situ condition can also be determined.
3. Through the low cost and stable network coverage GPRS/3G wireless transmission technology, the preprocessed monitored datum by the sub-station are transmitted to the controlling center. Then through the internet network, the datum exchange channel between the controlling center(located at Changsha) and the remote datum center(located at Wuhan) can be established. Thus, a whole remote monitoring system for high speed railway subgrade structure can be constructed.

The goal and design of the system can be expressed by Figure 1.

Research on monitoring parameter and layout for monitoring sensor. ***Monitoring parameter.*** The parameters are of two categories, the internal factors and the external factors. The internal factors include the property and compositional structure of the subgrade geomaterials while the external factors include the environmental condition in mountainous area and the high speed moving load prompting the development and evolution of disasters.

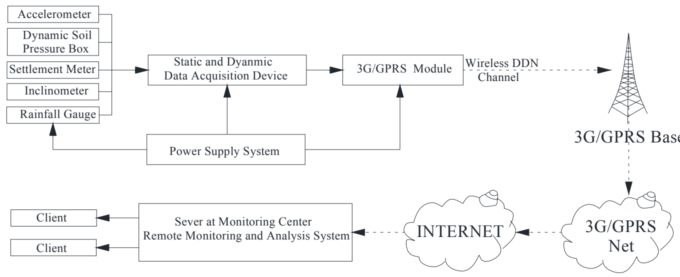


Figure 1.Objective and Design of the Monitoring System.

However, the disasters in high speed railway project are mainly caused by the geometrical property and environmental factors. Cyclic train loading can accelerate the disaster evolution process, which is reflected by the significant changes in the high speed railway subgrade and its related engineering properties. To ensure the reliability of this technology on the operational stage monitoring parameter, a physical parameters directly reflecting the variety of the subgrade structure should be adopted, for example, deformation parameters(vertical settlement or horizontal displacement etc.) and dynamic response indexes(acceleration or dynamic soil pressure etc.).

The monitoring parameters on the widely distributed engineering structures such as high filled slope subgrade and high slope, selected include: vertical settlement, horizontal incline, vibration acceleration and dynamic soil pressure etc.(for high filled slope subgrade) and horizontal displacement, relative deformation at surface, rainfall etc.(for high slope).

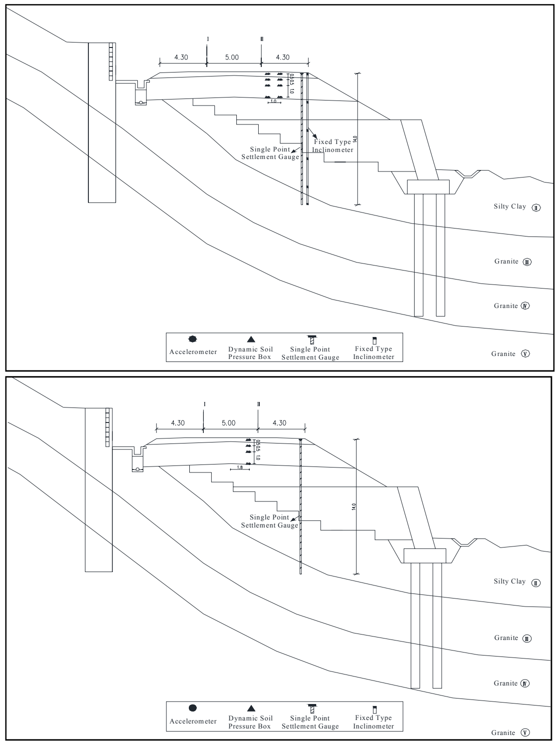
Selection of monitoring sensors. The sensors selected for the unmanned monitoring and data automatic acquisition realization is dependent on the characteristic features of the high speed railway subgrade in mountainous area. The strong adaptability, high reliability and low operational cost is also considered .The selected sensors include:

1. Deformation sensors: single point settlement gauge, inclinometer, surface displacement meter;
2. Environmental sensor: rainfall meter;
3. Dynamic response sensors: accelerometer; dynamic soil pressure box;

The deformation sensors can directly reflect the health status of the high speed railway subgrade since both the appearance of weakening and the disaster of the subgrade can be known from the angle of deformation. The environmental sensor reflects the relationship between the variety of the high speed railway subgrade and water from the angle of rainfall, which reflects the external influence on the variety of the subgrade induced by rainfall. The dynamic response sensors can monitor the dynamic response regularities before and after the status variety of the subgrade from the dynamic response angle. Through researching on the variety of the dynamic response, the subgrade status can be reflected indirectly.

Layout for monitoring sensors. In order to achieve the research goal, the monitoring sensors must be laid out in the positions directly reflecting the subgrade status. The sensors layouts are as follows:

Sensor layout for high filled slope subgrade. The test monitoring section length of high filled slope subgrade is 50m, with 1 key monitoring section and 2 general monitoring sections with an intervals of 25m. The specific sensor layout is shown in Figure 2.



(a) Key monitoring section (b) General monitoring section

Figure 2. Monitoring sensors layout for high filled slope subgrade.

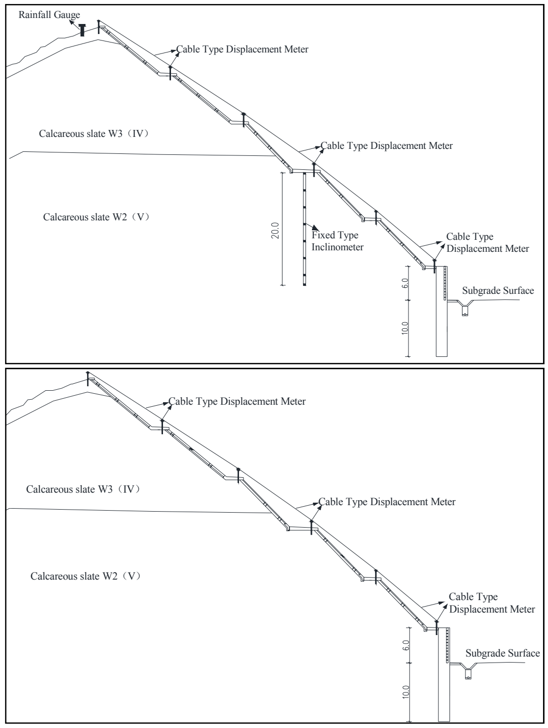
For the key monitoring section, the subgrade vertical and horizontal dynamic response is mainly focused on and the incline settlement deformations are also considered by setting up clinometers and settlement meter on the subgrade shoulder.

For the general monitoring section, the variation laws of the vertical dynamic response under track is mainly considered. The deformation factors are mainly focused on subgrade settlement.

Sensor layout for high slope. The monitoring section length of high slope is 40m. It is made up of one key monitoring section and one general monitoring section. The specific sensor layout is shown in Figure 3.

For the key monitoring section, the surface relative displacement and horizontal displacement in slope are monitored and the rainfall is also monitored. The specific monitoring sensors consist of cable type displacement meter, fixed clinometers and rainfall gauge. The fixed inclinometers are embedded at the middle of the slope to monitor the slope horizontal displacement. The cable type displacement meters are set along the slope surface to monitor the surface relative displacement. At the top of slope, a rainfall gauge is set to monitor the rainfall information in the test section.

The general monitoring section consist of surface displacement meters embedded along the slope surface.



(a) Key monitoring section (b) General monitoring section

Figure 3. Monitoring sensors layout for high slope.

Scheme for data acquisition and wireless transmission. For the static monitoring sensors, due to their long data acquisition cycle and small data mount, ordinary data acquisition card can meet the requirement. But for the dynamic sensors, the data acquisition is more complicated. On one hand, the dynamic sensors are featured with high frequency response and big data instantaneous change which needs the data acquisition can accurately catch the variety of the dynamic monitoring datum; on the other hand, the acquisition equipment should have a high resolving power to precisely reflect the dynamic datum. In addition, the dynamic data acquisition module also should have data processing ability, thereby the whole datum can be stored in time and the large amount of dynamic datum can be preprocessed in order to transmit the real time datum to the sever for the latter analysis.

Apparently, the dynamic data acquisition and wireless transmission equipment installed in situ is the key part of the whole monitoring system and its quality determines performance of the whole monitoring system. The key part of the dynamic data acquisition and wireless transmission equipment is the data automatic acquisition module.

Based on the previous research achievements and experience, the data acquisition scheme for both static and dynamic parameters is shown in Figure 4.

The scheme consist of a data processor, a data acquisition card and a wireless transmission module.

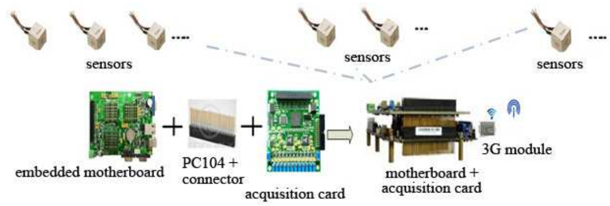


Figure 4. Scheme for data acquisition and wireless transmission.

Data processor. A high performance PC machine is used as the data processor to acquire and store the monitoring datum. Then it preprocesses the dynamic datum to obtain the key datum to reduce the amount of transmission data.

Data acquisition card. The data acquisition card is divided into two kinds: one is a high speed data acquisition card responsible for acquiring the dynamic parameters; the other is a low speed card to acquire the static parameters.

Wireless transmission module. Based on the field condition, data transmission amount, equipment stability and power consumption, the GPRS/3G module are selected as the wireless transmission equipment.

HARDWARE OPTIMIZATION OF THE REMOTE MONITORING AND ANALYSIS SYSTEM

Monitoring sensors optimization. ***Optimization principle.*** In order to determine the monitoring parameters of the high speed railway subgrade in mountainous area, the monitoring sensors should be selected optimizationally. The optimization should follow strong adaptability, high reliability and good economy principles.

1. Strong adaptability

Ability to adapt to the various complicated engineering environment. In other words, they can be embedded in any condition and their stability cannot be influenced by engineering construction. They especially meet the requirement of unmanned remote monitoring.

Factors considered for the selection of monitoring sensors include: ①Ability of embedding small volume of the sensor in any finite space without complex embedding construction; ② the sensors should have strong matching ability to be connected with the equipment for data acquisition to realize the purpose of automatic unmanned monitoring.

2. High reliability

Ability to meet the high and strict standards of the high speed railway engineering. At the same time, in bad engineering condition the sensors must guarantee the monitoring precision.

3. Good economy

Low in cost under the premise of monitoring accuracy. And their embedment should be easy without help of complicated machines.

Characteristics of the monitoring sensors.

1. Single point settlement gauge

The equipment is composed of a sensor body, a measuring rod, an anchor head and a flange plan. The monitoring accuracy is 0.01mm and the measuring range is 200mm. It can transfer the settlement to electronic signal and then transmit the signal to the data acquisition equipment. Therefore, cooperating with the automatic data acquisition equipment, the single point settlement gauge can realize the purpose of unmanned automatic monitoring and is convenient for long term monitoring. In addition, the equipment is little affected by environment. This equipment is mainly used for measuring the vertical settlement of the subgrade.

2. Inclinometer

The equipment adopts imported angle sensor as the sensing element, can measures the incline angle of the monitoring hole and then transfer the monitoring datum into electronic signal to transmit it to the data acquisition equipment. The accuracy is high(0.005°) and is little affected by environment. This equipment is mainly used to measure the horizontal displacement of the high filled slope subgrade and the high slope.

3. Surface displacement meter

The equipment is fixed on the slope surface and is connected to a fix point by flexible steel wire. The equipment can transfer the displacement data into electronic signal and then transmit it to the data acquisition equipment to realize the purpose of unmanned and automatic monitoring. The equipment is high in accuracy(0.01mm) and the measure range is 200mm. It is mainly used to monitor the displacement on surface of the high slope.

4. Rainfall meter

The equipment is capacitive type whose accuracy is 0.1mm, which can acquire rainfall information precisely and then automatically export pulse signal to the data acquisition equipment.

5. Accelerometer

The equipment is piezoelectric sensor with high sensitivity and has features of high rigidity, fast response and large range of frequency response. It can output voltage signal according to the requirements, which is convenient for matching the data acquisition device. The equipment is mainly used to measure the dynamic response of the subgrade under train moving load.

6. Dynamic soil pressure box

The equipment is resistance strain type soil pressure box whose pressure response element is strain gauge with high sensitivity and high frequency response. Compared with the traditional vibrating string type soil pressure box, this device has a larger range of vibration response, is accurate in pressure measuring and is little affected by environment. Meanwhile, it can output voltage signal, which is convenient for matching with the data automatic acquisition equipment. The device is mainly used for measuring the dynamic soil pressure response of the subgrade under train moving load.

Optimization of data acquisition and wireless transmission equipment. ***Optimization principle.*** The optimization of the data acquisition and wireless transmission equipment should consider the following:

1. Integration with the monitoring sensors

The monitoring of high speed railway subgrade status involve setting up two types of sensors: static deformation monitoring sensors and dynamic deformation monitoring sensors. Due to the obvious difference in frequency response and acquisition frequency between the two types of sensors, the integration between the sensors and the data acquisition device should be of particular note. Therefore, different static and dynamic data acquisition cards are selected: the static data acquisition card has a small volume and is programmable to control the data automatic acquisition; the dynamic data acquisition card is high in frequency response, high in accuracy and strong in automation performance. In addition, for data transmission mode from data acquisition card to data processor, the communication modes of PCI and USB are respectively chosen.

2. Data processing timeliness

Due to the large amount of datum and high frequency response, the datum should be processed in time in order to transmit monitoring parameters to server. As a result, high efficiency should be also taken into account in data processor selection. The IPC with small volume and low power consumption is selected as the data storage and processing part in this monitoring system research, whose features are fast in response speed, high in data processing ability and perfect in adaption with different data acquisition cards.

3. Special field condition adaption

For the data acquisition and wireless transmission system set up on the high speed railway project, the complicated field environment, such as power supply condition, wireless transmission condition and system working environment, should be considered in the round.

Characteristics of the data acquisition and wireless transmission device. The data acquisition and wireless transmission scheme is determined based on fully consideration of the integration with the monitoring sensors, timeless data processing and field special condition. The scheme is featured that:

1. The system is high in accuracy, whose resolving power is 16bit, can sense the physical quantity variety in 10-3 level and can acquire data in high accuracy, large range and fast speed.
2. The system can automatically acquire data stably, chronically, continuously to make the data acquisition unmanned and not influenced by environment.
3. The system is large in measuring range, strong in anti-interference ability and convenient in remote controlling. Additionally, the sampling frequency, data processing mode and data transmission way can be set at random.
4. The system can be controlled by remote connection, thereby, at any places with Internet, users can log in the controlling interface of the software system to revise the settings and can observe the real time data wave when the high speed train goes through the monitoring section.

The final equipment is shown in Figure 5.

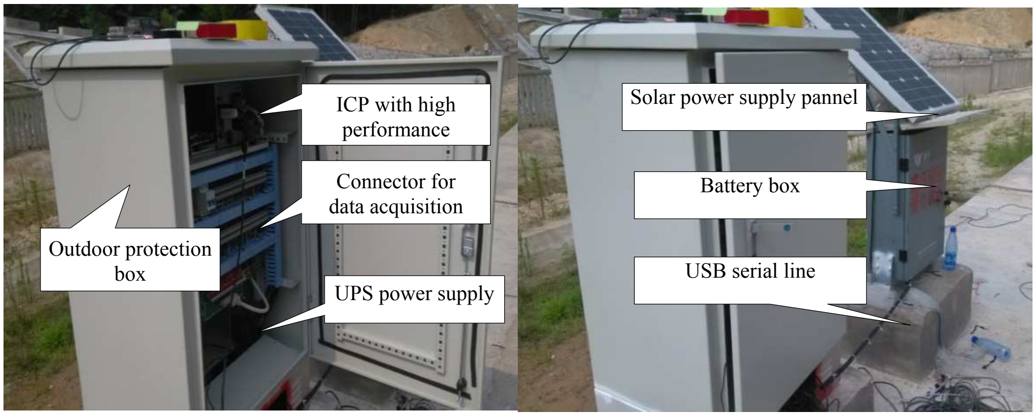


Figure 5. Data acquisition and wireless transmission device.

DEVELOPMENT OF REMOTE MONITORING AND ANALYSIS SYSTEM SOFTWARE

The remote monitoring and analysis system controlling software is composed of two sub-software: field data acquisition and processing software and server controlling software. The field data acquisition and processing software is responsible for acquiring the static and dynamic data, displaying the data wave, storing data, processing the dynamic data and communicating with the server. The server controlling software is responsible for receiving and storing data, displaying and querying history data. Meanwhile, the server software is also inserted with data analysis module, prediction and management function module and will be inserted with evaluation standard and early warning model for implementation of high speed railway subgrade safety grade evaluation in operation period.

The software is programmed based on Visual C++ and Access 2010. The 3G/GPRS wireless communication technology is applied to transmit signals between the two software.

Field data acquisition and processing software. The functions of the field data acquisition and processing software include: ① Ability to realize the automatic or manual data acquisition;②Ability for modifying sampling frequency according to different monitoring sensors; ③ Ability for setting the data wave display according to the sensor with different measuring range; ④ Ability for preprocessing datum to obtain the key data to reduce the amount of data; ⑤ Ability to be remotely controlled at any place through Internet. The whole functions can be expressed by Figure 6.

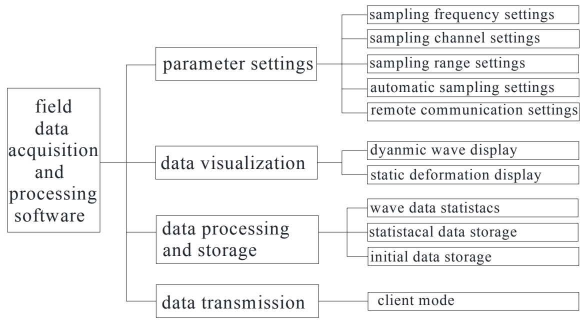


Figure 6. Functions of field data acquisition and processing software.

Server controlling software. The server controlling software can realize the classified management of monitoring data and project information and serves as a functions of data analysis, prediction and management, shown in Figure 7.

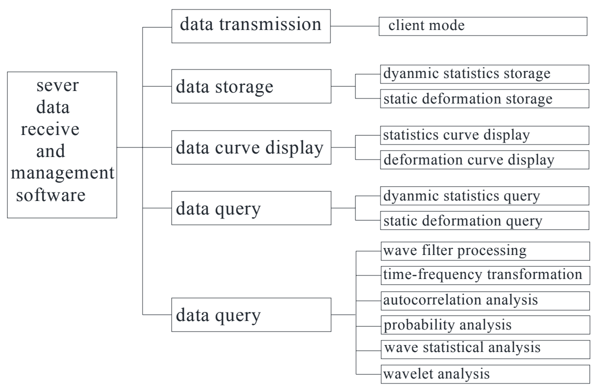


Figure 7. Functions of server data receive and management software.

The database of the server software codes the monitoring sensors in different sections in accordance with the characteristics of high speed railway project and the datum of different sensors is stored and managed according to the date. The software realizes the 'hierarchical and multi-objective' data storage, which means all kinds of data are archived for convenient query. As for data query, history datum of specific sensor can be selected by users through choosing the date. In addition, several important sensor information including hierarchical information, sensor type and buried depth and so on is also displayed in the upper place of the software.

For data visualization, the software can draw the variety curve of the data over time according to the data type. Meanwhile, the software also can realize the data dynamic monitoring, which means once there are datum received, the variety curve can be immediately displayed in the online monitoring window.

According to the large number of dynamic datum, for analyzing the dynamic response regularity of the high speed railway subgrade, the software is also inserted with different data processing and analysis functions, such as time-frequency transform, digital filtering, correlation analysis, probability analysis, statistical analysis and non-smooth analysis and so on. Through research on the transform and statistical characteristic values of the vibration datum, it can provide data analysis base for early warning and forecasting model.

APPLICATION EXAMPLE

The ragged topography in the region of Hunan passenger dedicated line composed of complicated geological conditions on dangerous mountainous terrain, has caused problems to engineers during construction while ensuring safety of the traffic use of the line. The line was constructed using cut and fill mode to pass through, which forms a lot of high filled slope subgrade and steep slope. Meanwhile, the geological condition is complicated, the structure is well developed and the hydrological climate is complex, which cause security threats to the railway safety operation.

In this region, the section of DK203+725.00~+775.00 has typical characteristics of high and steep slope subgrade. This line section passes through the mountainous area with big by cut and fill mode. The subgrade center maximum filling height is 8.46m, the slope maximum height is 14.8m and the cutting depth is 33.8m. The blueprint of this line section is shown in Figure 8.

The ballastless track is used on this passenger dedicated line and the sensor layout is the same with the description above (see Section 2.3). The performance of the sensors used in the application is also narrated above. (see Section 3.1)

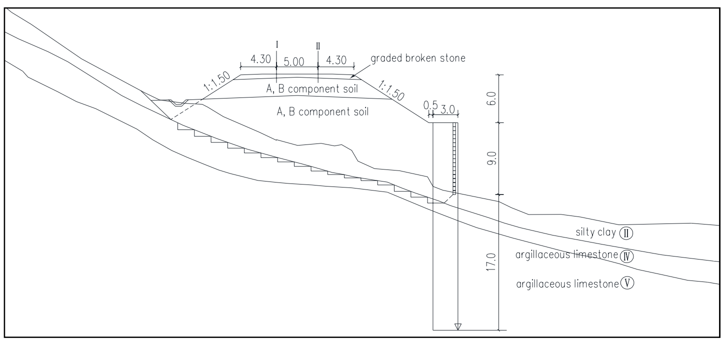
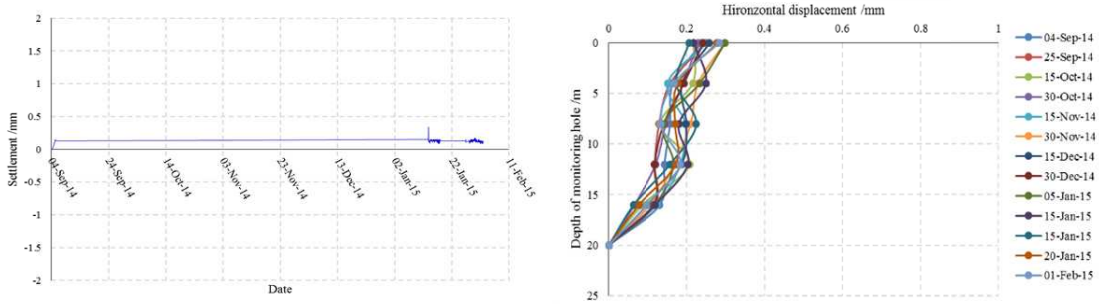


Figure 8. Blueprint of Shanghai-Kunming dedicated line DK203+725.00~+775.00.

Static deformation monitoring application. Figure 8 shows the deformation datum static sensors located at the key section. Figure 9 (a) is the settlement data curve and Figure 9(b) is the horizontal deformation data curves. It can be seen that on one hand the settlement of the subgrade is pretty small (less than 0.5mm) and fluctuates in a small range; on the other hand the horizontal displacements are also small and even the displacement at top of the inclinometer hole is less than 0.4mm. From these findings, it is illustrated that the subgrade structure is stable and makes the high speed train running safety.



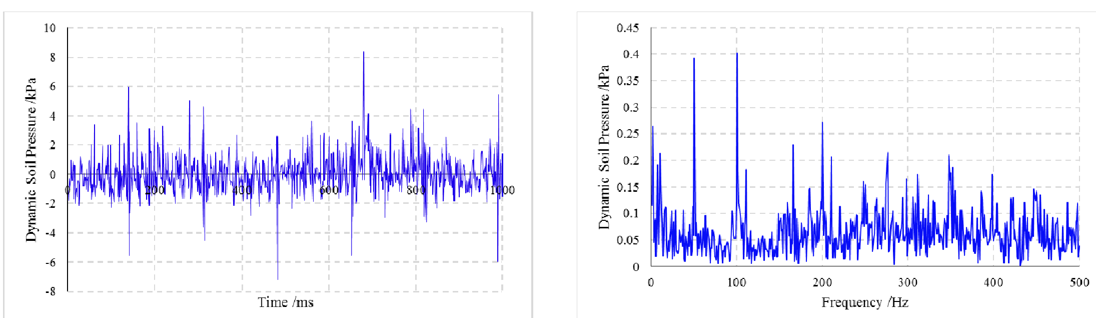
(a) Settlement (b) Horizontal displacement

Figure 9. Monitored deformation datum of key monitoring section.

Dynamic parameter monitoring application. Figure 10~11 gives the monitored curve of dynamic parameters (dynamic soil pressure and acceleration). From the Figure 10~11 it was observed that:

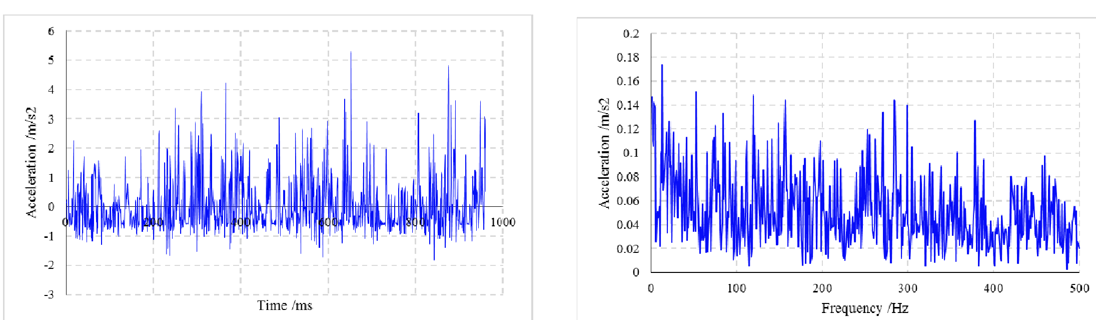
The peak of dynamic soil pressure in subgrade is only about 8kPa not enough to make the soil failure and it seem the subgrade permanent settlement is mainly caused by the vibration leading to increase in density and soil particles breakage or other factors, i.e. water.

From the datum of dynamic soil pressure and acceleration, although having no obvious peak value, the dynamic response frequency is mainly concentrated in the low frequency range (0~100Hz). It is shown that the length and structure of the train are the main reasons causing dynamic load.



(a) dynamic soil pressure datum vs time (b) dynamic soil pressure datum vs frequency

Figure 10. Monitored dynamic soil pressure curve.



(a) acceleration datum vs time (b) acceleration datum vs frequency

Figure 11. Monitored acceleration curve.

CONCLUSIONS

The remote monitoring and analysis system for high speed railway subgrade structure in mountainous areas is one of most effective method to ensure the safety operation. It has a strong practical significance. This paper is involved in the analytical study on diagnosis technology for high speed railway subgrade health status. For developing the system, the combining effort of the intelligent sensor, fast data acquisition, signal processing and wireless communication technologies, was ensured and a point-line-surface, multi-level and multi-objective remote monitoring system for high speed railway subgrade is established. The main conclusions from the diagnosis technology for high speed railway subgrade health status are as follows:

1. The high performance monitoring sensors automatically acquiring data have been optimized based on the aspects of accuracy, measuring range, adaptability to field environment and economy according to the high speed railway subgrade structure status.. At the same time, combining with the geological characteristics of the high speed railway project, the monitoring sensors have been laid out at the places where they can directly reflect the variety of the subgrade structure status.
2. Using Visual C++ as the programming platform and the Access 2010 as the database system, the controlling software for the remote monitoring and system analysis was developed. Based on 'client/server' mode, the software realize the functions of data automatic acquisition, storage, transmission and receiving. The server software has been also programmed with analysis functions, such as time frequency analysis, which provides technical support for the early warning model of the high speed railway subgrade.
3. For practical application, the monitoring and analysis system has been used on the monitoring demonstration on section DK203+725.00~DK203+775.00 located in Shanghai-Kunming passenger dedicated line in Hunan. The application effect has shown that the system can automatically monitor the structure status of the subgrade in time. It has good environment adaptability and stability and can provide technical support for the early warning model of the subgrade structure health status.

ACKNOWLEDGE

Financial support from the science and technology research and development project of Chinese Railway Corporation named "Research on Shanghai-Kunming dedicated line subgrade structure health status diagnosis technology in operation period" is gratefully acknowledged.

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