Bull Eng Geol Environ (2018) 77:409–427
https://doi.org/10.1007/s10064-016-0965-4

ORIGINAL PAPER

Remote monitoring for a high-speed railway subgrade structure state in a mountainous area and its response analysis

Jian Li[1] · **Shanxiong Chen**[1] · **Fei Yu**[1] · **Zhangjun Dai**[1]

Received: 19 April 2016 / Accepted: 18 October 2016 / Published online: 2 November 2016

Abstract High-speed railway engineering in mountainous areas suffers from occasional poor geological conditions, rugged topography, and complex hydrographic conditions. It is an important means of ensuring its safe operation to conduct real-time remote monitoring and analysis of the subgrade structure condition. Through analysing the stress characteristics of the mountainous subgrade, a complete monitoring system has been built and a corresponding software platform for datum acquisition and analysis has also been developed. After selecting a typical mountainous high-speed railway subgrade located in Hunan Province as the test section, the real-time monitoring of the subgrade structure in a static settling period, joint commissioning period, and an operational period was conducted and the primary condition datum was obtained. It is found that the dynamic response parameters have relatively slow attenuation velocities and the influencing depth of the high-speed train loads was about 4–5 m; when the structural state of the mountainous subgrade is healthy, subgrade deformations are small and, compared with the dynamic response datum of the subgrade in plain areas, the dynamic response of the mountainous high-speed railway subgrade was consistent. However, the long-term dynamic response and deformation of such mountainous subgrades still needs to be monitored, and analysed, continually.

Keywords High-speed railways · Mountainous terrain · Subgrade condition monitoring · Remote monitoring and analysis system · Dynamic response

Introduction

There is important practical and theoretical research significance to developing remote monitoring for geotechnical projects. Through building the remote monitoring system, the important information reflecting the structure state of the project can be obtained, which can help the engineers to evaluate the overall performance of the project and accumulate experience for similar projects in the future. Moreover, after back calculating the performance of the geotechnical engineering by utilizing the monitoring data, belonging to the inverse analysis technique (Hashash et al. 2006; Zhang et al. 2010; Wang et al. 2013, 2014), the engineers can have a better understanding of the influence of the project construction and quickly make contingency plans.

For the high speed railway subgrade projects, due to the lack knowledge of the dynamic response and failure mechanism of high-speed railway subgrades under the influence of the dynamic loads and environmental and geological factors, different severities of accidents have occurred on passenger lines, which affect the safe operation of high-speed trains (Chen et al. 2010; Bian et al. 2014a; Li 2013). So it is a key issue to be solved to know the dynamic response and deformation data of the subgrades, which can be utilized for the later assessment of their stability. In this sense, the remote monitoring system is more significant for the high speed railway subgrade engineering to clearly recognise its dynamic response and failure processes, especially for high-speed railway engineering operations in mountainous areas.

Along with the rapid development of intelligent sensing technology, wireless communication technology, and computer technology, the remote monitoring system for geotechnical projects have been more and more developed

---

✉ Jian Li
lij@whrsm.ac.cn

[1] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, Hubei, China

(Spencer et al. 2005; Xie 2009). In slope projects, several remote monitoring systems including warning and forecasting functions, proposed by Yang et al. (2015), He et al. (He et al. 1999, 2004, 2009), Wu et al. (2010), Xu et al. (2007), were successfully applied. In tunnel projects, Ye (2009) applied multivariate information automatic acquisition and wireless transmission technologies to a tunnel construction site. As for railway engineering, although studies on remote monitoring systems are rare, a few attempts have been made. For example, Feng et al. (2013) designed an automatic monitoring system for railway road bed subsidence; Yang et al. (2012, 2014) integrated a

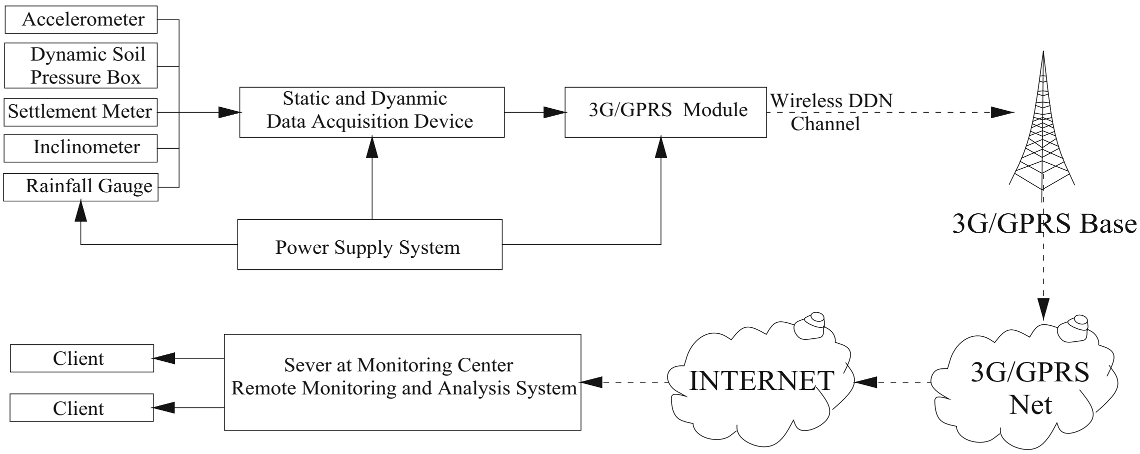
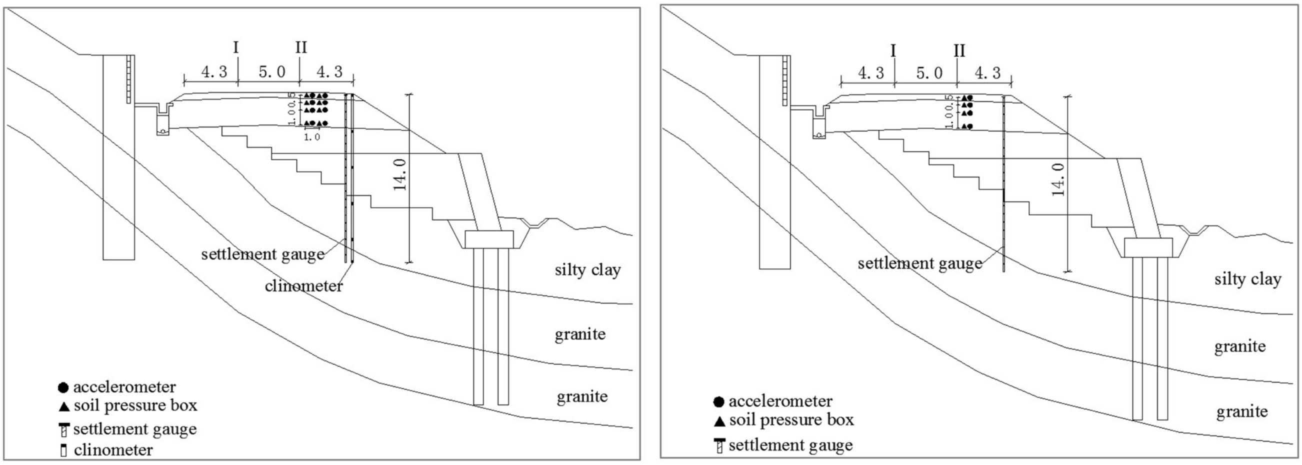


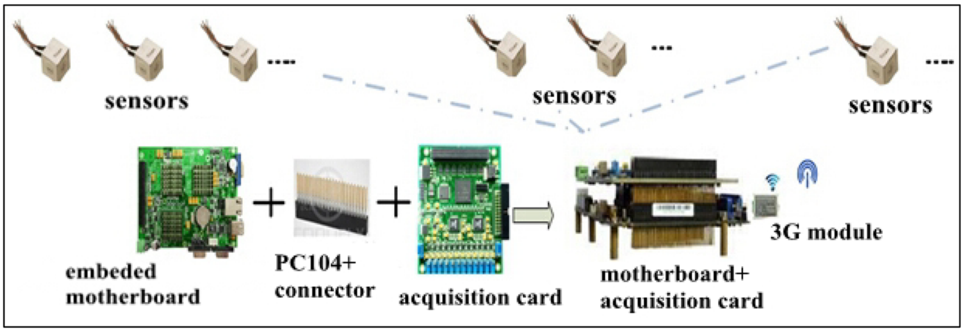
Fig. 1 The monitoring system



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

Fig. 2 Monitoring sensors in a high filled slope subgrade

Fig. 3 Scheme for data acquisition and wireless transmission



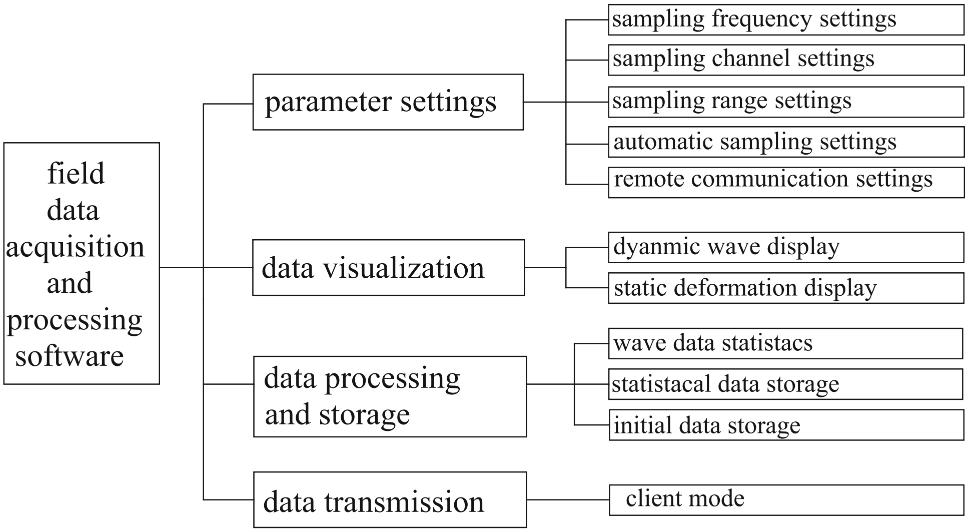
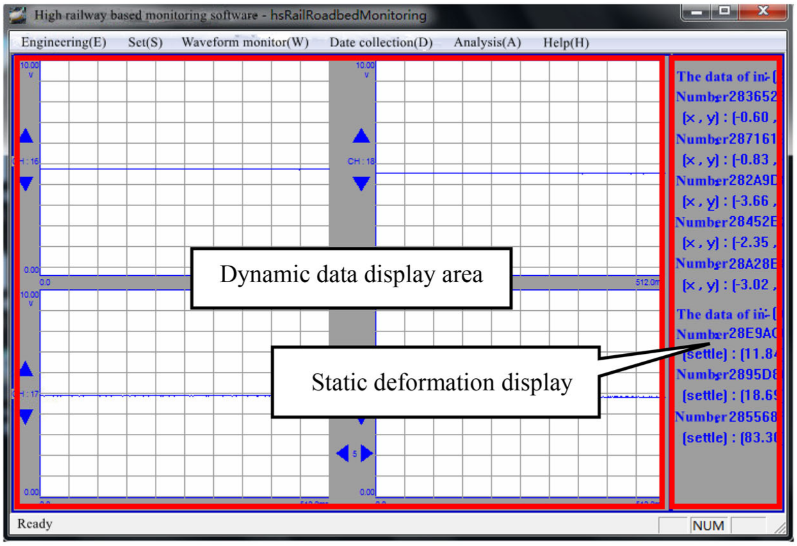
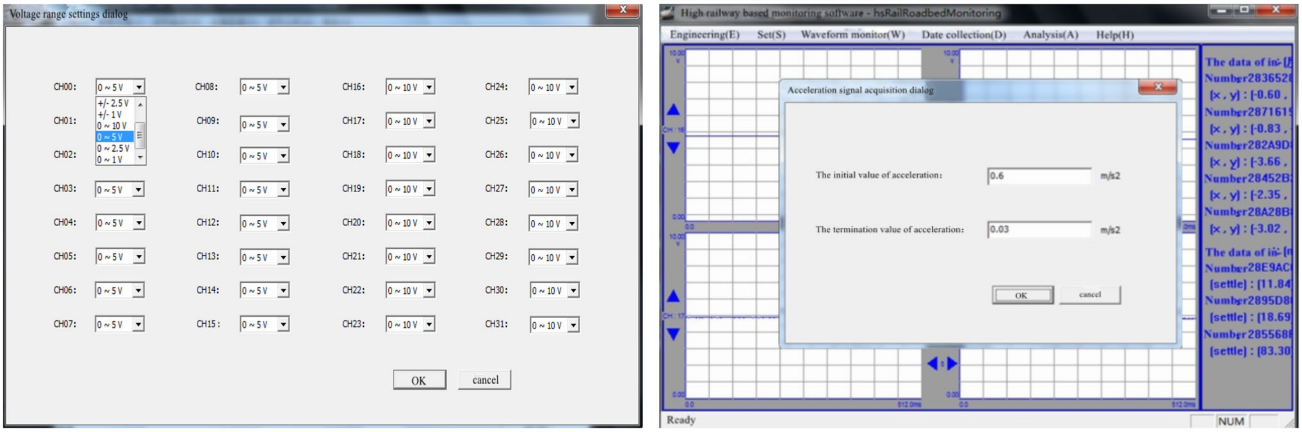


Fig. 4 Functions of field data acquisition and processing software



```
The data of in-[
Numbɛr283652
 [x , y] : [-0.60 ,
Numbɛr287161
 [x , y] : [-0.83 ,
Numbɛr282A9D
 [x , y] : [-3.66 ,
Numbɛr28452E
 [x , y] : [-2.35 ,
Numbɛr28A28E
 [x , y] : [-3.02 ,
The data of in-[
Numbɛr28E9AC
 [settle] : [11.84
Numbɛr2895D8
 [settle] : [18.69
Numbɛr285568
 [settle] : [83.30
```

(a) Main interface



CH00: 0 ~ 5 V
CH01: 0 ~ 5 V
CH02:
CH03: 0 ~ 5 V
CH04: 0 ~ 5 V
CH05: 0 ~ 5 V
CH06: 0 ~ 5 V
CH07: 0 ~ 5 V
CH08: 0 ~ 5 V
CH09: 0 ~ 5 V
CH10: 0 ~ 5 V
CH11: 0 ~ 5 V
CH12: 0 ~ 5 V
CH13: 0 ~ 5 V
CH14: 0 ~ 5 V
CH15: 0 ~ 5 V
CH16: 0 ~ 10 V
CH17: 0 ~ 10 V
CH18: 0 ~ 10 V
CH19: 0 ~ 10 V
CH20: 0 ~ 10 V
CH21: 0 ~ 10 V
CH22: 0 ~ 10 V
CH23: 0 ~ 10 V
CH24: 0 ~ 10 V
CH25: 0 ~ 10 V
CH26: 0 ~ 10 V
CH27: 0 ~ 10 V
CH28: 0 ~ 10 V
CH29: 0 ~ 10 V
CH30: 0 ~ 10 V
CH31: 0 ~ 10 V

The initial value of acceleration: 0.6 m/s2
The termination value of acceleration: 0.03 m/s2

(b) Conversion factor setting **(c)** Automatic data acquisition setting

Fig. 5 Interface of the field data acquisition and processing interface local wireless communication module and a DTU-GPRS module to remotely monitor the static deformation of railway subgrades; Feng et al. (2011) developed a system for monitoring the additional expansion and contraction of a high-speed railway bridge and seamless line.

Even so, from the existing remote monitoring system, it can be known that the existing remote monitoring methods mainly aim at static deformation monitoring, and research into the monitoring of dynamic variables is rare. The technical difficulties in the dynamic response monitoring lie in high-speed data acquisition, processing, analysis, and real-time transmission. In this paper, a new remote monitoring system for dynamic response measurement of the high speed railway subgrades, solving all the technical difficulties above, was introduced. A successful implemented remote and real-time monitoring on the test section DK203 + 725.00 to +775.00 of the Hu-Kun passenger line (design speed, 300 km/h) in Hunan Province was also presented. The analysis of the obtained monitoring data, on the one hand, verified the operation of the developed system, and, on the other hand, provided basic data for better understanding the variety of the dynamic response of the subgrade.

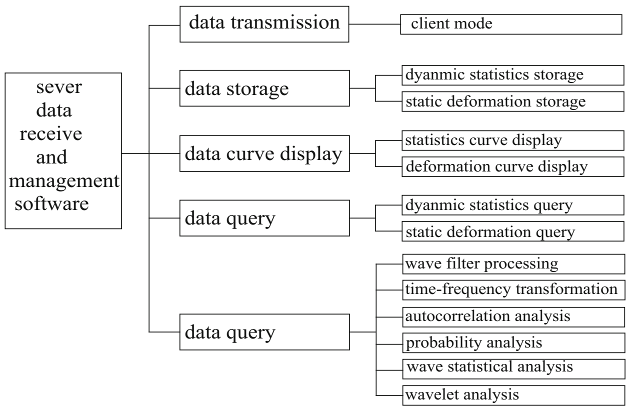


Fig. 6 Functions of server data receiving and management software

What is more, although the remote system proposed in this paper aims at dynamic response and deformation of the high speed railway subgrade in a mountainous area, it has good adaption to dynamic variables monitoring and dynamic data treatment that also makes it suitable for other geotechnical engineering focusing on dynamic stability. As long as making a few well-directed changes, such as the layout of monitoring sensors or data treatment mode, the system can be applied to other geotechnical projects.

Design and layout of the remote monitoring and analysis system

Design principles and guidelines

In view of grasping the state of a project and ensuring its safety, the design of the remote monitoring system should follow the following principles and guidelines:

1. Firstly, the clear knowledge of the purpose of the remote monitoring system construction should be confirmed, which is the footstone for later work.
2. Secondly, the weakness of the monitored project should be analysed. This information can be got using a combination of: (1) precedent or local experience with a similar project; (2) semi-empirical analysis methods; and (3) results of numerical simulation.
3. Thirdly, on the basis of the two points above, the right monitoring sensors should be selected. The sensors should satisfy the following demands: (1) enough accuracy; (2) uninterrupted output; (3) good compatibility; and (4) good economy. All these demands make sure the remote monitoring system can be successfully built and the obtained monitored results have a satisfactory reliability.
4. Fourthly, the adaptable data acquisition and transmission equipment should be used. The input format of the data acquisition equipment should match the output

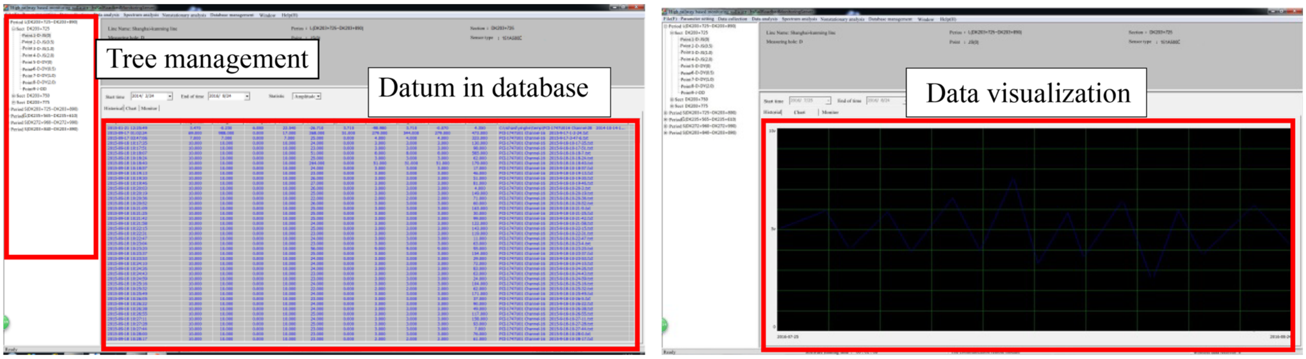
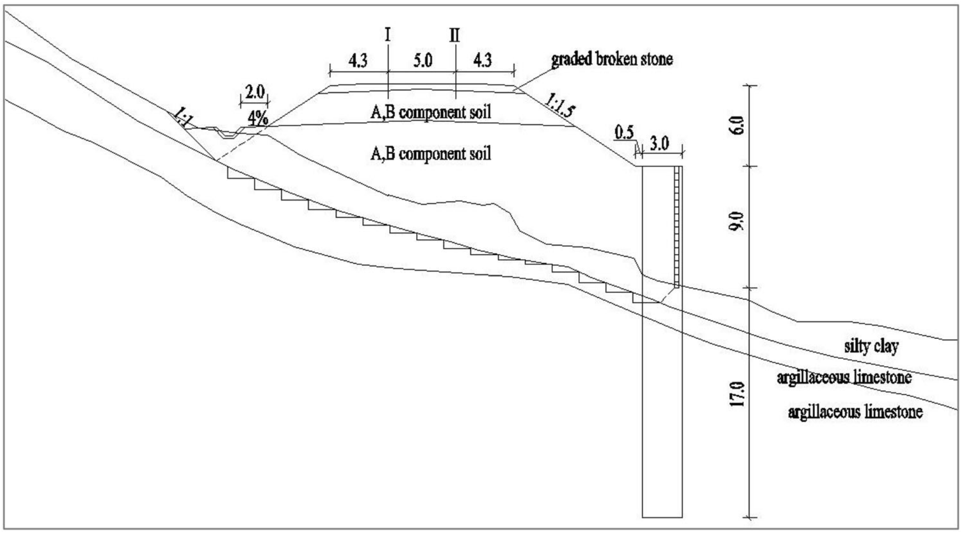
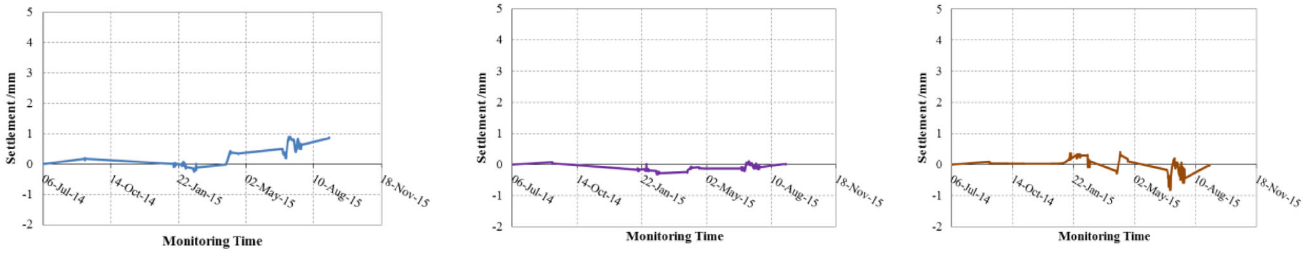


Fig. 7 Database management software for server

Fig. 8 The Shanghai–Kunming dedicated line DK203 + 725.00 to +775.00





(a) DK203+725.00 **(b)** DK203+750.00 **(c)** DK203+775.00

Fig. 9 Monitored settlement data

format of the sensors well. The equipment should have the ability to do data treatment, which can treat the mass data and transmit the key data to the user.

5. Last and most important, on the basis of the first two demands, the layout of the sensors should be well-designed. All the sensors should be set up at the key points. For example, the deformation monitoring sensor should be embedded at the weakness point in order to quickly find the dangerous deformation of the project. The dynamic monitoring sensor should be set up at the points that can catch the dynamic data easily.

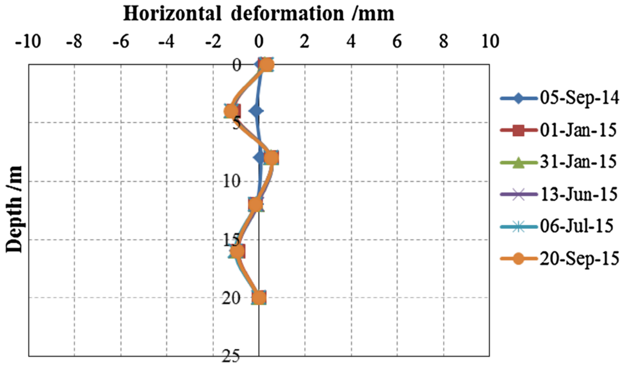


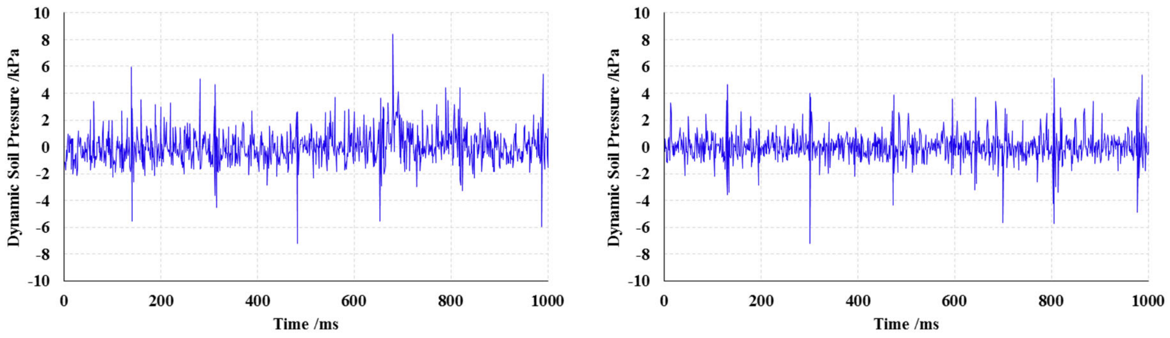
Fig. 10 Monitored horizontal displacements

In accordance with the above design principles and guidelines, an application example of remote monitoring system for high speed railway subgrades is introduced in the following sections.

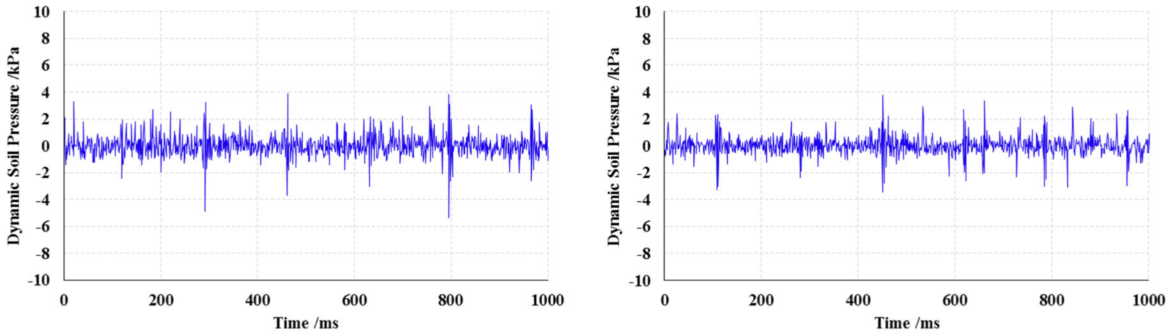
Overall design of the remote monitoring system for high speed railway subgrades

According to the local geology, combining an 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 investigated. The specific objectives and design concepts are as follows:

1. In view of the multiple types of sensors, the corresponding network communication measurement is researched and then formulated, which connects all the sensors in the same area. According to the type of monitoring parameters, network size, and real environmental conditions, the corresponding signal acquisition strategies (static and dynamic parameter

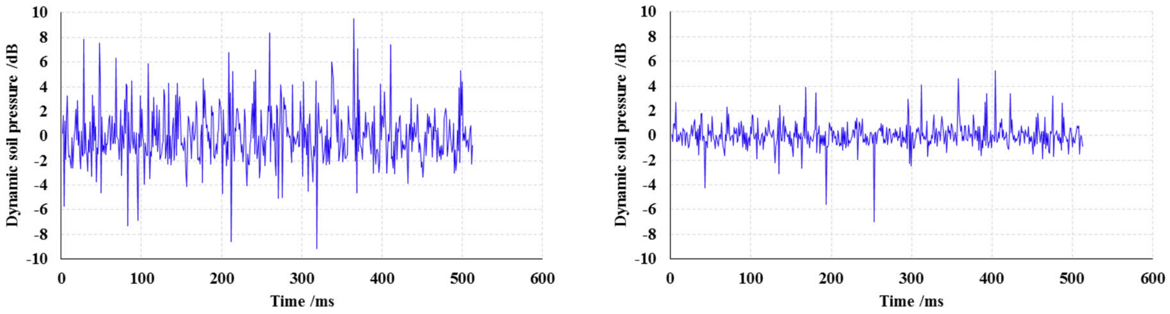


(a) subgrade surface **(b)** 0.5 m from the subgrade surface

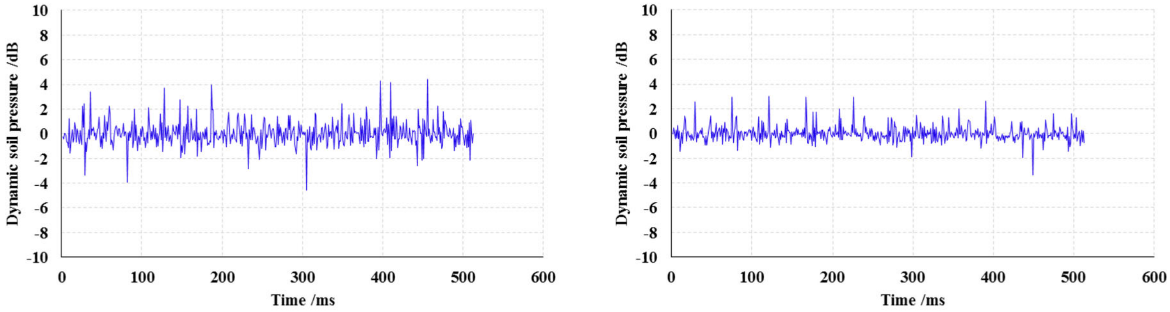


(c) 1.0 m from the subgrade surface **(d)** 2.0 m from the subgrade surface

Fig. 11 Monitored dynamic soil pressure curves at DK203 + 725.00 (data from 22 December 2014)



(a) subgrade surface **(b)** 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface **(d)** 2.0 m from the subgrade surface

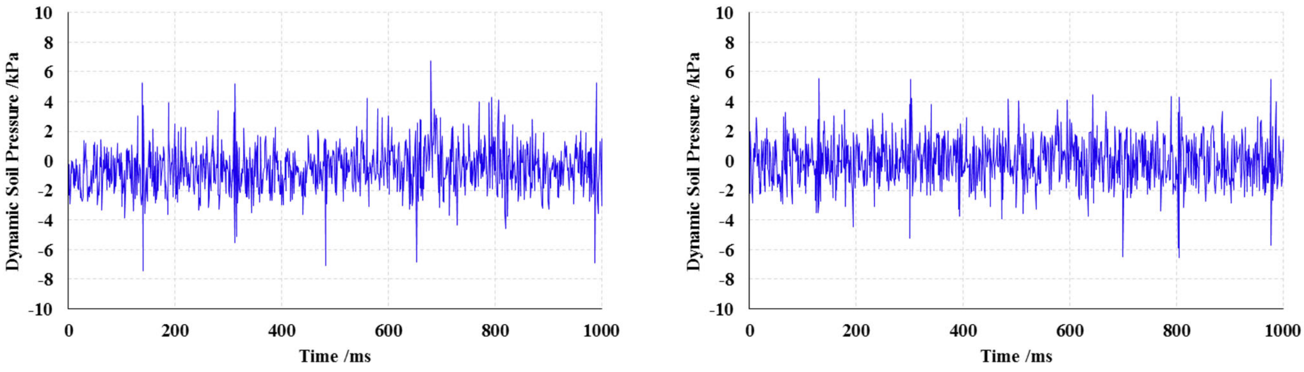
Fig. 12 Monitored dynamic soil pressure curves at DK203 + 725.00 (data from 20 September 2015) acquisition) are studied and then determined, which include the acquisition and storage method, the acquisition instruction control method, and so on.

2. By applying multi-channel data acquisition technology to integrate the monitoring parameters in different sections, a real-time, automatic, effective, cost-effective, and unmanned monitoring sub-station is formed. According to the electricity consumption, monitoring frequency and in situ conditions, the field power supply system (line power supply, solar panel, battery, etc.) can be determined.
3. Through applying GPRS/3G wireless transmission technology at low cost and with stable network coverage, the monitoring datum pre-processed by the sub-station is transmitted to the control centre. Then through the internet, the datum exchange channel between the control centre (in Changsha) and the remote centre (in Wuhan) can be established. Thus, a whole remote monitoring system for high-speed railway subgrade structures can be constructed (see Fig. 1).

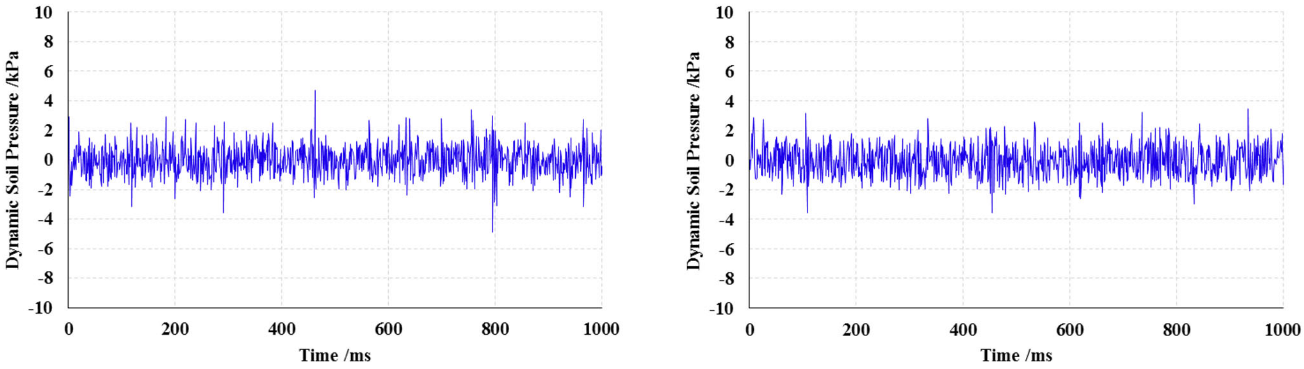
Research into monitoring parameters and sensor layout

Monitoring parameters

The properties and composition of the geomaterials determine whether failure occurs in a high-speed railway subgrade and its related engineering works. On the other hand, the environmental conditions in mountainous areas and the high-speed moving load are external factors prompting failure. As a result, disasters in high-speed railway projects are mainly caused by the geo-properties and environmental factors rather than the moving load; but, repeated moving loads can accelerate the failure process and is reflected by significant changes in the high-speed railway subgrade. Therefore, in the research on operational stage monitoring parameters, the physical parameters directly reflecting the inhomogeneity of the subgrade structure should be chosen, such as deformation parameters (vertical settlement, horizontal displacement, etc.) and dynamic response indices (acceleration, dynamic soil pressure, etc.).



(a) subgrade surface **(b)** 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface **(d)** 2.0 m from the subgrade surface

Fig. 13 Monitored dynamic soil pressure curves at DK203 + 750.00 (data from 22 December 2014)

Selection of monitoring sensors

In view of the features of a high-speed railway subgrade in a mountainous area, and based on the optimum selection principle of strong adaptability, high reliability, and better economy, the sensors can allow unmanned monitoring and automatic data acquisition. In addition, the sensors also should have strong adaptability, high accuracy, low cost, and convenient embedment. The chosen monitoring sensors are as follows:

- *Deformation sensors*: single point settlement gauge, inclinometer.
- *Environmental sensor*: rainfall meter.
- *Dynamic response sensors*: accelerometer; dynamic soil pressure box.

Among them, the deformation sensors can directly monitor the condition of the high-speed railway subgrade based on the angle of deformation. The environmental sensor reflects the relationship between the inhomogeneity of the high-speed railway subgrade and water from the angle of rainfall, which reflects the external influence on the variety of the high-speed railway subgrade induced by rainfall. The dynamic response sensors can monitor the dynamic response regularities before and after changes in the high-speed railway subgrade. By researching the variety of dynamic responses, the subgrade condition can be assessed.

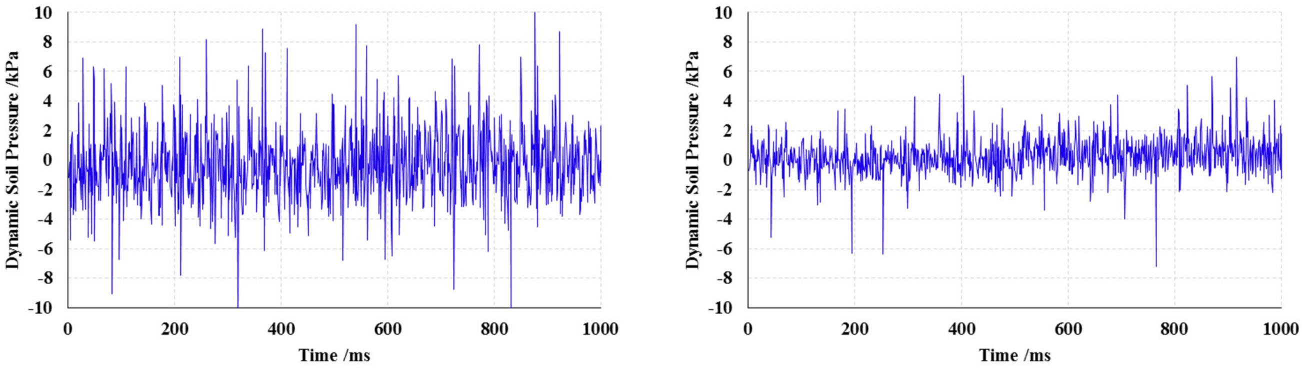
Layout of monitoring sensors

The monitoring sensors must be laid out in positions directly reflecting the status of the subgrade. As a result, according to those monitoring sections with different features, the specific sensor layouts are as follows:

Sensor layout for high filled sloping subgrade

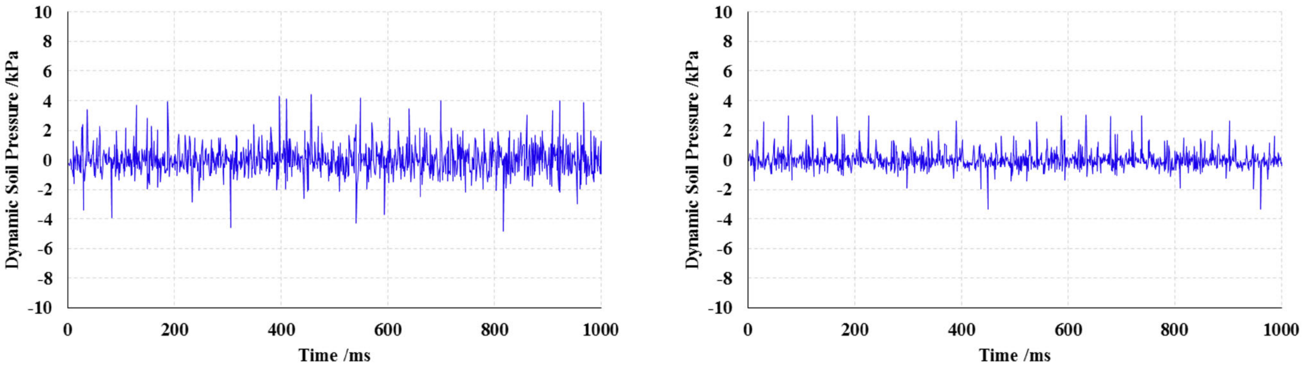
The test monitoring section length of a high filled sloping subgrade is 50 m, in which there are one key monitoring section, and two general monitoring sections at 25 m intervals (Fig. 2).

For the key monitoring section, the subgrade vertical and horizontal dynamic response are focused, and the



(a) subgrade surface

(b) 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface

(d) 2.0 m from the subgrade surface

Fig. 14 Monitored dynamic soil pressure curves at DK203 + 750.00 (data from 20 September 2015) incline and settlement deformations are also considered by setting up inclinometers and a settlement meter on the subgrade shoulder.

For the general monitoring section, the changes in the vertical dynamic response under the tracks are mainly considered. The deformation factors mainly focus on subgrade settlement.

Scheme for data acquisition and wireless transmission

For static monitoring sensors, due to their long data acquisition cycle and small amounts of data, an ordinary data acquisition card can meet operational requirements; however, for the dynamic sensors, data acquisition is more complicated. On the one hand, the dynamic sensors can capture high-frequency responses and big datasets capturing instantaneous changes; on the other hand, the acquisition equipment should have a high resolving power to reflect the dynamic datum. Based on previous research, the data acquisition scheme for both static and dynamic parameters is shown in Fig. 3.

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

1. Data processor

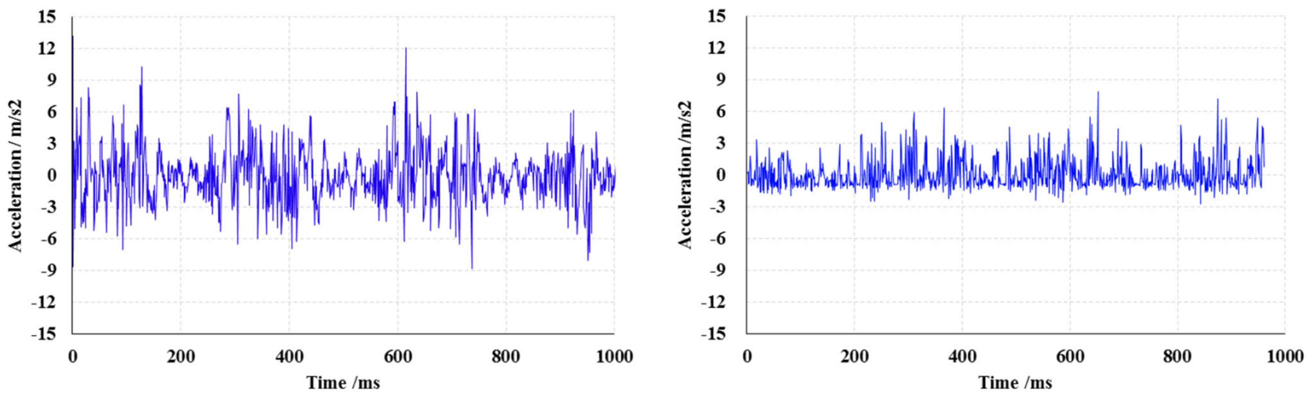
A high-performance PC is used as the data processor to acquire and store monitored data. Then it pre-processes the dynamic data to reduce the amount for transmission.

2. Data acquisition card

Two data acquisition cards are used: one is a high-speed data acquisition card responsible for acquiring the dynamic parameters; the other is a low-speed card used to acquire the static parameters.

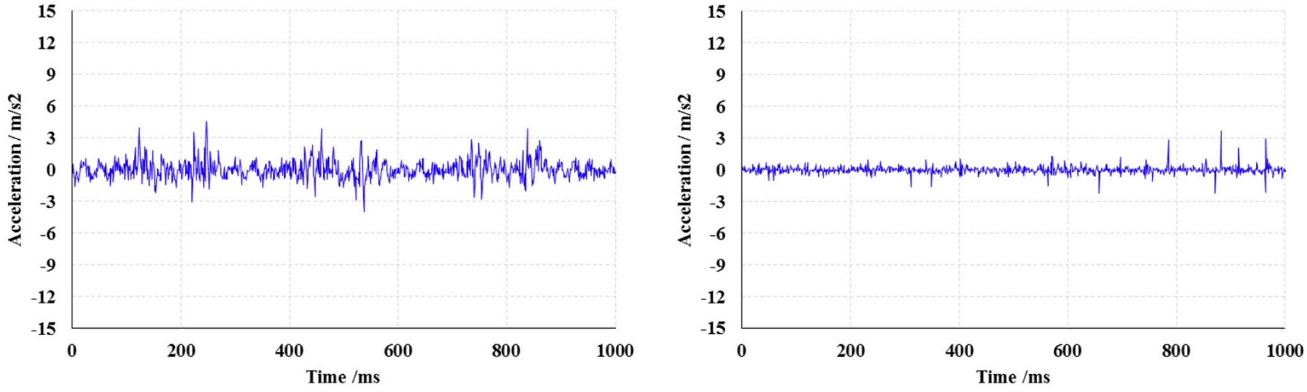
3. Wireless transmission module

Based on field conditions, dataset size, equipment stability, and power consumption, GPRS/3G modules are selected.



(a) subgrade surface

(b) 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface

(d) 2.0 m from the subgrade surface

Fig. 15 Monitored acceleration curves at DK203 + 725.00 (data from 22 December 2014)

Development of remote monitoring and analysis system software

The remote monitoring and analysis system controlling software is composed of two sub-routines: field data acquisition and processing software and server controlling software. Among them, the field data acquisition and processing software is responsible for acquiring the static and dynamic data, displaying the data waveforms, storing data, processing the dynamic data, and communicating with the server. The server-controlling software is responsible for receiving and storing data, and displaying and querying history data. Meanwhile, the server software also has a data analysis module, prediction and management function modules, and will be pre-set with evaluation standards and an early warning model for implementation of a high-speed railway subgrade safety grade evaluation.

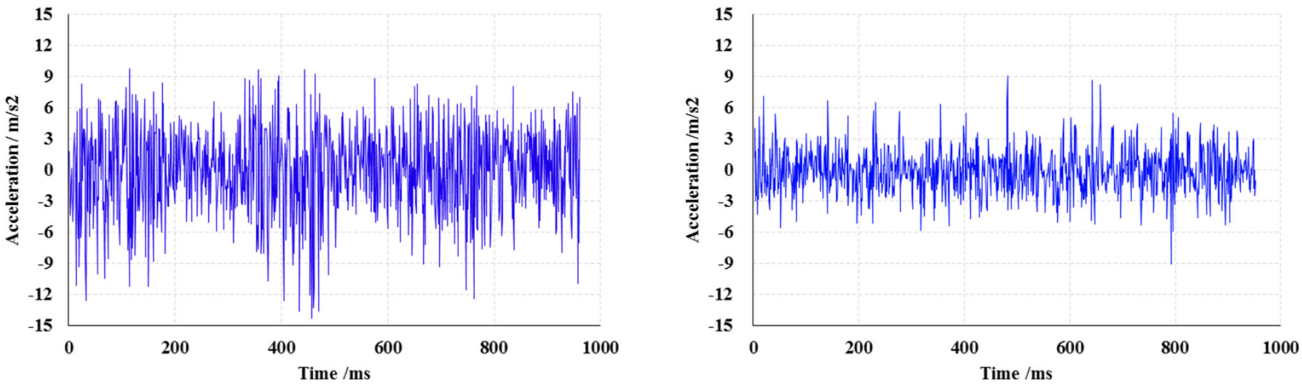
The software is programmed in Visual C++ and Access 2010. The 3G/GPRS wireless communication technology is applied to transmit signals between the two software.

Field data acquisition and processing software

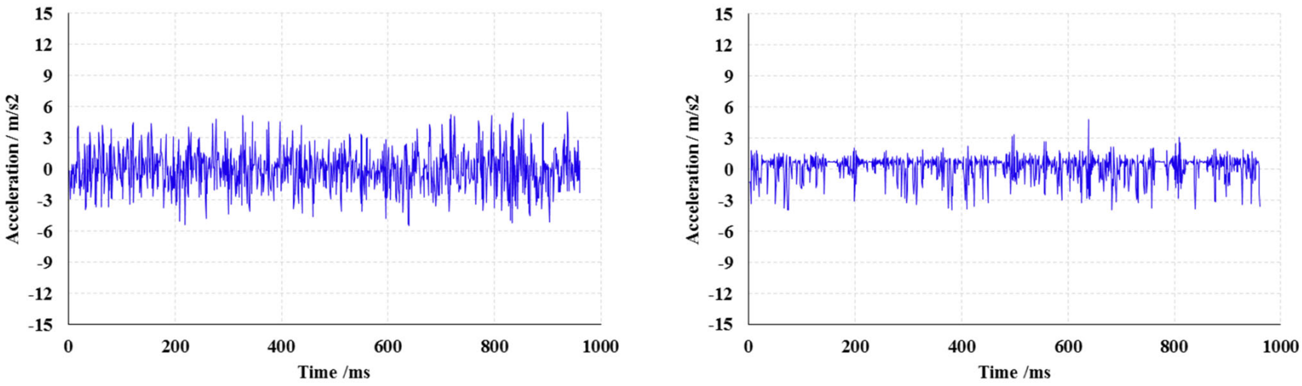
The field data acquisition and processing software can achieve the following functions: 1. the monitoring conditions can be set to realise either automatic, or manual, data acquisition; 2. the sampling frequency can be set according to different mdata to reduce the amount for transmissiononitoring sensors; the data waveform display can be set according to the sensor measuring range; the data can be pre-processed to obtain the key data only to reduce the amount of data; the software can be remotely controlled over the Internet. These functions are shown in Fig. 4 and the specific interface in Fig. 5.

Server-controlling software

The server-controlling software can realise the classified management of monitoring data and project information and has the functions of data analysis, prediction, and management. The functions are shown in Fig. 6.



(a) subgrade surface **(b)** 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface **(d)** 2.0 m from the subgrade surface

Fig. 16 Monitored acceleration curves at DK203 + 725.00 (data from 20 Sep. 2015)

Figure 7 shows the database management interface: the software realises ‘hierarchical and multi-objective’ data storage, which means that all kinds of data are archived for convenient querying at a later date. As for data queries, users can select a specific sensor to find historical data by choosing the date. In addition, important sensor information, including hierarchical information, sensor type, burial depth, and so on are also displayed.

For data visualisation, the software can plot data over time according to data type. Meanwhile, the software also can realise dynamic data monitoring, which means that once there are data being received, the plot can be immediately displayed in the on-line monitoring window.

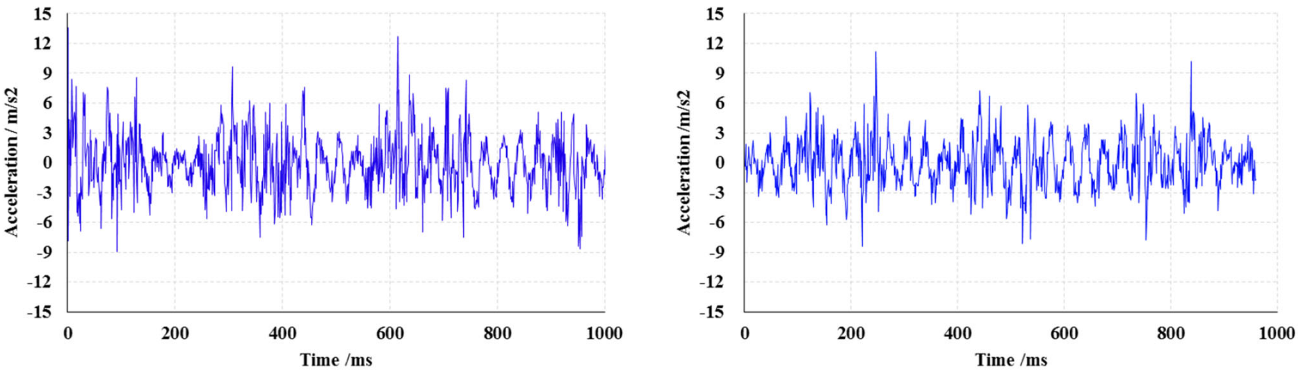
According to the size of the dynamic dataset for analysing the dynamic response regularity of the high-speed railway subgrade, the software is also equipped with different data processing and analysis functions, such as time–frequency transform, digital filtering, correlation analysis, probability analysis, statistical analysis, non-smooth analysis, and so on. Through research into the transformed, and statistical characteristics, and values of the vibration datum, a data analysis-based model for early warning and forecasting is realised.

Application examples

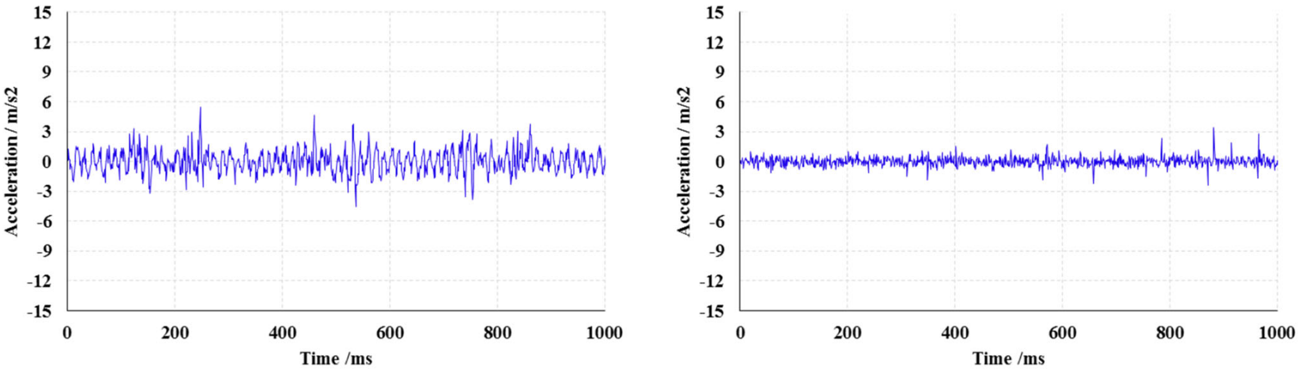
The Hu-Kun passenger dedicated line is a national “long-term railway network planning” project in the ‘four vertical and four horizontal’ fast passenger transport channel, which runs east from Shanghai, and west to Kunming railway trunk-line. Among the whole line, the section in Hunan passes through a dangerous mountainous area and the line is usually laid in the form of high filled slope subgrades, whose construction is difficult. Due to the complicated and changeable geological and climate conditions, the monitoring of the subgrade structure state becomes more important.

In this region, the section from DK203 + 725.00 to +775.00 has typical characteristics of a high, and steep, slope subgrade. This line section passes through the mountainous area by the cut and fill mode. The subgrade centre maximum filling height is 8.46 m, the slope maximum height is 14.8 m, and the cutting depth is 33.8 m (see Fig. 8).

After completion of the monitoring system in June 2014, the subgrade structure state monitoring for the test subgrade in the static settling period, joint debugging period, and operational period has been carried out. The static



(a) subgrade surface **(b)** 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface **(d)** 2.0 m from the subgrade surface

Fig. 17 Monitored acceleration curves at DK203+750.00 (data from 22 December 2014) deformation data and dynamic response data under high-speed moving loads are obtained, which can form a key datum for analysing subgrade conditions.

Static deformation monitoring application

Figure 9 shows the settlement datum of static sensors located at the key section. Figure 9a–c, respectively, give the settlement at three sections. It is seen that, on the one hand, the settlement of the subgrade is small (less than 0.5 mm) and fluctuates within a small range.

Figure 10 shows the horizontal deformations monitored by the inclined sensors. The horizontal displacements are also small and even the displacement at top of the inclinometer hole is less than 0.4 mm. Based on the monitoring datum, we can conclude that the subgrade structure is stable from the angle of deformation thereof.

Dynamic parameter monitoring application

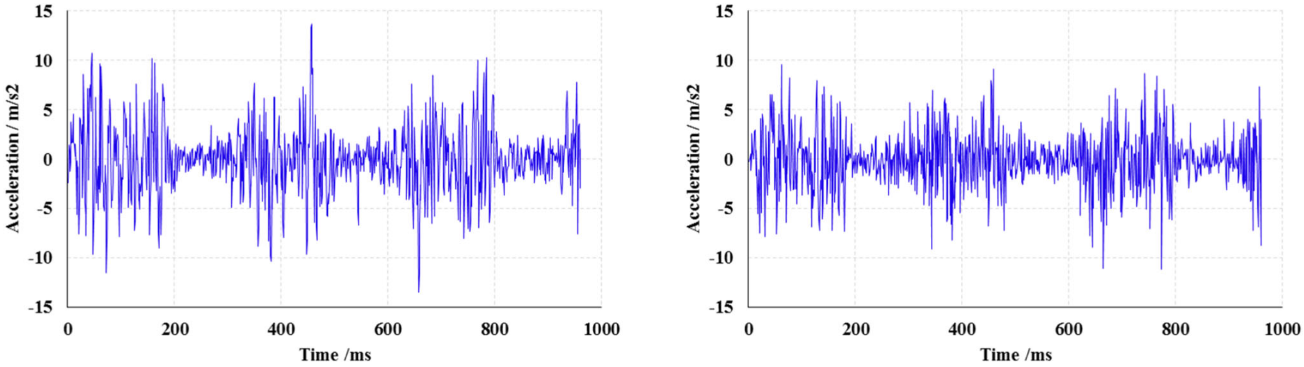
Dynamic response analysis of time history data

Dynamic soil pressure analysis Figures 11, 12, 13, 14, respectively, show the monitored dynamic soil pressure datum of DK203 + 725.00 and DK203 + 750.00 on two dates.

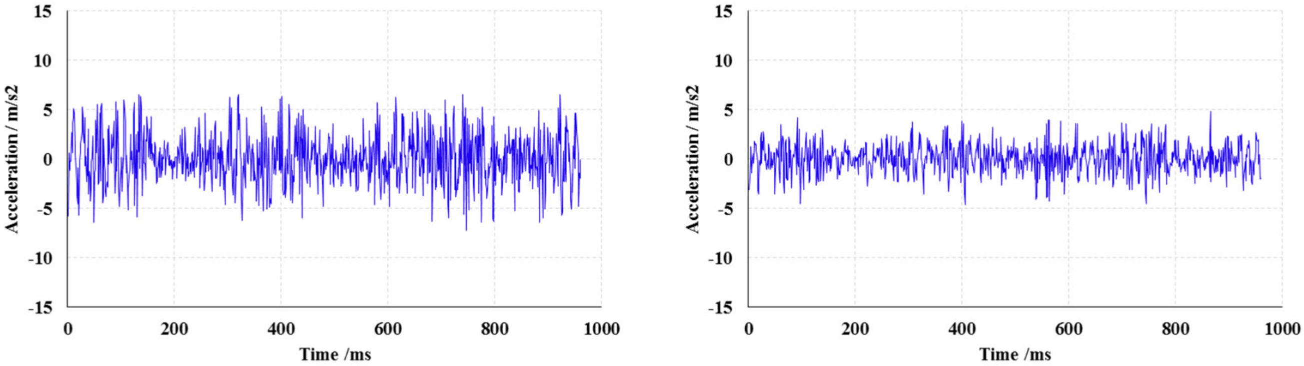
Compared with Figs. 11, 12, 13, and 14 the dynamic soil pressures at different sections are basically the same. The maximum value of the dynamic soil pressure at the subgrade surface is about 10 kPa, and the amplitudes of the dynamic soil pressure decrease as the depth increases.

From Figs. 11, 12, 13, and 14, it also can be seen that during the service period of nearly 1 year, the generated dynamic soil pressures caused by high-speed trains are basically the same and the maximum value remains at about 10 kPa. Also, the amplitudes in the depth direction are the same. This means that there is no obvious change in the subgrade structure during this period.

Acceleration analysis Figures 15, 16, 17, and 18, respectively, show the monitored accelerations from DK203+725.00 to DK203+750.00 on two dates. Compared with Figs. 15, 16, 17, 18, the accelerations at different sections are basically the same. The maximum acceleration at the subgrade surface is about 14 m/s^2, and the amplitudes of the dynamic soil pressure decrease as the depth increases.



(a) subgrade surface (b) 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface (d) 2.0 m from the subgrade surface

Fig. 18 Monitored acceleration curves at DK203+750.00 (data from 20 September 2015)

From Figs. 15, 16, 17, and 18, during the service period of nearly 1 year, the generated dynamic soil pressures caused by high-speed trains are basically the same and the maximum value remains at about 14 m/s^2. Also, the amplitudes in the depth direction are the same. This means that there is no obvious change in the subgrade structure during this period.

Dynamic response analysis of frequency domain data

Dynamic soil pressure spectrum analysis

Figures 19 and 20, respectively, show the dynamic soil pressure spectra from DK203 + 725.00 to DK203 + 750.00.

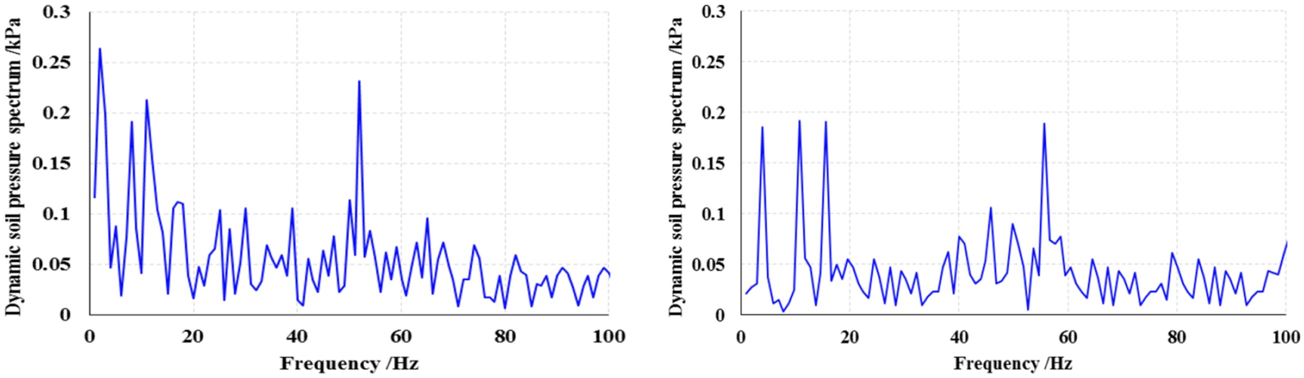
Analysing the data in Figs. 19 and 20 shows that the frequency characteristics of the dynamic soil pressure wave caused by high-speed trains are more obvious. There is a peak value in the low frequency part (smaller than 20 Hz, at about 8–15 Hz) and then another peak appears in the high frequency part (45–55 Hz).

The low frequency values in the dynamic soil pressure spectrum curve reflect the dynamic loads caused by the train bogies, whose frequencies are between 10 and 15 Hz. A lot of research demonstrates this, and along with the increase of the depth from the subgrade surface, the frequencies of this kind of dynamic loads decreases (Bian et al. 2014b; Zhai et al. 2015).

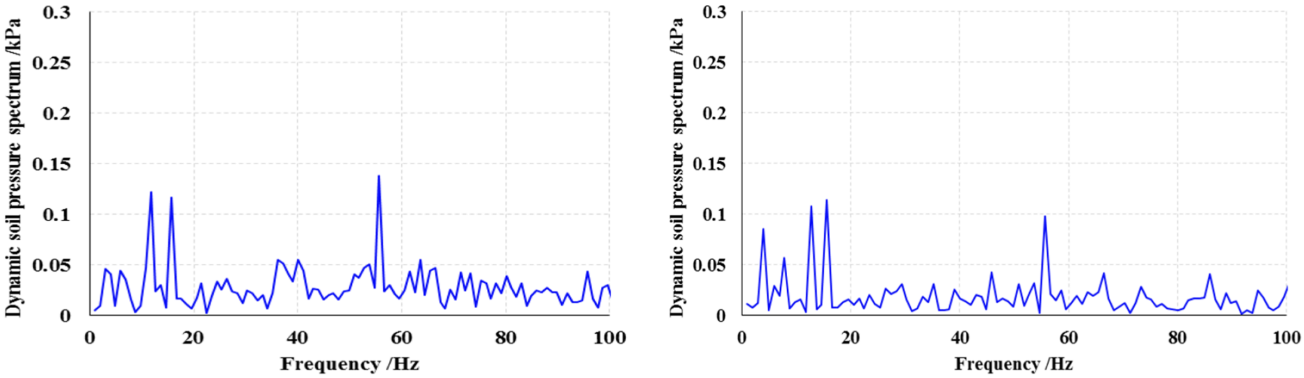
The high frequency part in the dynamic soil pressure spectrum curve is caused by train vibration resulting from factors such as track irregularity, wheel scars, and so on. Track irregularities, caused by rail abrasion and uneven subgrade settlement, is one of the reasons causing high frequency loads (Nie 2005; Lei 2015). In particular, the shorter the rail irregularity wavelength, the higher the frequency of the resulting dynamic loads. On the other hand, factors such as train wheel abrasion, eccentricity, etc. can also produce high-frequency vibration loads during the train traffic at high-speed.

Acceleration spectrum analysis

Figures 21 and 22, respectively, show the acceleration spectra at DK203+725.00 and DK203+750.00.

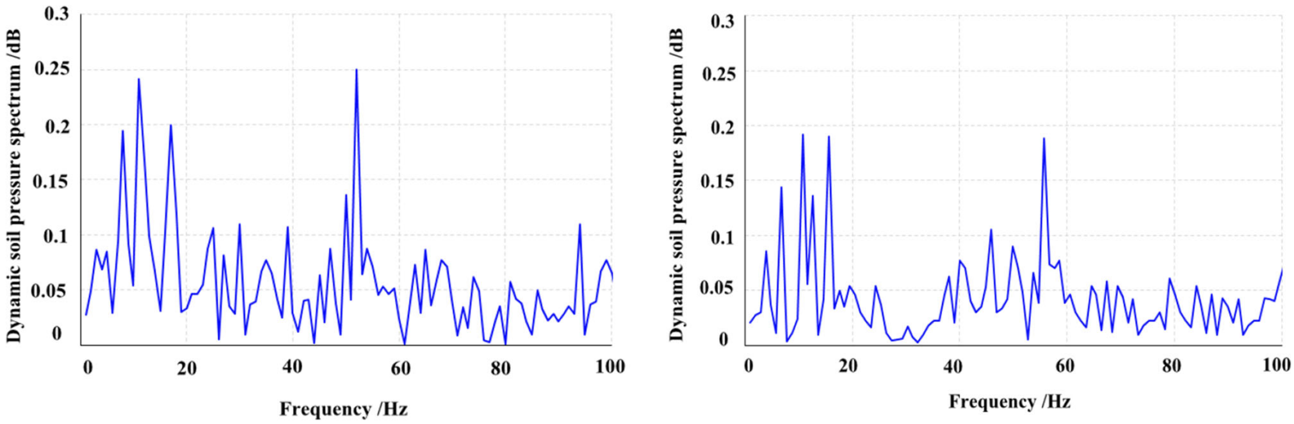


(a) subgrade surface **(b)** 0.5 m from the subgrade surface

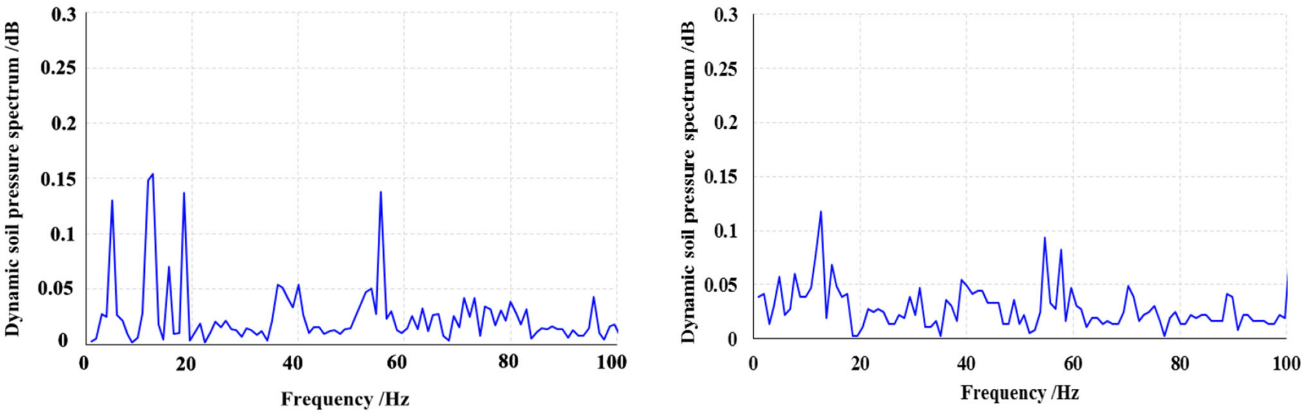


(c) 1.0 m from the subgrade surface **(d)** 2.0 m from the subgrade surface

Fig. 19 Dynamic soil pressure spectrum at DK203 + 725.00 (data from 22 December 2014)



(a) subgrade surface **(b)** 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface **(d)** 2.0 m from the subgrade surface

Fig. 20 Dynamic soil pressure spectrum at DK203+750.00 (data from 22 December 2014)

From Figs. 21 and 22, it can be seen that, similar to the characteristics of the dynamic soil pressure spectrum, the acceleration spectrum curve also has a peak in the low frequency part (less than 20 Hz, and focussed on 10–20 Hz): there are also peak values in the high frequency part at 45–60 Hz.

The low frequency values in the acceleration spectrum curve reflect the dynamic loads caused by the train bogies. The high frequency part reflects the dynamic loads and frequencies caused by factors such as rail irregularities, wheel scars, and so on.

Attenuation of the dynamic parameters

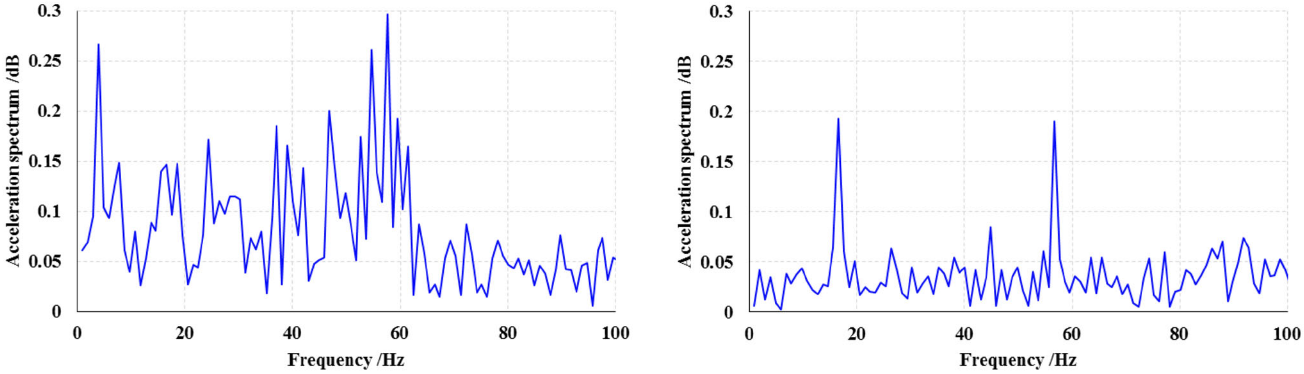
Dynamic soil pressure attenuation

Figure 23a–c, respectively, gives the dynamic soil pressure attenuation curves at three sections, which are caused by the high-speed train. Figure 24a–c, respectively, show the contrasting curves of dynamic soil pressure attenuation ratio at the three sections.

From Fig. 23, after 1 year of operation, the dynamic soil pressures caused by high-speed trains on the subgrade have changed little. The maximum dynamic soil pressure at the subgrade surface is 8–10 kPa and its amplitudes decrease slowly as the depth increases. The data reflect the fact that the structural state of the tested subgrade is unchanged, and that it is stable.

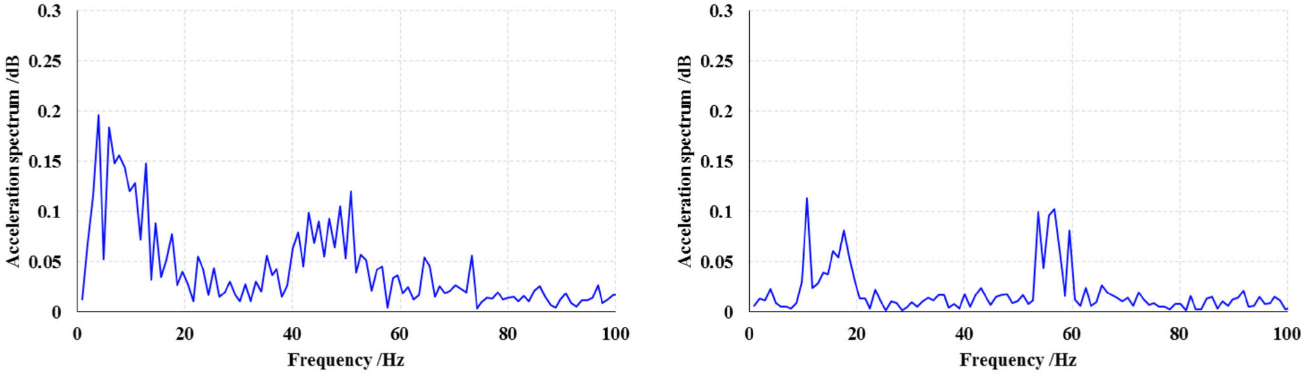
Figure 24 shows the differences in the dynamic soil pressure attenuation ratio among the measured datum, other line datum, and a model test. From the measured datum, we can see that the dynamic soil pressure decreases by 30% at 0.5 m depth, decreases by 40% at 1.0 m depth, and decreases by about 60% at 2.0 m depth. This means that the transmission range of the dynamic loads caused by high-speed trains is deeper than 2.0 m, and its influencing depth is about 4.0 m.

The attenuation of the measured datum is similar to that measured at the Wuhan-Guangzhou and Beijing–Shanghai passenger dedicated lines. This means that when the high filled slope subgrade is supported by a reinforcing structure with sufficient strength and the subgrade remains stable,



(a) subgrade surface

(b) 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface

(d) 2.0 m from the subgrade surface

Fig. 21 Acceleration spectrum at DK203+725.00 (data from 22 December 2014)

the transfer of dynamic soil stress has little difference compared to that of a normal high-speed railway subgrade.

Compared with the datum from a model test and an in situ test, we can conclude that the dynamic soil stress of the model test and in situ test decreases more rapidly than the measured dynamic soil stress. The difference is caused by the properties of the subgrade filling material and the dynamic load zone of areal influence. In the model test and in situ test, the subgrade filling material is relatively ‘soft’, and the damping of the subgrade soil is large. As a result, the energy of the dynamic loads can be quickly absorbed in the shallow parts of the subgrade. On the other hand, due to the small area over which the dynamic loads are applied in the model test and in situ test, the whole load is relatively small and through the absorption in the soil at the shallow part, the transfer depth for dynamic loading is small.

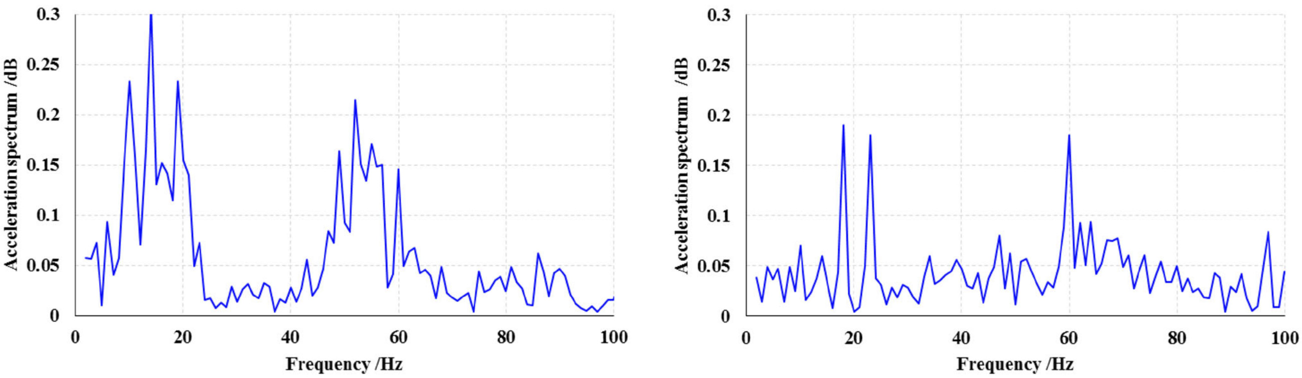
Acceleration attenuation

Figure 25a–c, respectively, show the acceleration attenuation curves at three sections, as caused by a high-speed train. Figure 26a–c, respectively, give the contrasting curves of acceleration attenuation ratio at the three sections.

Figure 25 shows the acceleration in the subgrade at three sections: the maximum acceleration at the subgrade surface is about 12–15 m/s^2 and the acceleration decreases slowly with increasing depth. Comparing data from different dates, the acceleration in the subgrade remained unchanged over nearly one year of operations, which means that the subgrade structure remained stable.

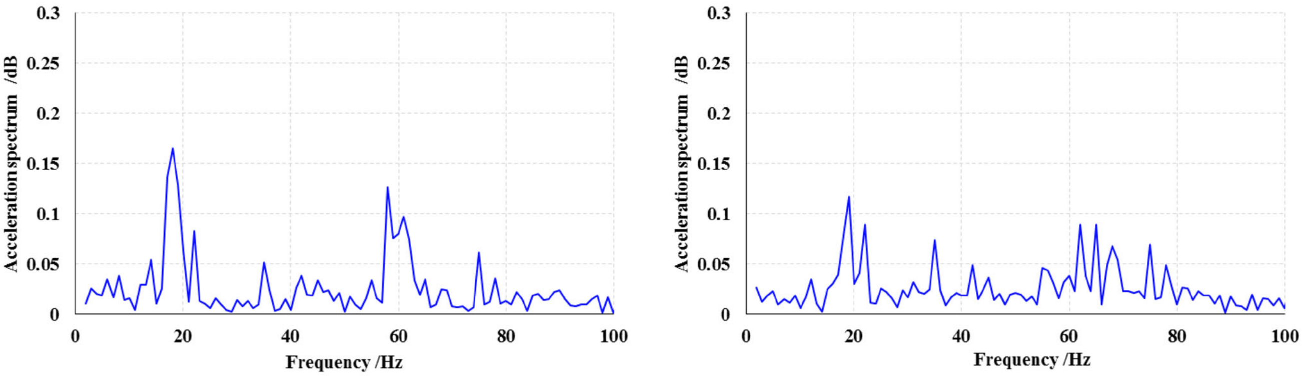
Figure 26 shows the acceleration attenuation in the depth direction: the acceleration decreases by about 20–35% at 0.5 m depth, decreases by 45–50% at 1.0 m depth, and decreases by 60–65% at 2.0 m depth. The attenuation of the acceleration is similar to that of the dynamic soil pressure, which demonstrates that the dynamic loads caused by high-speed trains have a zone of influence of about 4.0 m in depth.

The attenuation of the measured datum is similar to that at the Wuhan-Guangzhou and Beijing–Shanghai passenger lines. Similar to the dynamic soil pressure, the acceleration



(a) subgrade surface

(b) 0.5 m from the subgrade surface



(c) 1.0 m from the subgrade surface

(d) 2.0 m from the subgrade surface

Fig. 22 Acceleration spectrum at DK203+750.00 (data from 22 December 2014)

attenuation also verifies the conclusion that, when the high filled slope subgrade is supported by a reinforcing structure with sufficient strength, the transfer of acceleration is little different from that of a normal high-speed railway subgrade.

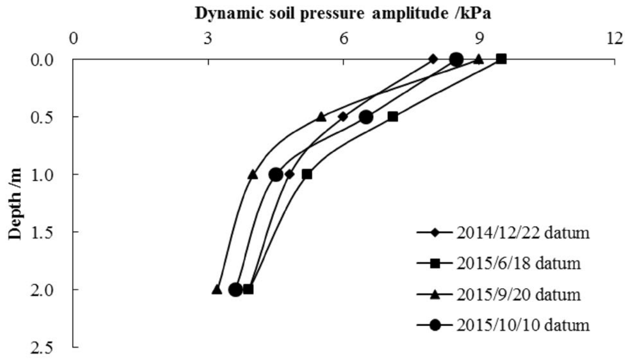
Conclusions

The real-time monitoring of subgrade structure condition is an important guarantee for the safe operation of a high-speed railway. This paper introduces the layout of the remote unmanned monitoring system for a high-speed railway in a mountainous area. Then, the system has been successfully used on the section from DK203 + 725.00 to +775.00 in Hunan Province, on the Hu-Kun passenger dedicated line. The subgrade structure state has been monitored during the static settling period, a joint debugging period, and an operational period. The main conclusions are as follows:

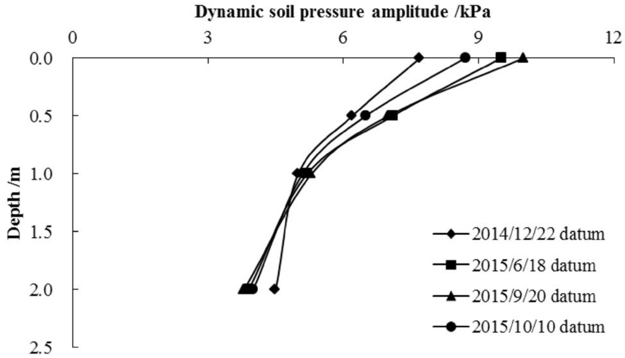
According to the characteristics of the high-speed railway engineering applied in mountainous areas, a subgrade structure state monitoring net has been completed, which includes deformation sensors, environmental monitoring sensors, and dynamic response sensors. The monitoring net can reflect the structural state of a high-speed railway subgrade in a mountainous area from several aspects such as deformation, environmental factors, and dynamic response.

The remote unmanned monitoring system must integrate both static and dynamic sensors into one system and then realise static and dynamic data acquisition, processing, and wireless transmission automatically. To solve this problem, a model including a data acquisition card, and an IPC and 3G network card has been adopted. The system can also process data dynamically to reduce data transmission amounts for economical efficiency.

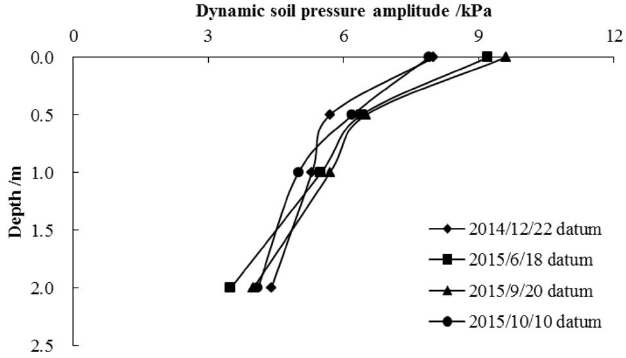
A set of control software routines has been developed in Visual C++, which includes an in situ data acquisition program and a server program. The controlling software can automatically collect, store, and process both static and dynamic data and then transmit them to the server. The server program can store, and analyse, the transmitted data for evaluating subgrade conditions.



(a) DK203+725.00



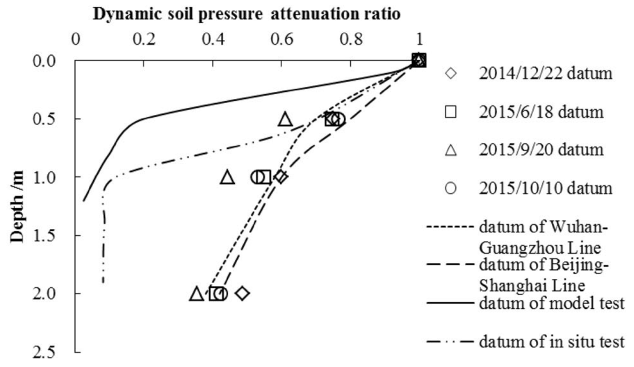
(b) DK203+750.00



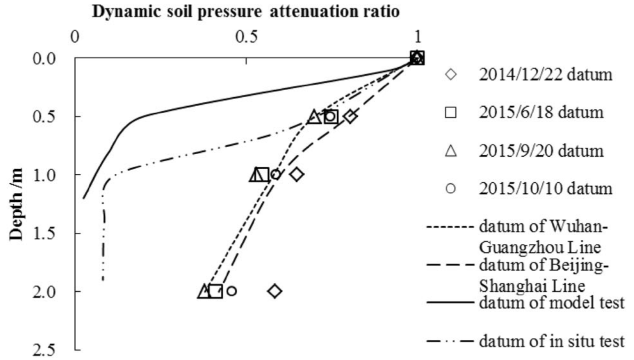
(c) DK203+775.00

Fig. 23 Dynamic soil pressure attenuation curves at different sections

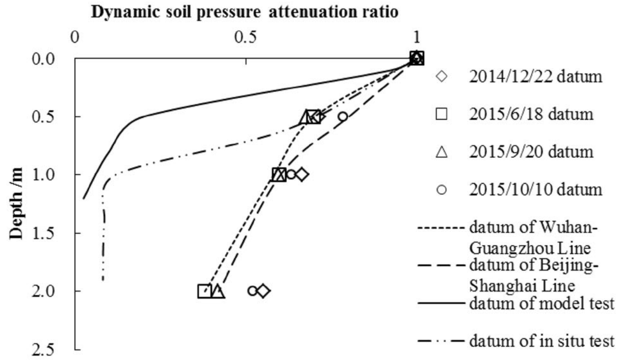
The monitoring of the section from DK203+725.00 to +775.00 shows that the deformation at the most dangerous part of the subgrade is small and the settlement and horizontal deformation of the subgrade are around 1 mm. As for the subgrade dynamic response, in nearly one year, the dynamic response of the subgrade underwent no obvious change. All the monitoring data reflect that the subgrade remained stable. Nevertheless, due to the poor geological



(a) DK203+725.00



(b) DK203+750.00

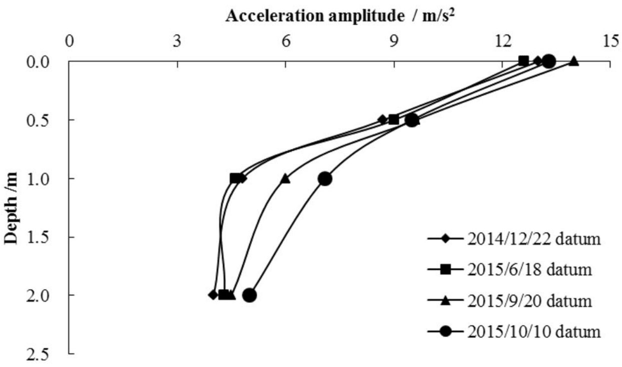


(c) DK203+775.00

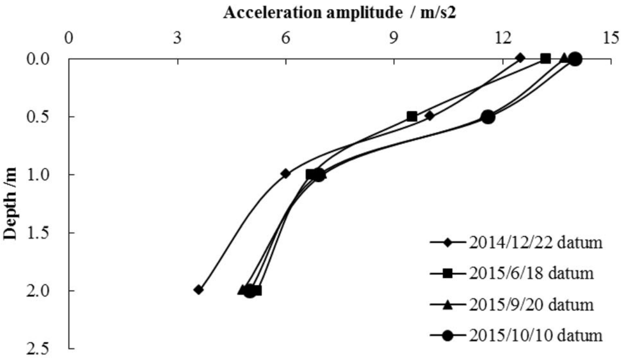
Fig. 24 Dynamic soil pressure attenuation curves at different sections

and environmental conditions, the subgrade still needs to be monitored and analysed continually.

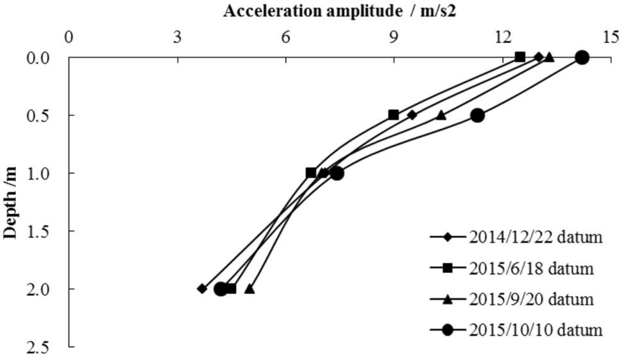
The transfer of the dynamic parameters varies little from that in the normal high-speed railway subgrades, when the high filled slope subgrade is supported by a reinforcing structure with sufficient strength. The maximum dynamic soil pressure and acceleration at the surface of the subgrade are, respectively, 8–10 kPa, and



(a) DK203+725.00

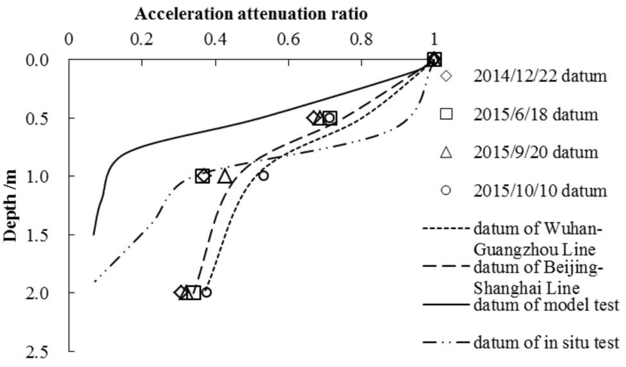


(b) DK203+750.00

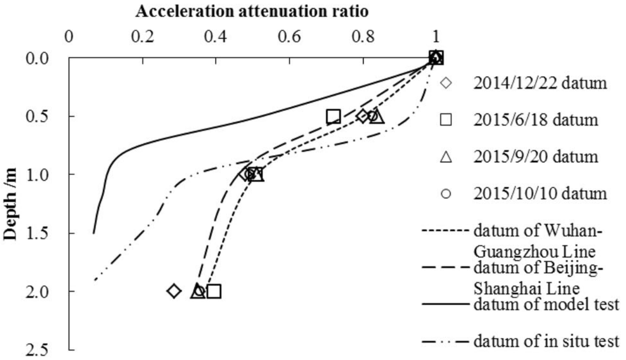


(c) DK203+775.00

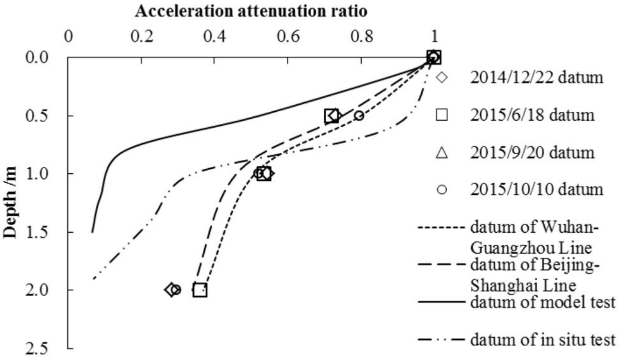
Fig. 25 Acceleration attenuation curves at different sections



(a) DK203+725.00



(b) DK203+750.00



(c) DK203+775.00

Fig. 26 Acceleration attenuation curves at different sections

12–15 m/s^2. As the depth increased, the dynamic, parameters gradually decreased. The depth of the zone of influence of the dynamic loads caused by high-speed trains is about 4.0 m.

From the spectra of the dynamic response parameters, it can be concluded that the frequencies of the high-speed train loads include two peaks: the low frequency part (below 20 Hz, focussed on 10–20 Hz) according to the dynamic loads caused by the train bogies, and the high frequency part corresponding to the dynamic loads caused by the rail irregularities, wheel scars, etc.

Acknowledgements Financial support from the Natural Science Foundation of Hubei Province (Grant No. 2015CFB363) is gratefully acknowledged.

References

Bian XC, JIANG HG, Cheng C et al (2014a) Full-scale model testing on a ballastless high-speed railway under simulated train moving loads. Soil Dyn Earthq Eng 66:368–384

Bian XC, Jiang HG, Cheng C et al (2014b) Full-scale model testing on a ballastless high-speed railway under simulated train moving loads. Soil Dyn Earthq Eng 66:368–384

Chen SX, SONG J, ZHOU QN et al (2010) Theory and practice for high-speed railway settlement and deformation observation and evaluation. China Railway Publishing House, Beijing

Feng SM, Lei XY, Zhang PF et al (2011) The remote monitoring and analysis of additional contractility from the CWR on bridge. J East China Jiaotong Univ 28(2):1–5

Feng Q, Zhang Y, Zhu N et al (2013) Design of remote rail time monitoring system based on GPRS for railway roadbed subsidence. J Geodesy Geodyn 33(3):155–157

Hashash YMA, Marulanda C, Ghaboussi J et al (2006) Novel approach to integration of numerical modeling and field observations for deep excavations. J Geotech Geoenviron Eng 132(8):1019–1031

He MC (2009) Real-time remote monitoring and forecasting system for geological disasters of landslides and its engineering application. Chin J Rock Mech Eng 28(6):1081–1090

He MC, Cui ZQ, Jiang Y, Jiang WB, Yao AJ (1999) Study on 3S engineering analysis system of the slope stability in the Three-gorges. J Eng Geol 7(2):113–117

He MC, Zhang JF, Heng CY, Mao LQ (2004) Research on critical inclination of cut slope of expansive soft rock in Yanbian region. J Liaoning Tech Univ 23(1):55–56

He MC, Tao ZG, Zhang B (2009) Application of remote monitoring technology in landslides in the Luoshan mining area. Min Sci Technol 19(5):610–614

Lei XY (2015) High speed railway track dynamics: model, algorithm and application. Science Press, Beijing

Li J (2013) On dynamic response of the red clay foundation under high-speed train loading. Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan

Nie ZH (2005) Study on vertical dynamic response of the track/subgrade in high-speed railway. Central South University, Changsha

Spencer BF, Gao Y, Yang G (2005) Distributed computing strategy for damage monitoring employing smart sensors. In: Proceedings of the Second International Conference on Structural Health Monitoring and Intelligent Infrastructure, Shenzhen, China, vol 11, pp 16–18

Wang L, Jin HH, Luo Z et al (2013) Probabilistic back analysis of slope failure—a case study in Taiwan. Comput Geotech 51:12–23

Wang L, Luo Z, Xiao J et al (2014) Probabilistic inverse analysis of excavation-induced wall and ground responses for assessing damage potential of adjacent buildings. Geotech Geol Eng 32(32):273–285

Wu K, Sheng Q, Zhang YH et al (2010) Development of real-time remote monitoring and forecasting system for geological disaster at subgrade slopes of mountainous highways and its application. Rock Soil Mech 31(11):3683–3687

Xie HC (2009) A new technology for structural health monitoring: smart sensor networks. J Sichuan Univ Sci Eng (Natural Science Edition) 22(4):1–3

Xu LK, Li SH, Liu XY et al (2007) Application of real-time telemetry technology to landslide in Tianchi Fengjie of Three Gorges. Chin J Rock Mech Eng 26(S2):4477–4483

Yang Q, Feng QB, Zhang B et al (2012) An automatic method and system for measuring and monitoring subgrade settlement using inclinometer. J Beijing Jiaotong Univ 36(6):52–56

Yang J, Feng QB, Gao Z et al (2014) On a method and system for automatically monitoring key parameters of railway subgrade. Acta Geodaetica Cartogr Sin 6:24–28

Yang X, Hou D, Tao Z et al (2015) Stability and remote real-time monitoring of the slope slide body in the Luoshan mining area. Int J Min Sci Technol 25:761–765

Ye Y, Mu QX, Zhang CP (2009) Tunnel construction multivariate information forewarning and safety management system research. Chinese J Rock Mech Eng 28(5):900–907

Zhai WM, Wei K, Song XL et al (2015) Experimental investigation into ground vibrations induced by very high speed trains on a non-ballasted track. Soil Dyn Earthq Eng 72:24–36

Zhang CP, Zhang DL, Luo JJ et al (2009) Remote monitoring system applied to the construction of metro station undercrossing existing metro tunnel. Rock Soil Mech 30(6):1861–1866

Zhang LL, Zhang J, Zhang LM et al (2010) Back analysis of slope failure with Markov chain Monte Carlo simulation. Comput Geotech 37(7–8):905–912