Development Status and Prospect of Deformation Monitoring Techniques for High-Speed Rails

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Abstract. This paper introduces the principles, technical and performance characteristics of subgrade and track deformation monitoring methods for high-speed rails such as hydrostatic leveling, hydraulic settlement gauge and track geometry car based on the subgrade and track deformation requirements for high-speed rails and the current application status in relevant engineering monitoring fields. Furthermore, development trends of the monitoring techniques are prospected.

Introduction

At present, subgrade deformation monitoring is carried out mostly for high-speed rails in China, which, according to the chronological order, has mainly experienced three stages: The first stage is from the 1960s to the 1990s, during which necessary measuring instruments were lacking due to backward technical means, and manual monitoring was mainly used. The second stage is from the 1990s to the beginning of the 21st century. With the development of communication and electronic technologies during this stage, China had developed a number of instruments suitable for railway subgrade deformation monitoring, such as observation piles, settlement plates and settlement gauges. The third stage is from the beginning of the 21st century till now. Since the entering of 21st century, China has gradually built the railway subgrade monitoring and command system suited to its national conditions, which has been developed continuously towards an integrated, intelligent direction.

Single Point Deformation Monitoring Technology

Depending on the monitoring requirements, the subgrade deformation monitoring can be classified into single point deformation monitoring and large section deformation monitoring. There are many ways of monitoring deformations, which can be classified into artificial leveling, single point displacement, hydrostatic leveling, full section plotter and hierarchical displacement meter according to different technical methods and monitoring positions.

Artificial leveling observation technology

The method by which the subgrade arching and settlement rates and changes are obtained by regular manual observation of rail elevation changes is referred to as the artificial leveling observation technology. Hierarchical embedding of plates is required on the site according to the settlement or arching observation requirements. Embedded casing is connected to the embedded plate vertical bar and then introduced to the subgrade surface, and the elevation of vertical bar is tested by specialists based on the observation frequency. The difference value of elevation of the same embedded plate vertical bar at different time periods is precisely the settlement or arching deformation at the location of the embedded plate at that time period.

The advantages of this method are simple equipment, easy observation and simple test data processing. However, the disadvantages of leveling observation are the need to specifically embed plates; besides, the casings and vertical bars introduced to the subgrade are vulnerable to damage. Once the embedded pipe is damaged, the deformation observation of corresponding section can only be terminated.
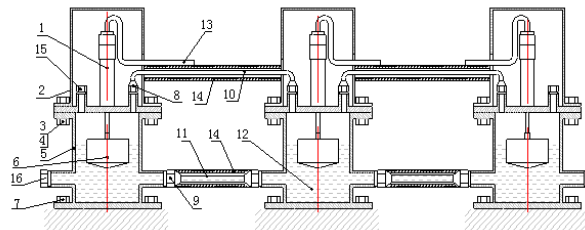
Fig. 1. Artificial leveling settlement observation

Hydrostatic leveling instrument

Hydrostatic leveling system is a precision instrument that measures the relative elevation changes between two or more points. The system is generally installed at a position equally high as the relative fixed point (bedrock), which collects data often using an integrated modular automatic measurement unit and connects to the computer via wired or wireless communication, thereby achieving automatic observation. As a high-precision online deformation monitoring system, it supports automatic network transmission.

Its basic principle is that a number of hydrostatic leveling instrument containers are connected by liquid pipe, and the liquid level of each container is measured by the magnetostrictive sensor, whose floater position changes synchronously with the changing liquid level, thereby allowing measurement of liquid level changes at various measuring points.

Hydrostatic leveling instrument determines the vertical settlement of measuring bodies primarily by measuring the liquid level. Its advantages include: high measurement precision, strong stability, low temperature resistance, etc. Its disadvantages are that due to the viscosity of liquid, the liquid inside the instrument's pipeline takes time to flow and balance, so high-speed measurement of arching and settlement changes is impossible.

1-Liquid level sensor; 2-Protective cover; 3-Nut; 4-Bolt; 5-Hydraulic cylinder; 6-Buoy;
7-Foundation bolt; 8-Gas pipe connector; 9-Liquid pipe connector; 10-Gas pipe; 11-Liquid pipe;
12-Antifreezing solution; 13-Traverse; 14-PVC wired hose; 15-Gas pipe plug; 16-Liquid pipe plug
Fig. 2. Hydrostatic leveling

Hydraulic settlement gauge

The hydraulic settlement gauge consists of stainless steel wire pressure sensor, liquid pipe, liquid storage tank, etc. that are contained in the corrosion-resistant steel cylinder. It is usually used for monitoring the settling volume at different parts of soil. The sensor housing of hydraulic settlement gauge is mounted on the base plate and connected to the reference station with a liquid-filled nylon tube with a stainless steel fitting. The liquid storage tank is set up inside the reference station, whose top is open to the atmosphere, and back higher than the installation elevation of the gauge. When the soil subsides or rises, the sensor embedded in the soil shifts accordingly. The settling volume at the gauge location can be calculated by measuring the pressure variations of pressure sensor. Its typical measurement principle is shown in Fig. 3. Since the sensor of hydraulic settlement gauge is pressure sensor, vibrating wire hydraulic settlement gauge is often used. The hydraulic sensors are largely affected by temperature, so after temperature correction, their accuracies are greatly improved.

Hierarchical displacement meter

The sensor used in the hierarchical displacement meter is designed according to the electromagnetic induction principle. When the sensor passes through the magnetic induction ring, the electromagnetic induction signal is generated and transmitted to the ground instrument to read the scale value of corresponding steel ruler on the pipe orifice mark point, which is the depth of settlement ring. Each measured value is subtracted from the previous measurement to obtain the deformation of corresponding measuring point.

The advantages of hierarchical displacement meter are high degree of automatic testing, easy automatic monitoring and ability to test displacements at different depth positions of foundation. The disadvantage is poor accuracy of hierarchical settlement observation, which can only reach ± 0.5 mm.

Fig. 3. Hierarchical displacement meter

Large Section Settlement Deformation Monitoring Technology

Subgrade is a large long structure filled directly with granular mixtures, where inhomogeneous deformation is produced in the length direction under the long-term gravity stress or unfavorable geological conditions, thus affecting the long-term service status of high-speed rail superstructure to impact the train operation safety. Therefore, long-term large section deformation is also an important aspect of high-speed rail deformation monitoring.

Intelligent station settlement deformation monitoring system

The intelligent station settlement monitoring system developed by China Academy of Railway Sciences offers the automatic leveling, automatic control, intelligent learning and automatic measuring techniques on the basis of total station. After measuring equipment fixation and automatic leveling, the system automatically search targets and performs elevation conversion based on the distance and angle measurements to achieve long section, multi-point and multi-time automatic measurement, thereby improving the measurement efficiency.

Fig. 6. Schematic diagram of intelligent station settlement deformation monitoring system

Its advantages are simple and easy operation, significantly faster measurement than traditional methods and implementation of automatic monitoring which conventional total station cannot achieve. The disadvantages are that the measuring instrument needs to be permanently fixed, observation prisms need to be arranged on the site, and the cost is slightly high.

INSAR railway deformation monitoring technology

Developed in the late 1960s, InSAR is a technique which utilizes the phase information of synthetic aperture radar (SAR) to extract the surface 3D information and elevation change information. It is now widely used for obtaining ground undulating information. During designing of high-speed rails, the appropriate track data are selected according to the line location, monitoring accuracy and SAR image coverage area, while D-InSAR and PS techniques are used for data processing and correlation analysis.
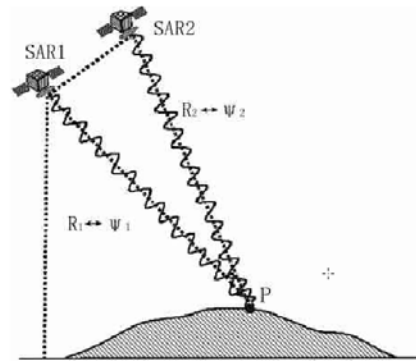
Fig. 4. Fundamental principle of InSARS system

The use of D-InSAR for ground settlement monitoring has many advantages: large scale data acquisition, high spatial resolution, relatively low cost, etc. More than 10 years of surface deformation can be monitored just using dozens of site images, which saves the time and cost of arranging permanent ground GPS observation station and laying out the leveling instrument, yet the precision is almost the same as these two measurement techniques.

Track geometry detector

The track geometry detectors at home and abroad are mainly classified into the relative track geometry detectors and the absolute track geometry detectors. Relative track geometry detector is a track detection device that analyzes the relative changes in the design parameters between monitoring points based on the observed data and makes track adjustment in the absence of external reference. Absolute track geometry detector is a track detection device that can identify the absolute position of track center aside from being able to detect the gauge, superelevation, cross level, versine, alignment, profile, twist and mileage in the presence of external reference.

Fig. 5. Composition of track geometry detector

Track geometry detector can reduce the workload and equipment investment for track fine tuning and can greatly improve the later fine tuning progress of long tracks to shorten the schedule. Nevertheless, surveyors are required to have the knowledge on track detector, in order to properly use the track detector for track smoothness evaluation. The short skylight time of high-speed rails also limits the use of track detectors.

High-speed comprehensive inspection train

High-speed comprehensive inspection train, with high-speed EMUs as the carrier, is installed with track detection, pantograph-catenary detection, wheel-rail dynamics detection, communication detection, signal detection and other sophisticated measurement equipment, which integrates advanced technologies such as modern measurement, space-time positioning synchronization, large-capacity data exchange, real-time image recognition and data synthesis and can perform constant velocity detection on the tracks, catenaries, communications, signals and other infrastructure states during high-speed operation. Thus, it is an important technical equipment for improving the detection efficiency of railway infrastructure, for guiding the site maintenance and repair, and for ensuring the safety of train operation.

Fig. 6. High-speed comprehensive inspection train

As an important technical equipment for dynamic detection of infrastructure, the high-speed comprehensive inspection train can improve the detection efficiency of high-speed railway infrastructure. The detection data can reflect the subgrade deformation information to guide maintenance and repair. Its manufacturing and maintenance costs are much higher than the general means of monitoring.

Conclusion

With the advance of science and technology and the development and maturing of monitoring technology, many new measuring means have been invented and used constantly. Its development trend is the combination of new technical means with the existing commonly used measurement methods. For example, the measuring distance of no prism ranging total station has increased greatly after the use of infrared laser technology, which has even exceeded 1 km; automatic tracking and alidade total station has been able to execute automatic tracking for 24 hours and does not require manual maintenance; new total station combining digital technology with total station not only allows object localization, but also enables object photogrammetry; and optical fiber sensing detection technology has cut a striking figure in the large section high-precision subgrade and slope deformations.

Firstly, a variety of sensors, automatic tracking total stations and digital close-range photogrammetry are gaining increasingly wide applications, which are developing towards a continuous, efficient, automated and dynamic monitoring direction as well. Secondly, the space-time sampling rate of deformation monitoring is greatly improved, and the data obtained is more abundant. Thirdly, data processing and analysis are developing towards a more automated, systematic and networked direction, with particular emphasis on the forecasting model research. It is thus clear that the development prospect of digital signal processing technology is very broad, and relevant scope of application is also expanding. High-speed rail deformation monitoring will continue to be an important, long-standing research topic.

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