A Remote Subgrade Settlement Monitoring System Based on Optical Method

Jianye Xu¹ · Xin Li² · Jing Yang³ · Yan Gao⁴ · Sijin Wu²

Received: 27 July 2019 / Revised: 27 August 2019 / Accepted: 29 August 2019 / Published online: 9 September 2019
© The Author(s) 2019

Abstract Monitoring of subgrade settlement in railway and highway helps to maintain traffic safety and reduce infrastructure losses. When an excess subgrade settlement is detected, maintenances of the unqualified subgrade will be processed in time, and early warning of constructions will be processed to prevent the occurrence of safety accident. In this article, a noncontact, real-time, and unattended system based on optical method is introduced to monitor the subgrade settlement remotely. Several high-power infrared LED targets are mounted on the subgrade and they will move as the subgrade subsides. The movements of the LED targets are detected by an optical detection device based on the principle of optical imaging. The displacement data is remotely transmitted to a server for analysis via GPRS. The remote monitoring system has been applied to the monitoring of subgrade settlement of Zhensheng highway in Guizhou province of China in 2014. This technology helped to detect the subgrade settlement that was caused by the construction of Beiyinpo railway tunnel. Four test points on road surface were monitored at a sampling rate every 20 minutes. The effectiveness of the system has been verified by the practical application.

Keywords Subgrade settlement · Remote monitoring · Optical sensor · Optical image processing · High-power infrared LED · Railway · Highway

1 Introduction

As an important part of railway and highway, subgrade plays a key role in traffic safety, efficiency and comfort. Problems of subgrade may cause serious traffic accident and property loss. Subgrade settlement is one of the widespread subgrade problems, which is often generated due to dynamic loading, embankment weight, saturated fine-grained soils, groundwater drawdown, ground loss, and construction in the vicinity [1–3]. Excessive and differential subgrade settlement can damage tracks or pavements and even raise personal safety concerns. For railways, especially the high-speed railways, the over-limit subgrade settlement can lead to track irregularity and train derailment [4]. For urban tracks, especially subways built on soft soil, excessive and uneven subsidence will have a significant impact on structure waterproofing and safe driving [5]. For highway, the uneven deformation of the subgrade may apply a large additional stress on the pavement structure and then result in early damage to the pavement structure [6]. When the settlement after the construction of the highway subgrade exceeds the safety range of 4–7%, it will cause large roughness of the pavement and thus hazard the safe driving. Therefore, real-time monitoring of the subgrade settlement and timely alarm when the settlement exceeds the limit is of great significance for maintaining traffic safety and reducing property damage. In addition, the monitoring data also aids in the accurate prediction of the future subgrade settlement [7, 8].

Various subgrade settlement monitoring methods and systems have been introduced. The most common and easy

✉ Sijin Wu
swu@bistu.edu.cn

¹ Guizhou Transportation Planning Survey and Design Academe Co. Ltd, Guiyang 550081, China

² School of Instrumentation Science and Opto-electronics Engineering, Beijing Information Science and Technology University, Beijing 100192, China

³ Key Laboratory of Luminescence and Optical Information of Ministry of Education, Beijing Jiaotong University, Beijing 100044, China

⁴ Linda Liu & Partners, Beijing 100013, China

Communicated by Baoming Han.

method is the use of electronic total station [9, 10]. However, it is not recommended for long-term monitoring due to time consuming and manual operation. Other commonly used methods, such as observation pile and settlement plate, suffer the similar problem. The automatic monitoring can be realized by using electronic sensors. For example, automatic monitoring of subgrade settlement can be realized by using multiple highly sensitive pressure sensors to detect the differential of fluid pressure in different places [11, 12] or using an inclinometer to sense the incline caused by the subgrade settlement [13]. Optical fiber sensors, such as fiber Bragg grating, are also competitive candidates for remote monitoring of the subgrade settlement, but they are susceptible to ambient interference, especially temperature fluctuation [14, 15]. In recent years, novel methods, such as satellite differential interferometric synthetic aperture radar technology, have been tried in practice, but only used in a limited number of operational applications [16].

In 2013, we proposed a new optical method for remote monitoring of subgrade settlement [17]. Multi-point measurement was also carried out by using a nose-to-tail arrangement with which the transmission of measurement error is not easy to be avoided. In this article, a remote subgrade settlement monitoring system based on similar principle but with different arrangements is introduced. The composition of the system and the features of key parts are described in detail. The successful application of the system in the real-time remote monitoring of settlement in subgrade adjacent to the Beiyinpo tunnel in Guizhou province of China verifies the effectiveness of the system.

2 Remote Monitoring System Based on Optical Method

2.1 System Composition

The remote monitoring system, depicted in Fig. 1, mainly consists of a detection device, several LED targets, and a server. The LED targets, with high-power infrared LED

Fig. 1 Remote Subgrade Settlement Monitoring System composition

point light sources on their front surfaces, are mounted on the ground surface of the points under test. The subsidence of the ground surface caused by the subgrade settlement yields the vertical movements of the LED targets. These movements are tracked by the detection device which is fixed on a reference pile. The principle of target detection will be discussed in Sect. 2.2. The sampling frequency can be modified to meet the engineering requirement. The monitoring data is packaged and then transmitted to the server via GPRS and internet. Authorized users can access this data through the software installed on a network user terminal such as a computer and a cell phone. An alarm signal will be sent to the users whenever over-limit settlement data is detected.

2.2 Principle of Detection

The key function of the remote monitoring system is the precision detection of the movement of LED targets. This is fulfilled based on the object–image relationship between the infrared LED point light sources on the LED targets and the detection device. The detection device consists of several independent imaging units. Each unit consists of a fixed-focus image lens and a linear CCD which works as an image detector. Each imaging unit of the detection device tracks the movement of each point LED. The imaging relationship between a point LED and imaging unit of the detector device is illustrated in Fig. 2. When the point LED moves from point A to point B, its image on the linear CCD is correspondingly moved from A' to B'. The displacement of the point LED is indicated by h , and the movement of its image is identified as h' . The object distance s represents the distance between the point LED and the image lens while the image distance s' indicates the distance between the image lens and the linear CCD. Based on the Gaussian imaging formula, the object–image relationship can be expressed by

Fig. 2 Diagram of the relationship between the detected movement and the record on image

$$h = \left(\frac{s}{f} - 1 \right) h' = \frac{h'}{\beta} \quad (1)$$

where f is the focal length of the imaging lens and $\beta = f/(s - f)$ is the horizontal magnification. The horizontal magnification of each pair of imaging unit and LED target is definitive during the monitoring, so the settlement will be measured after the displacement of the image point is determined.

The horizontal magnification can be automatically determined by using an in situ self-calibration method. Besides the infrared LED for displacement detection, a pair of visible LED point light sources is symmetrically located on both sides of the infrared LED for displacement detection with a precisely calibrated distance between the two visible LEDs. In calibration mode, these two visible LEDs are turned on and their images are captured by the detection device. Taking into account the distance between the two visible LEDs as h and the distance between their images as h' , the horizontal magnification β can be calculated according to Eq. (1).

From Eq. (1), it can be found that the measurement error of subgrade settlement is related to the errors in the determinations of the horizontal magnification and the image displacement. The relationship is described as

$$\varepsilon_h = \frac{1}{\beta} \varepsilon_{h'} - \frac{h'}{\beta^2} \varepsilon_\beta \quad (2)$$

where ε_h is the total error of measurement, $\varepsilon_{h'}$ is the error of the measurement of image movement, and ε_β is the error in the determination of the horizontal magnification. The error of the measurement of image movement is mostly caused by the irregularity of the image, the noise in CCD sampling, and the spatial resolution of CCD sampling. The irregularity of the image and the noise of CCD sampling lead to the difficulty in the determination of image position, while the spatial resolution of CCD sampling allows the presence of a minimum quantization error. In the presented method, these errors related to the measurement of image movement are minimized by the use of a weighted centroid algorithm in the determination of image position. The weighted centroid algorithm is a sub-pixel algorithm that can minimize the error of image positioning to a large extent. The error in the determination of the horizontal magnification is divided into two parts, the miscalibration of the horizontal magnification and the change in the horizontal magnification over time. The former is mainly related to the error in the determination of the distance between the pair of visible LED point light sources for calibration and the error of image positioning. The latter is mainly caused by the fluctuation of ambient temperature and can be minimized greatly by the optimized structure of the image units.

3 An Application of the Remote Monitoring System

In July of 2014, the remote monitoring system was utilized to monitor the subgrade settlement of Zhensheng highway (mileage: K2106 + 750) which is a highway in service in Guizhou Province in China. By applying the Remote Subgrade Settlement Monitoring System, Zhensheng highway (mileage: K2106 + 750) was detected subgrade settlement and furtherly found that the subgrade settlement was caused by the excavation of Beiyinpo railway tunnel in Guizhou province. The railway tunnel runs under the highway subgrade, with a relatively high difference of 18.4 m from its vault to the highway subgrade and a cross angle of 22°. Tunnel excavation would cause highway subgrade settlement, so it was necessary to detect the settlement in real time during and after the tunnel construction period, in order to prevent traffic safety accidents caused by excessive settlement of subgrade.

The layout of monitoring of highway subgrade settlement is illustrated in Fig. 3. Four locations above the tunnel were selected as the test points on which the LED targets were mounted. The reference point was located in a place far away from the tunnel. The geology surrounding the reference point was stable, so it stayed away from the impact of the tunnel construction. A large steel pipe was piled underground at the reference point as a reference pile. The detection device was mounted on the reference pile. The photograph of the real layout is shown in Fig. 4.

The distances between the test points and the reference point were 27.00 m, 59.88 m, 50.96 m, and 71.53 m, respectively. In conventional imaging systems, such large object distances produce a very small horizontal magnification which will decrease the measurement sensitivity. In the remote monitoring system, a specially designed telephoto lens with a focal length of 400 mm was used to increase the measurement sensitivity. According to the Gaussian imaging formula, the image distances, indicated by s' in Fig. 2, were 469.6 mm, 428.6 mm, 434.1 mm, and 423.7 mm, respectively. Such long imaging distances made the detection device large in size, and its structure was prone to be deformed when ambient temperature fluctuated, so an optimized design of structure and material was executed to improve the anti-deformation capability of the detection device.

Due to the requirement of 24-h weatherproof monitoring in the field, the ability to resist ambient light interference was also a key consideration. Since infrared light has high penetration in rain and fog days and does not interfere with the normal driving of the car driver, it was chosen as the light to be detected during the monitoring. A high-power infrared LED (SFH4750, Osram Opto Semiconductors)

Fig. 3 Layout of subgrade settlement monitoring **Fig. 4** Photograph of the remote monitoring system, including (a) the detection device at the reference point and (b) the four LED targets at the test points

with a centroid wavelength of 850 nm and a maximum total radiant flux of 3.5 W was used to emit near-infrared light. A pulse width modulation (PWM) with a duty factor of 1:1200 (flashing every 20 min for 1 s) put the LED in pulse operating mode, aiming at the reduction in power consumption of the LED targets powered by batteries. In the detection device side, high-sensitivity CCDs (TCD1103GFG, Toshiba) with a typical sensitivity of 79 V/lx•s were used as the image detectors. Such CCDs, along with specially designed large-aperture lenses, ensured that faint infrared LED light from a distance can be detected. The large CCD cells made the imaging alignment easy. Bandpass spectral filters were inserted into the optical paths to minimize the influence of ambient light. An automatic background subtraction method [17] was used to remove the background noise, improving its adaptability to changes in the intensity of ambient light.

A GPRS (general packet radio service) based data wireless transmission unit (EIC-CG16, Beijing Eastcent Technology Co., Ltd.) was utilized for the data

communication. The detected data was packaged and then sent to the internet via the GPRS channel which is an ideal channel for data communication in the field. This data was accessed and processed by a remote end device, a personal computer on which an independently developed data processing software was running. The function of data processing mainly included three parts, data conversion, invalid data culling, and data averaging. The original data was the values of pixel number. Owing to the use of sub-pixel algorithm, the pixel number values with two significant numbers after the decimal point were obtained. This data was then converted to the amount of the subgrade settlement in millimeters. Abnormal data, generated mainly by vehicle blocking, was culled. The median of the rest of the monitoring data at each point in each day was plotted to show the historical change in the subgrade settlement. The software alerted when the data was out of limit. Figure 5 shows the subgrade settlement at test point C from July 6th to 21st when the tunnel construction continued intermittently.

Fig. 5 Cumulative amount of settlement at test point C

4 Conclusion

A remote monitoring system based on optical method is introduced to monitor subgrade settlement. The system has the advantages of high-resolution detection, easy installation, and low cost. The system is suitable for different applications, including the monitoring of subgrade of high-speed railway, subway, light rail, highway, and so on. It can also be used during or after the subgrade construction, even when the railway or highway is in service.

Owing to its low cost and the use of GPRS communication, the remote monitoring system can be widely used in different places for monitoring of subgrade settlement, forming an extensive monitoring network. The data from this monitoring network can be used for alert and the investigation of the geological conditions.

The remote monitoring system was successfully utilized in the monitoring of subgrade settlement of Zhensheng highway (mileage: K2106 + 750) in Guizhou Province of China, in that case four test points on the road surface with space intervals of 20 m ~ 80 m were monitored and recorded every 20 minutes. The resolution of monitoring was up to submillimeter level. The monitoring lasted 15 days and covered the entire tunnel excavation process.

Acknowledgements The work is supported by the Qin Xin Talents Cultivation Program, Beijing Information Science and Technology University (QXTCP B201702), and the Science and Technology Plan of Beijing Municipal Education Commission (KM201911232019).

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Li D, Selig ET (1995) Evaluation of railway subgrade problems. In: Transportation Research Record 1489, TRB, National Research Council, Washington, DC, pp 17–25
- Soeung S, Lee SH, Lee SJ, Kim BJ, Yune CY (2018) Causing factors of additional settlement in high-speed railways in Korea. *KSCE J Civ Eng* 22(10):3843–3851
- Jeon SS, Park YK, Eum KY (2018) Stability assessment of roadbed affected by ground subsidence adjacent to urban railways. *Nat Hazards Earth Syst Sci* 18:2261–2271
- Cao Y, Qu J (2017) Influence of subgrade differential settlement on riding performance of high-speed train. In: Recent developments in railway track and transportation engineering, pp 121–132
- Li G, Huang T, Xi G, Jiang M, Zhang D (2011) Review of researches on settlement monitoring of metro tunnels in soft soil during operation period. *J Hohai Univ (Nat Sci)* 39(3):277–284
- Du Q, Zhang X, Li Y, Liu Y, Zhang L (2017) Effect on the stresses and strains within pavements due to uneven settlements of subgrade. In: 2nd international conference on new energy and renewable resources, Guangzhou, China, June 24–25, pp 155–159
- Li Y, Leng W, Nie R, Mei H, Zhou S, Dong J (2019) A combined prediction model for subgrade settlement based on improved set pair analysis. *Math Probl Eng* 2019:1064246
- Gao H, Song Q, Jun H (2016) Subgrade settlement prediction based on least square support vector regression and real-coded quantum evolutionary algorithm. *Int J Grid Distrib Comput* 9(7):83–90
- Qiu D, Liang Q, Li Q, Wu R (2009) Safety monitoring information system of urban subway. In: 2009 WASE international conference on information engineering, Taiyuan, China, July 10–11, pp 426–428
- Yang P (2009) Application of total station instrument in engineering deformation monitoring. *J Gansu Sci* 21(1):125–128
- Zhang Y, Du Y, Sun B, Liang J (2013) High-speed railway ballastless track roadbed settlement monitoring method based on fluid pressure differential. *J Beijing Jiaotong Univ* 37(1):80–84
- Dong H, Tang L, Wu P (2017) Improved design scheme for the automatic monitoring system of settlement. *Adv Eng Res* 86:136–138
- Yang J, Feng Q, Zhang B, Cui J (2012) An automatic method and system for measuring and monitoring subgrade settlement using inclinometer. *J Beijing Jiaotong Univ* 36(6):52–56
- Ye XY, Ni YQ, Yin JH (2013) Safety monitoring of railway tunnel construction using FBG sensing technology. *Adv Struct Eng* 16(8):1401–1409
- Wang X, Wu L, Zhou Y, Wang Y (2015) The long-term settlement deformation automatic monitoring system for the Chinese high-speed railway. *Shock Vib* 2015:147972
- Tan Q, Xie C (2012) Comparison and analysis of permafrost railway subgrade settlement deformation monitoring. *Mech Mater* 226–228:1651–1654
- Yang J, Feng Q (2013) A new method for measuring subgrade in high-speed railway by using a linear CCD. *Measurement* 46(5):1751–1756