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Experimental research on daily deformation monitoring of steel box girder bridge based on BDS/GPS①

Chen Jian(陈 健), Yue Dongjie②, Liu Zhiqiang, Zhu Shaolin, Chen Hao
(School of Earth Science and Engineering, Hohai University, Nanjing 211100, P. R. China)

Abstract

In order to investigate the feasibility of BDS/GPS in the deformation monitoring of long-span bridges, analysis and research on aspects like number of visible satellites, PDOP value and monitoring precision are carried out. To analyze daily deformation characteristics of steel box girder bridge, observation data for 48 consecutive hours is computed by self-programmed software. Experiment results show that the monitoring-points on the bridge demonstrate obvious periodicity and recoverability in vertical and horizontal directions, meanwhile, changes in the elevation direction are relatively stable. The deformation-monitoring results of BDS/GPS combination system and GPS single system show good consistency. However, in a complex environment of the bridge, especially under the condition that satellite signals are severely affected, the advantages of BDS/GPS combination over GPS single system are more obvious.

Key words: dynamic deformation monitoring, BDS/GPS, baseline solution, daily repeatability, long-span bridge

0 Introduction

The long-span bridge has long been affected by traffic loads, wind force, temperature changes as well as external factors like earthquakes and ship collision during operation, therefore it would be distorted in structure. Through grasping the scope and trend of bridge structure deformation timely by monitoring the deformation of bridge structures during operation, the safety and reliability of bridge structures could be assessed and safety warning could also be given, which is of great significance to guarantee the bridge's safe operation[1,2].

With the development of GPS technology, the sampling rate of its receiver can generally reach up to 10 – 20Hz, and the positioning precision can reach the millimeter level. Therefore, its distinct advantages in the monitoring of bridge are shown. Compared with other deformation monitoring methods in bridge engineering, GPS measuring holds characteristics such as high precision, all-weather, and real-time dynamic. What's more, it could provide exact three-dimensional deformation information, which can grasp the overall bridge state[3]. Therefore, domestic and overseas scholars have carried out a lot of experiments. Xu[4], et al. used the PPP (precise point position) technology to process short period GPS signals, with the horizontal direction measurement accuracy reaching 2 – 4mm and the vertical direction accuracy better than 10mm. Yigit[5], et al. adopted an experimental method to evaluate the performance of PPP technology. By comparing the results of the accelerometer with the GPS double difference technique, it is pointed out that with the PPP technique, the amplitude of structural vibration could reach to 1 – 2cm. Meng[6], et al. utilized the short baseline method to analyze the error characteristics of GPS static measurement. It was found that the GPS measurement error changed with the daily cycle of the star, and after being filtered by the adaptive filter, the measurement error of GPS measurement signal could reach the millimeter level. Roberts[7], et al. used the adaptive filtering (AF) method to monitor the processing of GPS data, and it was identified that vibration displacement of the main bridge beam could reach millimeter level.

Beidou Navigation Satellite System (BDS) is a global satellite navigation system which is self-developed and implemented independently by China. At present, with the dense networking of Beidou, the nav-

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② To whom correspondence should be addressed. E-mail: yuedongjie@163.com
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igation accuracy and positioning continuity, reliability and stability are gradually increasing. The function and advantages of BDS are becoming increasingly prominent[8-10]. Many researchers at home and abroad have carried out in-depth research on the measurement accuracy of BDS. Yang[11], et al. collected receiver data based on Beijing area, and elaborately evaluated the visibility, PDOP value, the accuracy of ranging code and carrier phase observation value, single point positioning, the differential positioning of ranging code and carrier phase in the BDS service area. Xiao[12], et al. conducted experiment and improved the algorithm, in a result that in the experimental area, the calculation precision of BDS short baseline was within 1mm in horizontal direction, and that was less than 2mm in elevation direction. According to the study by Shi[13], et al., it showed that the satellite performance and ranging accuracy of the Beidou second generation system were basically the same as those of GPS, yet with little research on the application of BDS in bridge deformation detection. It is of great significance to carry out related research on bridge health inspection on the basis of BDS and then build a bridge exterior detection system based on it through making full use of the BDS resources.

In this paper, the BDS/GPS combination system is used to monitor the key parts of the bridge for 48h continuously. The dynamic deformation regularity and daily repeatability of steel box girder bridge during 24h of a single day were analyzed so as to evaluate the self-recovery ability of the bridge's short-term static deformation. What's more, the feasibility, accuracy and reliability of BDS system are assessed in monitoring the deformation of large cable-stayed bridges.

1 Date acquisition

The distribution of base points and monitoring points on Sutong Bridge is shown in Fig. 1. In this paper, the dual-base station strategy is adopted, where horizontal control network Base01 on Sutong Bridge is selected as the main base station and Base02 as the auxiliary base station. Base01 is 1.1km away from the south end of the main bridge and 3.3km from the north end. Base02 is 1.4km away from the south end of the main bridge and 3.4km from the north end. Both Base01 and Base02 are not more than 3.5km away from all monitoring points. The baseline solution can theoretically meet the requirements of the monitoring accuracy of 5mm, and the dual-base station can ensure the reliability of the monitoring results. The horizontal height angle 10 ° above Base01 and Base02 has no obvious barriers, with relatively stable geology and away from electromagnetic interference sources.

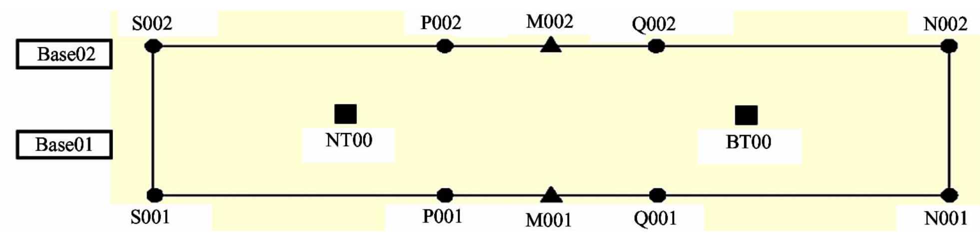


Fig. 1 The base station and monitoring points of Sutong Bridge

Fig. 2 Field data collection of the monitoring points

BDS/GPS receivers and antennas are installed at all base points and monitoring points (as shown in Fig. 2), and the data sampling frequency at all receivers was uniformly set as 1s. In addition, the satellite cutoff elevation was set to be 15°. Data were collected during the period from 8:00 December 20, 2017 to 8:00 December 22, 2017 of the local time.

2 Processing and analysis of monitoring data

2.1 Availability analysis and data quality assessment of BDS satellite at bridge site

2.1.1 Assessment on the continuous availability of BDS positioning on complex bridges

The observation data of M002 on December 21, 2017 is analyzed. It can be seen from Fig. 3 and Fig. 4 that the BDS/GPS combination system increases the number of satellites and reduces PDOP value compared with BDS single system and GPS single system, which has effectively improved the observation precision. At the same time, there are nine visible satellites from the BDS at bridge site, which is equivalent to the number of GPS satellites. However, the PDOP value of Beidou shall be greater than that of GPS mostly because BDS at present mainly utilizes GEO/I-GSO which mainly covers the Asia-Pacific region, whose monitoring station distribution is relatively inferior to that of GPS. In Fig. 4, there is a large jitter in the Beidou PDOP value

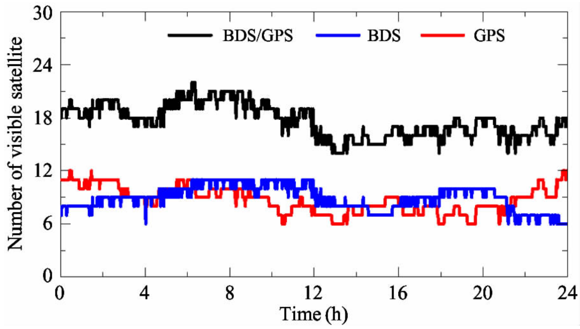


Fig. 3 Number of visible satellites

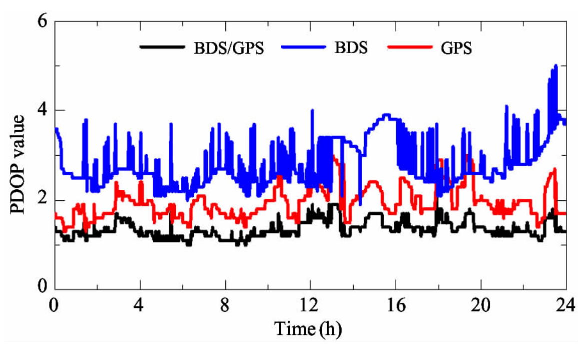


Fig. 4 PDOP value

mainly because all IGSOs at corresponding time are in the south of the observation site.

2.1.2 BDS observation data quality assessment under complex bridge environment

In order to analyze the environmental factors affecting the satellite quality around the monitoring points, the multipath effect of the observation and signal-to-noise ratio of BDS are evaluated. In BDS measurement, there would always be multipath effect error. The pseudo-range multipath error can be estimated through simultaneous transformation of carrier phase observations and pseudo-range observations:

$$
\begin{aligned}
MP1 &= P_1 - \frac{f_1^2 + f_2^2}{f_1^2 - f_2^2}\lambda_1\varphi_1 + \frac{2f_2^2}{f_1^2 - f_2^2}\lambda_2\varphi_2 + N_{P1} \\
MP2 &= P_2 - \frac{2f_1^2}{f_1^2 - f_2^2}\lambda_1\varphi_1 + \frac{f_1^2 + f_2^2}{f_1^2 - f_2^2}\lambda_2\varphi_2 + N_{P2}
\end{aligned} \tag{1}
$$

where, f_1 and f_2 are the frequencies of carrier phase observations, φ_1 and φ_2 refer to carrier phase observations, P_1 and P_2 mean the pseudo-range observations, N_{P1} and N_{P2} are ambiguities of the two combinations, $MP1$ and $MP2$ refer to the multipath errors on P_1 and P_2 pseudo-range. It can be learned from Eq. (1) that the multipath error is determined by both the ambiguities of carrier phase observations and pseudo-range observations. By taking the average of multiple calendars of a satellite cycle, and then subtracted by the sequence of the ambiguity parameters, the pseudo-range MP sequence is obtained, and thus pseudo-range errors could be extracted.

Signal-to-noise ratio (SNR) is the ratio between signal power P and noise power N, which is used to describe performance of functional modes:

$$SNR = 10\log_{10}\frac{P}{N}(\text{dB}) \tag{2}$$

SNR can better reflect the quality of satellite signals, and the SNR value will change correspondingly when the multipath effect occurs. The higher the SNR, the better corresponding signal quality and the higher the observation accuracy.

In order to analyze the data quality of BDS system on bridge, C01 satellite of Beidou GEO, C06 satellite of Beidou IGSO and C14 satellite of Beidou MEO are compared and analyzed, where the above represents the C/A code observation, and the below indicates the $P1$ code observation. Fig. 5 shows the relationship among multipath errors of observation data, SRN and satellite elevations at M002.

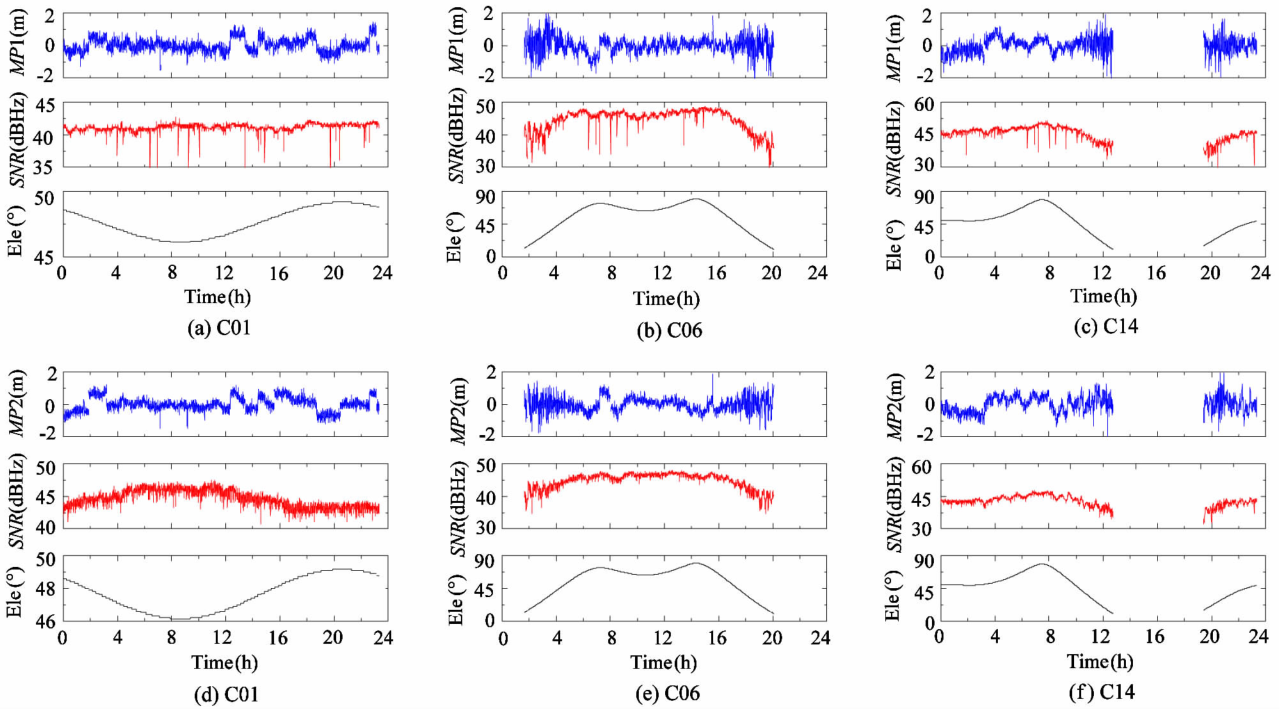


Fig. 5 The relationship among multipath errors of observation data *SRN* and satellite elevation angles at M002

Fig. 5 shows that Beidou C01 satellite can realize continuous tracing in 24 hours. Except for C01 satellite, the multipath effect of both C06 and C14 satellites demonstrates the decreasing trend with the increase of elevation angle, while all their *SNR* shows the apparently-increasing trend with the increase of elevation angle. Theoretically, the multipath and *SNR* of C01 satellite should be in a stable state, but in the actual bridge, the *MP* value and *SNR* value of a satellite are both fluctuated because of the influences of traffic jam and water surfaces. Due to space limitations, other constellations of BDS share the similar results.

2.2 Analysis on monitoring results

For the field data at all BDS/GPS monitoring points of the main bridge and data of Base01and Base02, the period of time is set as 15mins each, and the baselines formed by base stations and all monitoring points are respectively calculated with unqualified baseline eliminated. The baseline fixed solution is taken for calculation and the calculation process is shown in Fig. 6. The base station coordinates are combined with the baseline data to calculate the ITRF2008 coordinates of all monitoring points. In order to ensure the reliability of the monitoring results, the mean value

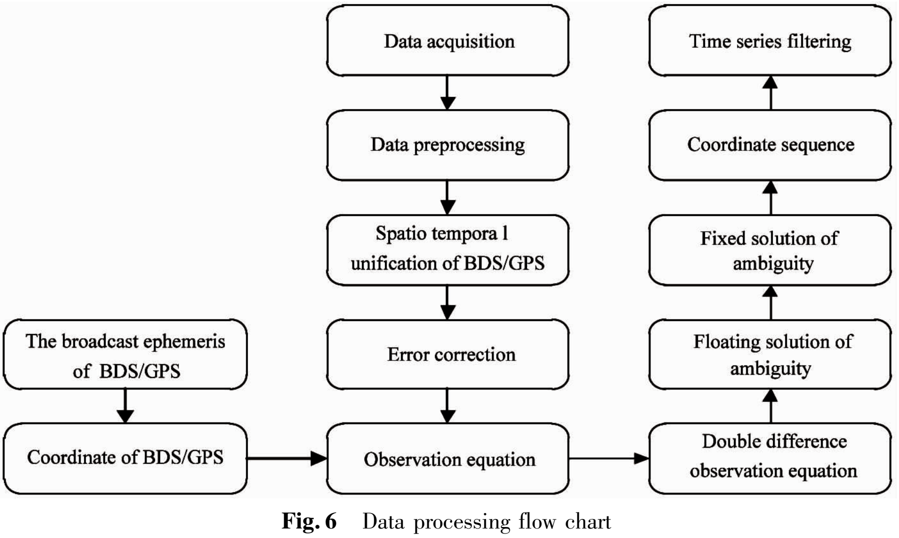


Fig. 6 Data processing flow chart

of the monitoring points coordinates of Base01 and Base02 of the base station are taken as the results of the ITRF2008 coordinate of the monitoring points and then converted into the axle coordinates of the bridge, where dx represents the vertical direction of the bridge, while dy refers to the horizontal direction. Geodetic elevation is adopted to indicate the changes of monitoring points in elevation direction.

2.2.1 Analysis on the dynamic deformation monitoring results of the main bridge based on BDS/GPS combination system

In order to facilitate the analysis, selected reference values are deduced from the coordinate values of each monitoring point to reflect the change amplitude of the monitoring points over time. For the baseline of vertical and horizontal positions of bridge axle, the average position from eight to nine on December 20, 2017 is select as the benchmark. For geodetic height datum, the mean value of the geodetic height of all observation values is regarded as the benchmark. Fig. 7 – Fig. 13 demonstrate the daily deformation of south end (S002), north end (N002), south 1/4 cross (P002), north 1/4 cross (Q002), mid-span (M002), north cable tower (BT00) and southern cable tower (NT00) of upper reaches of the main bridge.

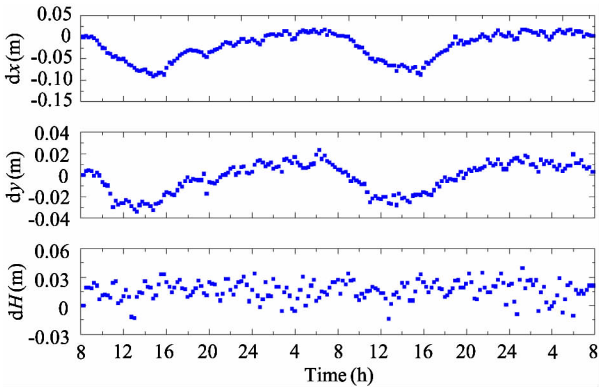


Fig. 7 Daily deformation at S002

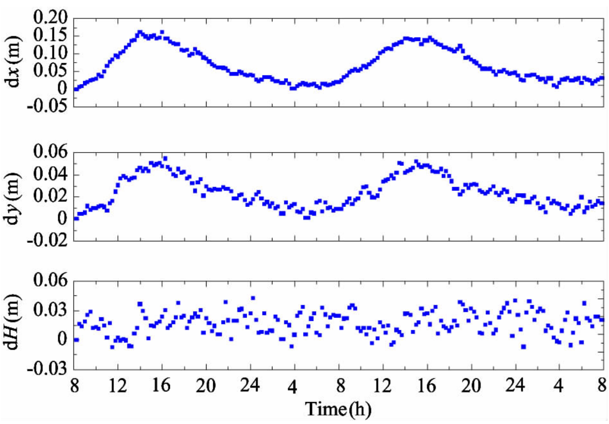


Fig. 8 Daily deformation at N002

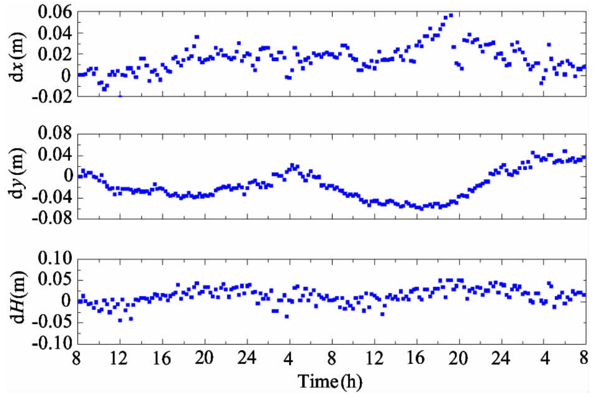


Fig. 9 Daily deformation at P002

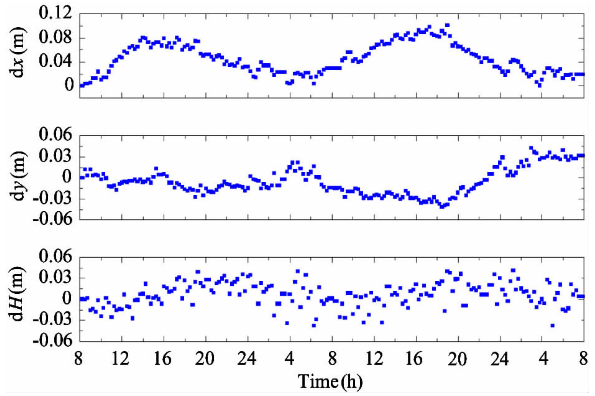


Fig. 10 Daily deformation at Q002

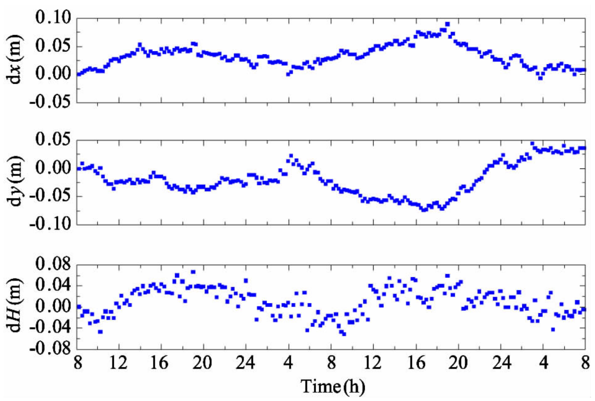


Fig. 11 Daily deformation at M002

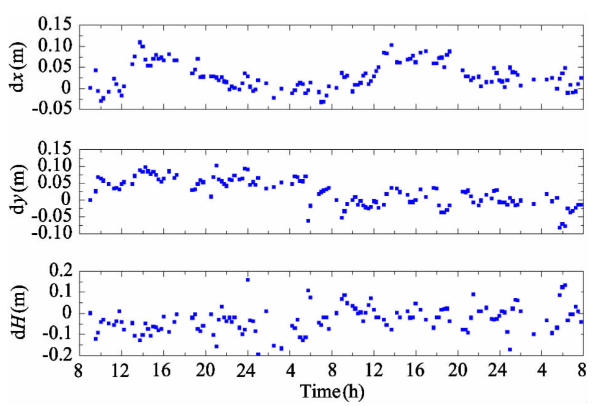


Fig. 12 Daily deformation at BT00

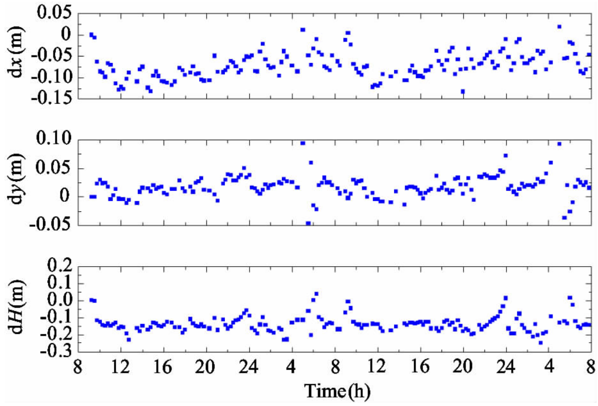


Fig. 13 Daily deformation at NT00

From Fig. 7 to Fig. 13, it can be obtained that:

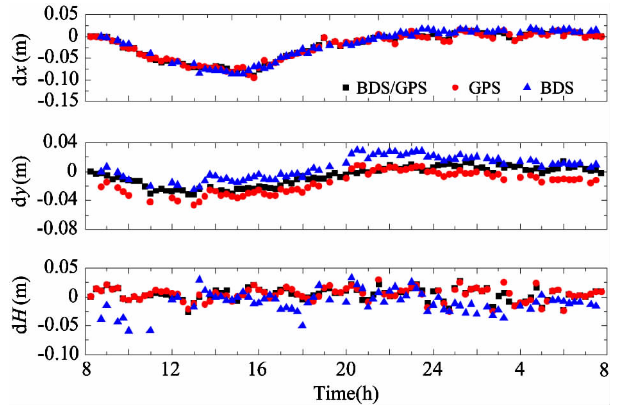
1) On the vertical and horizontal directions, S002, N002, M002, P002 and Q002 of the bridge all show obvious daily periodicity and recoverability, mainly because of the influences of sunshine and temperature on the steel box girder. As the direction of sun changes, the temperature of the sunny side of the steel box girder is getting higher than the back face side. This temperature differences will cause faster expanding of the steel plate on the sunny side and inducing large torsional deformations of the bridge. As time goes on, the direction of the sunshine changes periodically. Monitoring points in the elevation direction are relatively stable.

2) The vertical direction of the BT00 shows daily periodicity, while the daily periodicity of the vertical and horizontal directions of the NT00 and the vertical daily periodicity of the BT00 are not significant. The main reason is that the antenna placement is overshadowed by the concrete wall, which leads to the instability of the BDS/GPS signal receiving. Monitoring points in the elevation direction are relatively stable too.

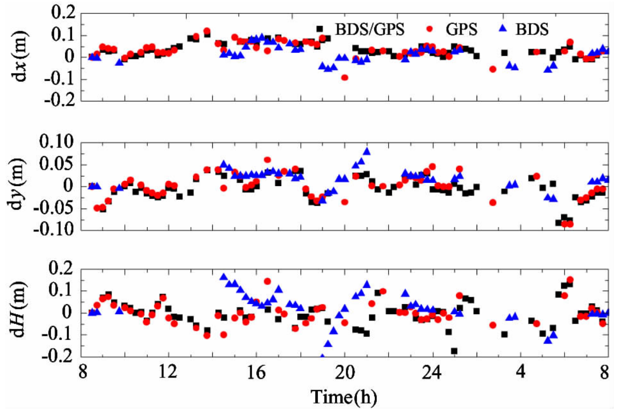
2.2.2 Comparison of monitoring results on BDS/GPS, GPS and BDS

The monitoring experiment adopts three schemes: BDS/GPS combination, GPS single system, BDS single system. The observation data from 8:00 December 21 to 8:00 December 22 is calculated, and the results are shown in Fig. 14 (Due to space limitations, N002 and BT00 are taken as the example).

As can be seen from Fig. 14, the test results of BDS/GPS combination system have a good consistency with those of the GPS single system, while the results of BDS single system are consistent only at certain period, and the number of periods with effective solution is reduced obviously. Fig. 15 demonstrates a comparative diagram of the number of periods with effective solution of the three schemes in a single day. It can be seen that the number of the effective periods of BDS/GPS combination system is equivalent to that of GPS single system. Except for the north cable tower and south cable tower, where the number of the effective periods of BDS/GPS effective period is more than 93%, that of the BDS single system is only 83% (N002), and the minimum is 12% (BT00).



(a) N002



(b) BT00

Fig. 14 Comparison of BDS, GPS, BDS/GPS results

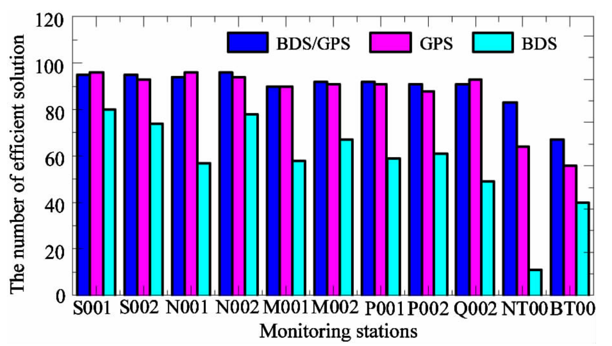


Fig. 15 Comparison of the number of single day periods with effective solution of BDS, GPS, BDS/GPS

As the two sides of the positions where BDS/GPS antenna of the south cable tower and north cable tower are both overshadowed by concrete walls, satellite signal reception is seriously affected by the environment.

At this point, the advantages of BDS/GPS combination system for deformation monitoring are significant. In addition, at other monitoring points where the satellite signal reception is in good condition, the calculation results of the BDS/GPS combination system and the GPS single system are quite similar. For the BDS single system, the number of orbiting satellites is small, as restricted by this, the number of periods at each point used for effective calculation is significantly less, compared with the previous two schemes.

3 Conclusions

The feasibility and reliability of the current monitoring model based on BDS/GPS technology are verified by experiments. It can comprehensively reflect the overall synchronous deformation of the key parts on the main bridge. Through experimental data, this paper analyzes the daily deformation characteristics of steel gird bridge. The following conclusions can be drawn.

1) BDS/GPS positioning enriches the data resources and improves the geometrical structure of spatial distribution of the satellites as well as the positioning performance of BDS/GPS.

2) When the number and geometry of satellites are in good condition, the monitoring results of BDS single system are in agreement with the results of the GPS single system and BDS/GPS combination system. However, currently, with the limitation of BDS's number of satellites in orbit, the effective solution time available for BDS single system is significantly reduced. With speeding up of the BDS's networking process bridge monitoring based on BDS single system will be realized gradually and advance the development of satellite navigation technology in our country into a new stage.

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Chen Jian, born in 1993. He received his M. S. degree from Anhui University of Science and Technology in 2016. His research interests include GNSS precise positioning, bridge deformation monitoring.