Sensors and Materials, Vol. 38, No. 8 (2026) 4817–4832
MYU Tokyo

S & M 4595

Research and Application of Key Technologies for Precision Construction Survey of Superhigh-rise Buildings

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(Received July 26, 2024; accepted June 18, 2026)

Keywords: Beidou GNSS, superhigh-rise building, precise control survey, deformation measurement

Traditional measurement technologies cannot meet the construction requirements of superhigh-rise complex structures owing to the characteristics and difficulties of superhigh-rise construction projects. In this study, we develop new instrumentation and propose an automatic high-precision elevation transfer methodology for supertall buildings taking into consideration the characteristics and challenges of supertall building engineering and through a comprehensive review of construction measurement techniques for supertall buildings in China. Combined with several new technologies, such as precise Beidou global navigation satellite system (GNSS) measurement, Beidou GNSS positioning technology, an intelligent total station, and high-quality and high-precision measurement benchmarks, precise construction control points, and fast and high-precision monitoring points are obtained. The integration of Beidou GNSS technology into superhigh-rise building construction monitoring is a major innovation of precise engineering measurement and has broad application prospects.

1. Introduction

In the process of China's rapid economic development, skyscrapers have sprung up like mushrooms. The higher the building, the greater the challenge of measurement work.(1–3) At present, the traditional measurement methods in the construction of superhigh-rise buildings include elevation and plane control methods. The elevation control method is the steel ruler direct measurement or suspension steel ruler method. However, cumulative error cannot be avoided, many manpower and material resources are consumed, and economic benefits are poor. The plane control method adopts the laser lead direct casting point method. With the increase in the total height of the building, the laser divergence angle also increases and is transmitted in sections resulting in error accumulation. The complex and changeable environment at high altitudes affects the stability of the structure. When the height of the building reaches more than 500 m, new measurement methods must be explored to meet construction needs.(4–9) The construction measurement technology of some large foreign projects has been monopolized, and the field technology of domestic superhigh-rise building construction is not mature, so there is

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https://doi.org/10.18494/SAM5254

ISSN 0914-4935 © MYU K.K.
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no reference. By reviewing the literature, we found that the current measurement methods for superhigh buildings are difficult to apply to transmitting the axis and controlling the height of superhigh buildings, the verticality of the tower control, and unique shapes of superhigh buildings.[10–15] Therefore, considering the characteristics of superhigh-rise building engineering, in this study, we aim to establish a strict engineering measurement system, the innovative use of Beidou-compatible Beidou GNSS/GLONASS satellite positioning technology, superhigh-rise elevation precision control measurement technology, Beidou GNSS precision swing return measurement technology, and the design of superhigh-rise structure delay data deformation measurement technology to ensure the smooth construction of superhigh-rise buildings and the safety verification of engineering structures.

2. Materials and Methods

2.1 Study area

The study area is a plot located in the central area of Futian District, Shenzhen, surrounded by Yitian Road, Fuhua Road, Center Road 2, and 5 Fuhua Road. The surrounding buildings are dense, and there are high-end shopping malls and residential and office areas with dense populations. The north Linfuhua Road of the study area is a 60-m-wide two-way six-lane municipal trunk road. Yitian Road on the east side is a two-way eight-lane municipal trunk road with a width of about 60 m. Under Yitian Road is the Guangzhou–Shenzhen–Hong Kong high-speed railway, the shield section of which has not yet been constructed. Owing to the construction of the Guangzhou–Shenzhen–Hong Kong high-speed railway, the local roads are closed; the central second road on the west side is a municipal road of about 20 m width, and Metro Line 1 operates on the north side of Fuhua Road. An image of the study area is shown in Fig. 1.

Fig. 1. (color online) Map of study area.

2.2 Study ideas and methods

Given the characteristics and difficulties of superhigh-rise building engineering, an innovative rigorous engineering measurement system combined with precision Beidou GNSS measurement, an intelligent total station, and other new technologies should be established for engineering survey general control and building control networks. To this end, the following ideas are pursued in this study: the development of a "superhigh-elevation and high-precision automatic transfer process method" combined with the Beidou GNSS positioning technique; the design of a "laser electronic total station photographic receiving device" and other utility model patents; accurate elevation measurement benchmarks for buildings; the adoptation of the small-angle steel ruler method and external deformation monitoring; rapid problem-solving methods to obtain delayed component design pretuning data; the provision of technical support for construction safety; the adoption of a self-developed Beidou-compatible Beidou GNSS and a fixed base station based on a Beidou-compatible receiver; the completion of the axis of high-precision vertical transmission; the use of the high-precision single calendar solution algorithm of a double base station of a Beidou compatible receiver; the determination of the self-vibration frequency of a building; the determination of the deformation of the height and plane of superhigh-rise buildings along with the temperature difference between day and night; the management of the construction with self-correction in accordance with the measured deformation value and swing situation of a building; and the confirmation of the verticality of a building.

2.2.1 Beidou-compatible GNSS/GLONASS satellite positioning technology—new vertical transmission technology for superhigh-rise buildings

Taking the characteristics of the engineering structure into consideration, a high-precision Beidou GNSS measurement general control network was established during the process of engineering construction, and the vertical survey technology of the traditional construction measurement reference point was innovated. The Beidou GNSS receiver suitable for engineering was developed independently of Beidou compatibility along with a new algorithm to provide an accurate measurement baseline for engineering construction. The 10 Hz sampling rate and the Beidou-compatible Beidou GNSS receiver were used in this experiment.[6] A special anti-multipath antenna, which can work all day long, was used to improve the performance of the antenna and more effectively suppress the multipath interference signal.

We carried out the measurements using the plane control network, jointly tested the set reference point and the construction reference point or the urban control point in the field area, and conducted static observations for no less than 48 h. After the fieldwork, we downloaded the observation data promptly and solved the baseline to test the synchronous loop closure, the asynchronous loop closure, and the repeated baseline. For observation data involving large residuals and frequent cycle slips, we excluded problematic satellites and truncated valid time intervals to ensure the accuracy and reliability of baseline solutions. The data processing is shown in Fig. 2.

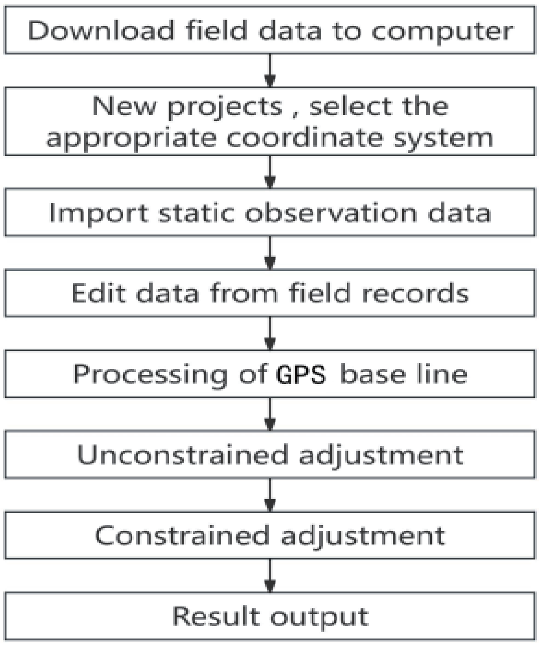


Fig. 2. Data processing.

2.2.2 Superhigh-elevation precision control measurement technology

Owing to the limitations of traditional elevation control technology and combined with engineering characteristics, we developed an automatic transmission method with high precision to fulfill the need for high-precision and rapid vertical height transfer in supertall buildings. We monitored steel columns and corrected the elevation transmission in real time using Beidou GNSS technology to solve the worldwide problem of elevation transmission.

2.2.2.1 Superhigh-elevation and high-precision automatic transfer process method

A superhigh-rise elevation high-precision automatic transfer method can solve the shortcomings of traditional elevation transfer methods. This method is not limited by the building height, and data can be directly and rapidly passed from the same reference point with high-precision instrument reading using special software for data processing, thereby eliminating artificial and cumulative errors.

Firstly, the forced centering device is set at the position of the bottom transfer elevation, and the laser electronic total station is set up on the bolt on the forced centering device. From the temperature and barometer measurements, the laser electronic total station is corrected and set, and the initial value of the laser electronic total station instrument is obtained. Secondly, the telescope of the laser electronic total station is pointed to the zenith (the screen value is 0°), and the support of the photographic receiver is placed at the reserved hole. Thirdly, the laser electronic total station is used for ranging at four positions of 0°, 90°, 180°, and 270°. The laser receiver records the position of the laser point for each position, and the vertical alignment distance d_i from the laser electronic total station to the photographic receiver is obtained. Finally, after obtaining the vertical distance from the laser electronic total station to the laser receiver, a level instrument is set up. The level staff reading a_i is taken and input to the computer, and the program automatically calculates the elevation reading b_i of the level staff at the working layer's +1.000 m elevation point.

Through the above steps, the calculation formula of the b_i reading at the 1.000 m elevation level is

$$b_i = \mathrm{a}_1 + d_i + K + a_i - H_i. \quad (1)$$

In the formula, K is the height difference between the laser receiver and the base transfer point on its mounting device, which is a predetermined constant obtained through prior testing; H_i is the elevation of the +1.000 m datum point at the working level.

2.2.2.2 Beidou GNSS elevation checking technique

To verify the accuracy of the transmission elevation, the Beidou GNSS static positioning technology is used to check the transmission elevation after a certain stage of building construction.[9] Shenzhen has built the CORS network. 1) A control point from the Shenzhen Metro system, located in the mangrove park approximately 4 km southwest of the Ping An International Finance Center, was selected as Monitoring Benchmark No. 1 (HSL01). Within the construction site of the Ping An International Finance Center, a monitoring pillar was established on the roof of the supervision building's second floor as Benchmark No. 2 (XMB02).. The overall arrangement is shown in Fig. 3 below. 2) The location of the building ± 0.000 is copied and tested with the reference point to obtain the altitude of ±0.000. 3) The heights derived from GNSS observations are ellipsoidal heights. Since a height anomaly exists between the ellipsoidal

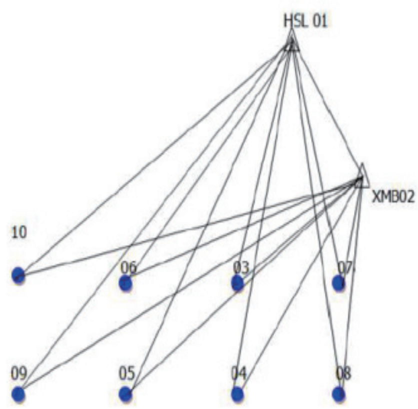


Fig. 3. (color online) Triangular mesh.

height and the quasi-geoid, it is necessary to resolve the height anomaly in the vicinity of the project. 4) The elevation of base point 2 is determined by the leveling method, followed by the determination of the elevation anomaly of point 2. Because point 2 is on the construction site, the elevation anomaly value of point 2 is the elevation anomaly near the project. At the roof point, the high altitude is obtained by height-anomaly correction. The elevation of ±0.000 points is subtracted from the elevation of the roof to determine the building height.

2.2.3 Beidou GNSS high-precision swing centering measurement technology

(1) Monitoring benchmark

We employed the same technology as that for Beidou GNSS elevation.

(2) Monitoring point layout

Five observations were expected for a 48 h period at a sampling rate of 10 Hz and a cutoff height angle of 10°.(10) Each measurement operation was accompanied by the simultaneous recording of meteorological parameters, including temperature and wind speed, and coupled with the execution of one accelerometer measurement.

(3) Calculating data

1) Process the datum point coordinates

The reference points for all the processing data are HSL 01 and XMB 02, which are the key to determining the calculation accuracy and stability of all data, in the second 60 h data. The data from Beijing, Lhasa, Wuhan, Taiwan, and other IGS stations are selected at the same time through G AMIT analysis for joint calculation. The geocentric coordinates in the two reference stations of the WGS system are known starting coordinates projected to the 500 m plane.

2) New baseline static algorithm based on a fixed dual base station

During the monitoring test, the test environment was still under construction and was complex with scattered scaffoldings and cement pump pipes, and welding tasks and crane operations interferred with the receiving satellite signals. Moreover, the number of satellites detected at each monitoring point was different. Even when using Beidou-/GPS-compatible reception, the requirements of eight points with the same five satellites still could not be met, Therefore, the two reference points with known edges were used to calculate the coordinates of the monitoring points. Using the reference stations HSL01 and XMB02 together with each monitoring point, eight triangles were formed. The coordinate increment closure errors of these triangles were checked in the X, Y, and Z directions, yielding a total of 264 results. The triangular mesh is shown in Fig. 3.

Static multi-baseline software was used to set the baseline. After processing the data, the synchronous closure difference and the coordinates of each triangle in the X, Y, and Z directions were determined, and then the leveling difference was processed.

3. Results

3.1 Application and results of BDS-compatible GNSS/GLONASS for vertical measurement transfer in supertall buildings

On the basis of the actual site conditions and aforementioned factors, the control network was established in two tiers. A Grade I traverse was surveyed and underwent rigorous adjustment, with four benchmark points verified. The results of this verification served as the plane control network for the site area. This control network, as illustrated in Fig. 4, was rechecked every six months.

The control points for the Grade II structural plane control network were located in open spaces within the site and on the top surface of the primary support system. Since these points were in close proximity to the building's foundation pit (some were directly installed on the primary support), they were significantly affected by pit deformation. Therefore, they were re-surveyed monthly. Additionally, on the basis of the foundation pit monitoring report, a comprehensive analysis was conducted. When substantial displacement was observed, the survey frequency was increased.

The verification of the control network for various axes at the working level was carried out using GNSS RTK technology. A GNSS receiver was set up at the GNSS reference point as a base station to directly collect coordinates of the transferred axis control points. These coordinates

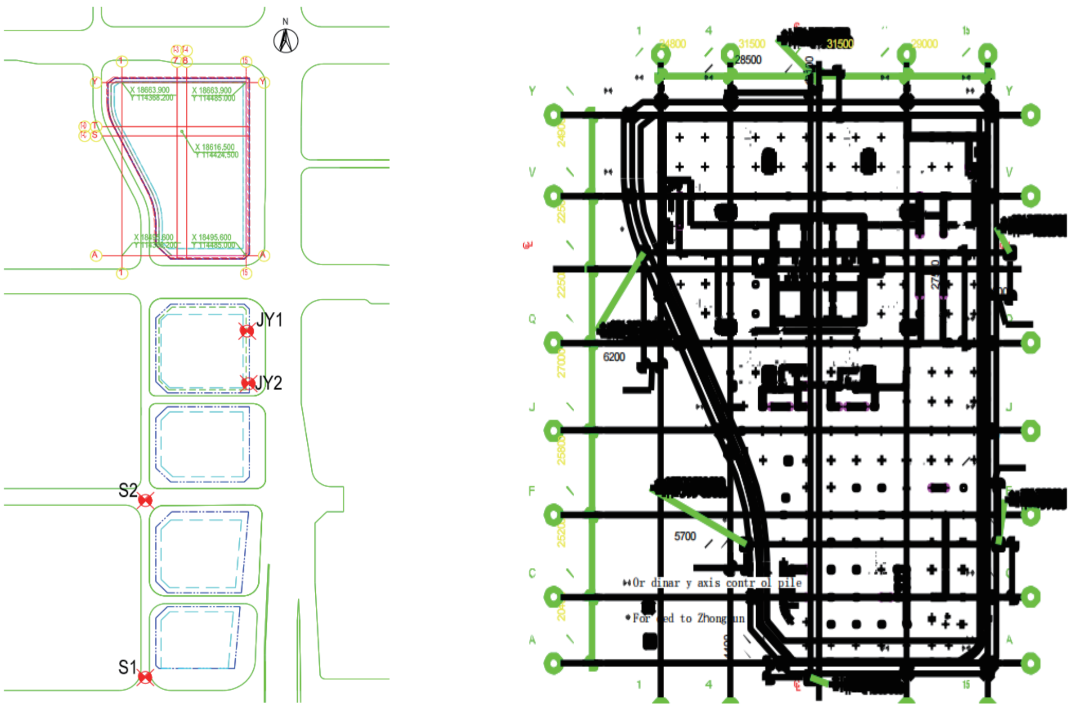


Fig. 4. (color online) Grade I structural plane control network.

were then compared with their theoretical values. Alternatively, the relative distances between points at the construction level were measured using a steel tape measure. The reliability of the results was verified from the outcomes obtained from these methods.

3.2 Precision control measurement results of superhigh-elevation structures

The derivation formula is as follows:

$$H_i = \mathrm{a}_1 + d_i + K + a_i - b_i, \tag{2}$$

where K is the height difference between the laser receiver and the base transfer point (a constant), determined in advance through testing, and H_i is the elevation of the operation layer at the +1.000 m elevation point.

Let the reading errors of a_1, a_i, and b_i be m_L, and take the error of the constant K to be m_K. Considering the deviation θ, the actual distance is $d = d_i{\cdot}\cos\theta$.

$$m_H^2 = 3m_L^2 + m_K^2 + \cos^2\theta \cdot m_d^2 + \frac{d_i^2 \sin^2\theta \cdot m_\theta^2}{\rho} \tag{3}$$

Assuming that the total station resolution V is 30 and the distance D is 20 m, $m_L = \frac{60''}{V} \cdot \frac{D}{\rho} = 0.19$ mm.

The quantity error of the constant K is assumed to be $m_K = 1$ mm.

Assuming that the nominal accuracy of the instrument is 1″, 1 mm + 1 ppm, and since θ is small, $\sin\theta \approx 0$, $\cos\theta \approx 1$. Then, $m_H^2 = 3m_L^2 + m_K^2 + \cos^2\theta \cdot m_d^2 + \frac{d_i^2 \sin^2\theta \cdot m_\theta^2}{\rho}$, $m_H = \pm 1.46$ mm.

Reading of the leveling specification: the accidental errors of the elevation difference of the second, third, and fourth leveling measurements were ±1.0, ±3.0, and ±5.0 mm, and the accidental errors of the one-way observation were ±1.4, ±4.2, and ± 7.1 mm. From the calculated data in this paper, the accuracy requirements of Grade II leveling were met, so the scheme was considered feasible.

Taking the data of the first calculation as an example, the average height of the building was 555.6324 m. According to the synchronous deformation monitoring data, the foundation and compression of the building were both 4 cm, that is, the measured elevation of satellite positioning was 555.632 m + 0.04 m = 555.672 m. The measured elevation by satellite positioning and the design elevation differed by 555.672 m − 555.676 m = −4 mm. The measured height of the building was only 4 mm different from the designed height, which verified the correctness and feasibility of the high-precision automatic transfer technology for superhigh-rise elevation and the preadjustment technology of the compression deformation of steel columns.

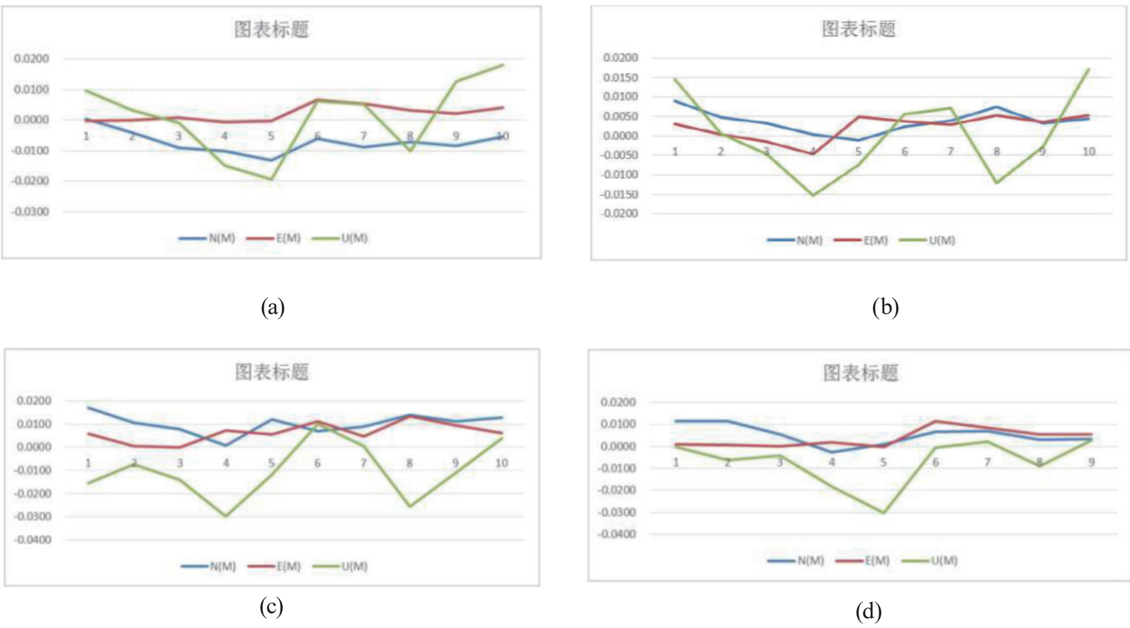
3.3 High-precision swing return measurement results of Beidou GNSS

3.3.1 Deformation of the building by daytime and nighttime temperatures

The N, E, and U coordinates calculated at different times (10–16, 16, 20–20, 10–10) are plotted in Fig. 5. A 3 cm deformation of the building was caused by the difference between daytime and nighttime temperatures. The plane deformation was small on the millimeter order.

Phases 3 and 2 were measured at the same point, and only two 500-ton damping units were added (see Table 1 for the changes in point location coordinates).

It can be seen from Table 1 that the *X* value of the eight points on the roof is smaller, the maximum change is 0.0367 m, the minimum change is 0.0204 m, and the average change is 0.029 m. The *Y* value is basically unchanged and the *Z* value is larger.



(a) (b) (c) (d)

Fig. 5. (color online) Diurnal variation curves of N, E, and U components for each point.

Table 1
Point changes in phases 2 and 3.

	dx (m)	*dy* (m)	*dz* (m)
03	−0.0358	0.0052	0.0034
04	−0.0367	0.0002	0.0243
05	−0.0326	0.0005	0.0089
06	−0.0218	−0.0030	0.0173
07	−0.0204	0.0094	0.0355
08	−0.0233	0.0006	0.0215
09	−0.0286	0.0035	0.0151
10	−0.0328	0.0062	0.0279

3.3.2 Overall deformation trend of the building

The multifrequency observation value of the three systems was detected and repaired by the cycle slip method, and the double-difference solution was found to resolve cycle-slip ambiguity. Then, the sequential leveling method was used to find the epoch solution.[11] Figure 6 shows the results of the single-epoch E and N direction calculations at No. 4 point.

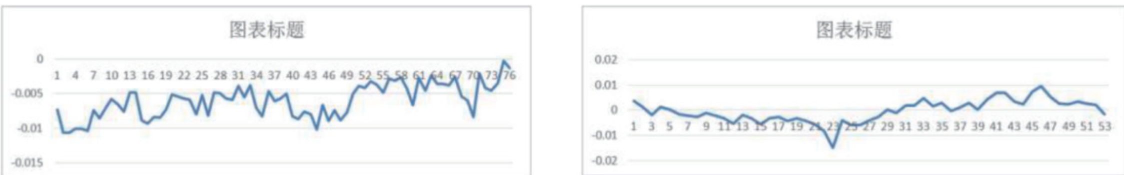
According to the basic principle of wavelet transform, the low-frequency coefficient reconstruction provides the overall deformation trend of the three directions of the building, as shown in Fig. 7.

3.3.3 Oscillation amplitude

Owing to the four points observed in phase 4, the sampling time was 24 h, and the sampling rate was 10 Hz, that is, the sampling data in 1 h was 36000 calendars, and the amount of observation data is very large. Taking PA04-01 points as an example, the *X* and *Y* coordinates of 400 points were taken to draw the time course curve diagram, and the results are shown in Fig. 8.

Similarly, taking PA05-02 points as an example, the *X* and *Y* coordinates of 700 points were taken to draw the time course curve, and the results are as shown in Fig. 9.

As can be seen from Figs. 8 and 9, the *X* direction is ± 1.5 cm and the *Y* direction is ± 3 cm. Centering correction of the building is performed using the swing amplitudes in the X and *Y* directions.



(a) (b)

Fig. 6. (color online) Results of single-epoch (a) E and (b) N direction calculations at No. 4 point.

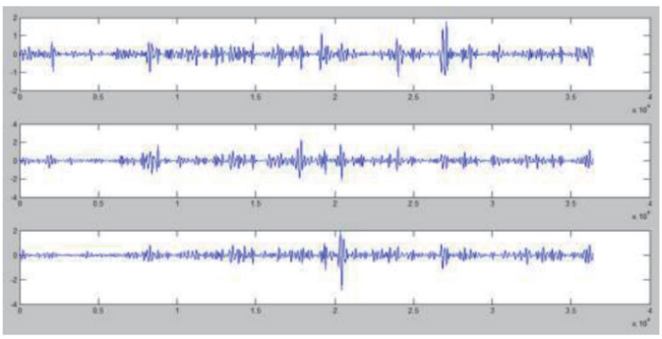
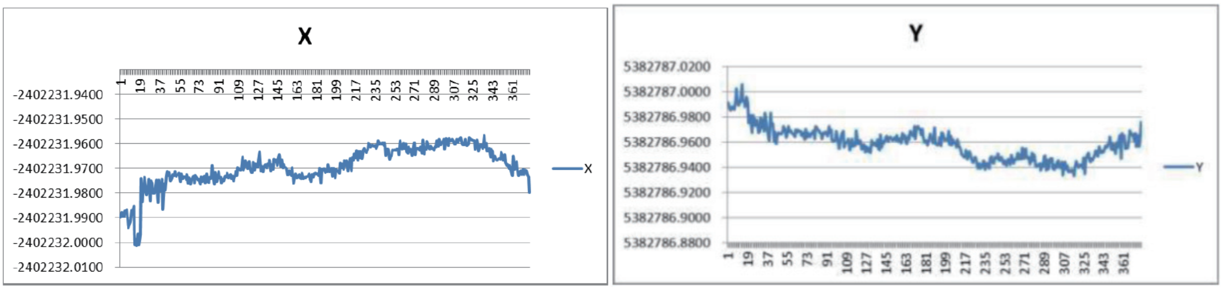
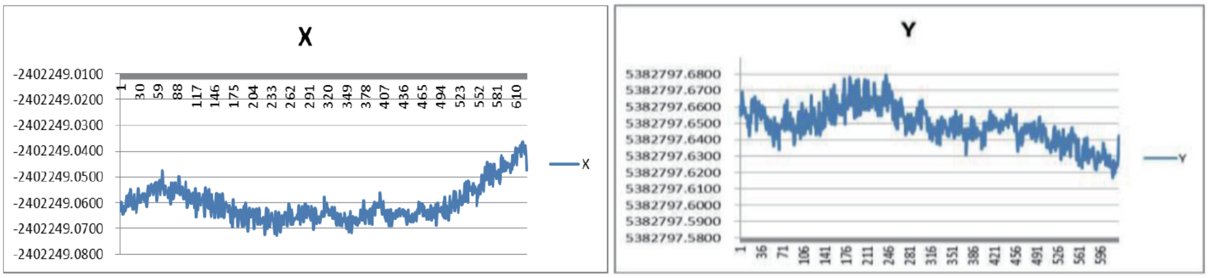


Fig. 7. (color online) No. 4 point single-epoch E, N, and U direction vibration curves.



(a) (b)

Fig. 8. (color online) Vibration amplitude of the cleaning unit platform in Period 4.



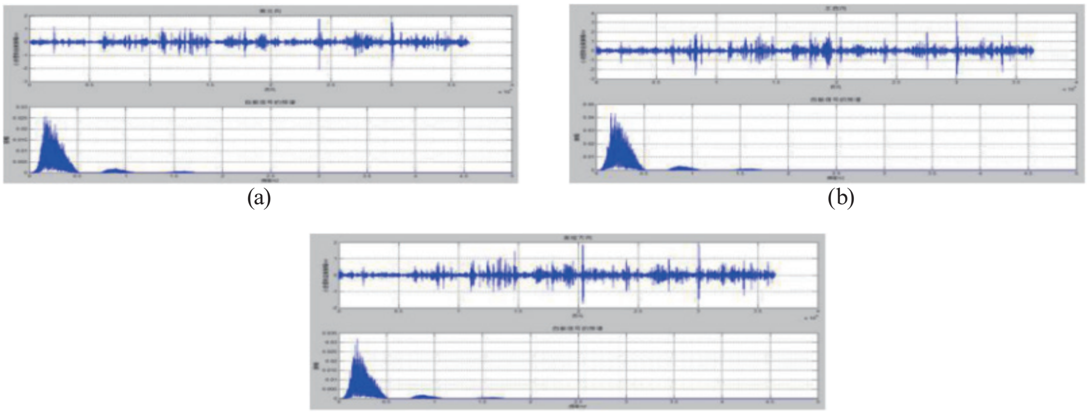
(a) (b)

Fig. 9. (color online) Vibration amplitude of the gemstone seat in Period 5.

3.3.4 Building vibration frequency verification

Three accelerometers were used to test the power characteristics of the Shenzhen Ping'an Building: #4, #5, and #6. The accelerometer sensor measures the vibration in both the horizontal and vertical directions.

1) Beidou GNSS observation data processing
   The 10 Hz building vibration frequency can be obtained by the wavelet decomposition of the sampled data and Fourier transform, as shown in Fig. 10 and Table 2.
   The spontaneous vibration frequencies of the building are 0.1711 Hz north–south and 0.1944 Hz east–west, and the elevation direction is 0.1892 Hz.
2) Accelerometer test book
   On January 22, 2016, the dynamic characteristics test was conducted in Ping An Building, Shenzhen. Three accelerometers were used: #4, #5, and #6. The accelerometer sensor can measure the vibration in the horizontal and vertical directions. The sampling-time parameters are listed in Table 3.
   See Fig. 12 for the condition 1 spectrum of measured frequency:
   East–west horizontal vibration frequency, 0.127 Hz; torsion frequency, 0.303 Hz; north–south horizontal vibration frequency, 0.127 Hz; vertical vibration frequency, 1.826 Hz.
   The spectrum of working condition 2 is shown in Figs. 11 and 13, and the measured vibration



(a) (b) (c)

Fig. 10. (color online) Vibration frequency of the building. (a) E, (b) N, and (c) U.

Table 2
Elevation, base vibration frequency, and amplitude of the building measured by satellite positioning technology.

Number of times	Beidou GNSS test elevation (m)	Temperature /wind-force	Frequency (HZ)			Amplitude (cm)		Construction status
			North and south	East and west	Altitude	North and south	East and west	
First, second times	555.633	12°C 3.0 m /s	0.1711	0.1944	0.1892	±1.75	±0.75	Built to 555.637 m
Third time	555.659	22°C 9-10 m /s	0.1765	0.1915	0.1912	±3.0	±2.0	Load of 1,000 tons
Fourth time	567.984	28.5°C 1.0 m /s	0.1783	0.1891	0.1967	±1.5	±1.0	Window cleaning platform: 567 m
Fifth time	589.466	26°C 2.3 m /s	0.1787	0.1875	0.1979	±1.5	±0.75	Gemstone seat: 589 m

Table 3
Sampling schedule.

Data file	Start time	End time	Sampling duration (min)	Each session (s)	Mean count
20160122szpa-01\Test_2016_01_22_2	11:01	12:01	60	102	70
20160122szpa-01\Test_2016_01_22_4	12:16	12:54	38	102	45

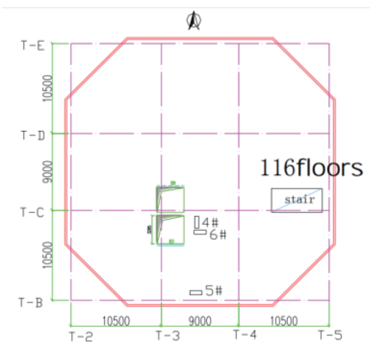


Fig. 11. (color online) Dynamic test working condition 2 sensor layout.

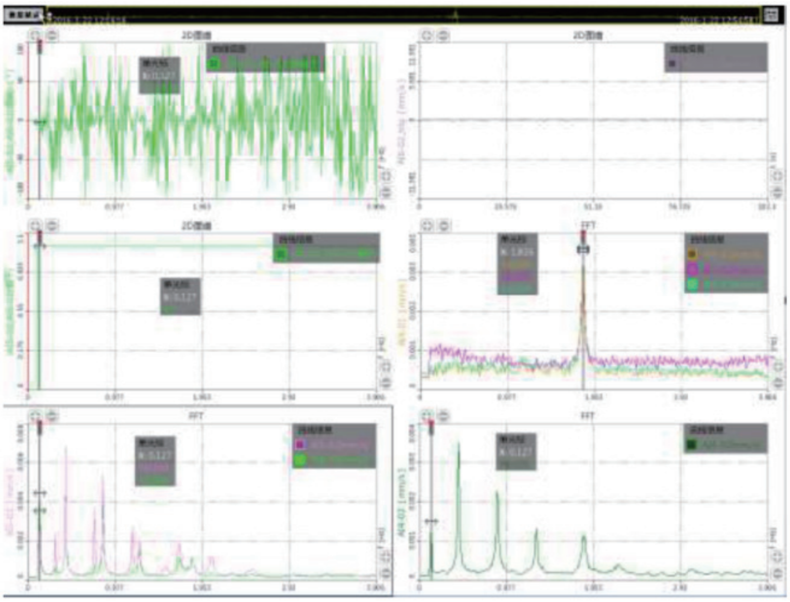


Fig. 12. (Color online) Condition 2 spectrum, 5/6 coherence, and transfer function.

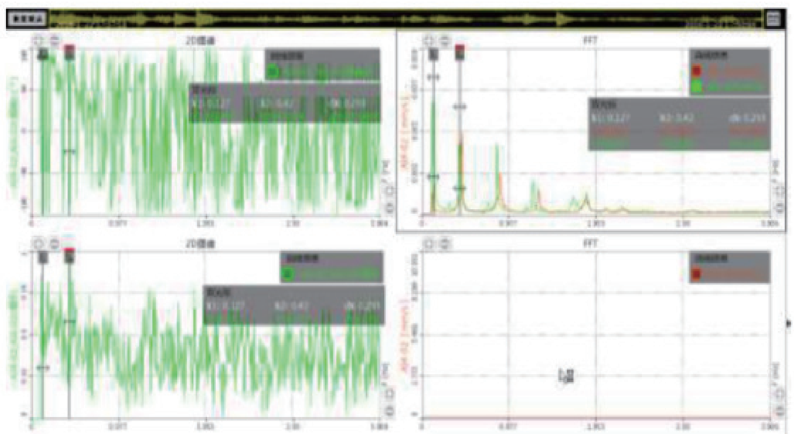


Fig. 13. (Color online) Case 2 spectrum map, 4/6 coherence and transmission function.

Table 4
Situations for sensors #4 and #6.

Sensor	Position	Direction	Frequency (Hz)	Amplitude	Amplitude ratio	Frequency (Hz)	Amplitude	Amplitude ratio
4#	central section	north and south	0.127	0.002	1/3.5	0.439	0.004	1/1.5
6#		east and west		0.007		0.42	0.006	

frequencies are as follows.

East–west horizontal: 0.127 Hz

North–south horizontal: 0.127 Hz

Vertical: 1.826 Hz; The Situations for sensors #4 and #6 are listed in Table 4.

Owing to the different observation times, locations, and numbers of layers of the accelerometer and satellite positioning, the measured frequency difference was within 5% and generally consistent, indicating that the data is reliable.

4. Conclusions

China is accelerating the internationalization of its major cities, with superhigh-rise buildings emerging as a trend in urban development. There is a growing number of high-level, large-scale, sophisticated, and cutting-edge construction projects. The construction monitoring of superhigh-rise buildings and operational monitoring after completion fall within the scope of ultrahigh-precision engineering surveying. Obtaining high-quality, high-precision measurement benchmarks, accurate construction control points, and rapidly established high-precision monitoring points is crucial for construction surveying and monitoring.

In this study, we integrated multiple new technologies, including precise GNSS surveying, intelligent total stations, and GNSS positioning technology, to establish a general engineering control network and a building control network. A laser electronic total station photographic receiving device was designed to provide an accurate elevation measurement benchmark for buildings. Additionally, by combining the small-angle steel tape edge intersection method inside the building with external deformation monitoring, we addressed the challenge of rapidly providing pre-adjustment data for delayed component designs, offering technical support for construction safety. Furthermore, using self-developed Beidou-compatible GNSS technology and a joint static algorithm based on dual-base station fixed baselines with Beidou-compatible receivers, along with high-precision single-epoch resolution algorithms, we achieved the high-precision vertical transmission of axes, captured the building's natural vibration frequency, and measured the height of the superhigh-rise structure as well as deformations in the plane caused by day–night temperature variations. On the basis of the measured deformation values and oscillation conditions, guidance was provided for construction recentering corrections to ensure the building's verticality.

We resolved multiple challenges in the precise construction surveying of superhigh-rise buildings, and the proposed surveying method has been successfully applied in projects such as the Ping An Finance Center in Shenzhen, the China World Trade Center Tower III, and the Beijing CITIC Tower. Moreover, it has facilitated the timely summarization of specialized techniques and successful experiences, where each technology was derived through thorough verification and practice.

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