Application of GNSS displacement monitoring system in measurement of open sea structure

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Abstract: With the development of deep water port and marine engineering, more and more marine structures are located in open sea area. The measurement development of open sea area structure is restricted by abominable marine environment, no control point and difficult data transmission. Combined with the deep water offshore bucket-based breakwater, the displacement measurement technology of open sea structure is studied. The global navigation satellite system (GNSS) is built to realize real-time monitoring of bucket structure displacement. Different monitoring schemes are formulated based on the characteristics and precision of the structure in the sea conveyance floating stage, installation stage or operation stage. It is found that displacement in the structure along the axis of the breakwater is less than that perpendicular to the axis by monitoring data, and the displacement laws of horizontal displacement and settlement in each stage of the structure are obtained. It has very important guiding significance for the structure construction and post-construction stability control in open sea area.

1. Introduction
Port and marine engineering have gradually focused on the deep water in recent years, which brings about more and more offshore structures located in open sea area. In fact, the measurement of offshore structures during hauling and installation is critical to structural stability and post-construction settlement. Nevertheless, many obstructions, such as the harsh environment of open seas, the lack of control points in the vicinity, the difficulty in data transmission and the abominable condition for manual monitoring, prevent the conventional monitoring methods from achieving real-time observation of structures and severely restrict the measurement of open sea structures. The global navigation satellite system (GNSS) can be applied to measurement of open sea structures, because it does not require manual measurement and is less affected by the marine environment.

At present, GNSS is mainly dependent on GPS system, and has been applied in many engineering practices (e.g. bridge and road). Mori et al [1] used GPS measuring instruments to monitor the displacement of the main beam of the Akashi Strait Bridge and analysed the relationship between the monitoring and design values to accurately diagnose the reliability of the bridge, which benefits the safe operation of the bridge. The West Gate Highway Bridge in Australia is about 2.6 km and its maximum vertical displacement can reach several centimeters. Raziq and Collier [2] adopted GPS to dynamically monitor the bridge. It was found that the monitoring results are consistent with the
theoretical analysis results, which proves that GPS can find vertical displacement of about 3 cm or more. Ogaja et al. [3] used GPS to perform real-time dynamic monitoring of the Republic Square building in Singapore. The monitoring data indicates that GPS can achieve the measurement accuracy of centimetre-level displacement. Du et al. [4] proposed a positioning algorithm by combining vehicle Global Navigation Satellite System (GNSS) and mobile RFID readers. The positioning accuracy was better than ±5 m with an identification distance of 160 m. This method can be used in the outdoor positioning with a rapid and accurate locating of the target objects, which is very helpful for the specific objects positioning and change detection in daily urban management and regulations. Linty et al. [5] described the scientific, technological, and logistical challenges of installing an ionospheric monitoring station in Antarctica, based on a multi-constellation and multi-frequency GNSS data grabber and a software-defined radio receiver. The GNSS system is also developing rapidly in China. Xiao [6] used GPS to monitor the deformation of Shimenzi Reservoir. According to the analysis of monitoring datum, the displacement accuracy of GPS geodetic height through the plane fitting in the vertical direction is comparable to that of the ordinary third-class levelling measurement, which can observe horizontal and vertical displacements simultaneously.

From the research status mentioned above, it can be found that the GNSS system has been well applied in many civil and traffic engineering. However, most of these projects are on land or in offshore ports. The application of GNSS in open seas has not been investigated yet. Therefore, this study focused on the deformation measurement technology of open sea structures based on the breakwater project in Lian Yu-gang Port. The GNSS displacement monitoring system is successfully applied to the construction and post stability control of open sea structures.

2. Deformation measurement of open sea structures

2.1. Deformation monitoring method for open offshore structures in deep water

The conventional deformation monitoring method achieves the vertical settlement, horizontal displacement and inclination value by control points with known coordinates, which is performed by a level, a theodolite or a total station. Nevertheless, it is difficult to find control points of known coordinates near the structure due to the characteristics of the open sea environment. According to the ‘National First and Second Level Measurement Specifications’, deformation monitoring can be carried out by the theodolite inclination method, the ranging triangle elevation method or the GPS levelling method when the sight length is greater than 3500 m. In view of the high efficiency and precision of GPS technology, GNSS deformation monitoring system can be used to realize real-time observation of open sea structure during construction and operation. Meanwhile, the system has the following advantages:

- It has a high precision and is not limited by the distance;
- Natural weather has a little influence on it, which results in all-weather measurement;
- Compared with the conventional measurement method, it does not require point-to-point communication, and has the advantages of saving of time and labor, as well as reducing engineering costs;
- The mesh shape is unconstrained, and any graphic control network can be arranged according to the known points of the survey area;
- It greatly improves the quality of marine measurement and is hardly affected by human beings. The whole operation process is controlled by electronic and computer technology, which can realize automatic recording, adjustment calculation and data pre-processing.

2.2. Base principles of GNSS system

In the GNSS measurement, the navigation message and the ranging code are transmitted by the GNSS satellite. Then, they are transmitted through the path, and the signal is transmitted by the GNSS receiver on the ground. At the same time, the satellite signal is tracked and the time taken by the satellite signal in the propagation path is calculated. Moreover, the distance from the station to the
GNSS satellite can be obtained based on the time and speed of propagation. The spatial instantaneous coordinates of the GNSS satellite are achieved from the ephemeris of the satellite. Finally, the spatial coordinates of the survey site are derived by the method of distance space intersection.

The GNSS deformation monitoring system integrates high-precision GNSS solution technology, wireless communication technology and computer technology. It can remotely transmit GNSS solution data to the terrestrial data control center through the wireless bridge in the place without public network coverage, which leads to the characteristics of convenient deployment and cost saving.

2.3. Short baseline test of GNSS system

In the open sea projects, the accuracy of deformation measurement of structures is very rigorous. In the general dynamic construction process, the structural displacement measurement is accurate to 1.0 cm, while it is 2.0 mm during operation. In order to verify the feasibility of the GNSS deformation monitoring system in an open sea environment, this study conducted a short baseline test. Two GPS stations were built on the roof of department of geotechnical engineering of Nanjing Hydraulic Research Institute, with a distance of 37m. The equipment used is the GMX902GG receiver and the AR10 antenna. In the meantime, the GMX902GG receiver is used to control the data collection by the Leica Spider software. The two stations are named as Base and GPS1, of which Base point is used as the base station. The sampling frequency is 1HZ, and the coordinates of Base are: X=-2601912.3745m, Y=4746920.5684m, Z=3361941.5989m (WGS84 spatial rectangular coordinate system).

![Figure 1. Displacement stability curve of Ellipsoidal Height](image1)

![Figure 2. Displacement stability curve of X direction](image2)

![Figure 3. Displacement stability curve of Y direction](image3)

![Figure 4. Displacement stability curve of Z direction](image4)

2.3.1. Stability analysis. From 10:34 to 10:54, Base and GPS1 are stable. The real-time WGS84 geodetic coordinate of GPS1 is calculated by Spider, and the geodetic coordinate system is converted into a WGS84 spatial rectangular coordinate system. It can be found that the average value during this period is: X=-2601912.3745m, Y=4746920.5684m, Z=3361941.5989m. In the meantime, the calculated horizontal distance between two points: 36.756m. Then, the error of X is 0.0021m, the error of Y is
0.0025m, and the error of Z is 0.0025m. The high average value of the ellipsoid is 107.873m, and the medium error of the ellipsoid height is 0.0033m. The ellipsoidal height and the stability curves in all directions are shown in Figures 1-4. It can be seen that the data stability meets the monitoring requirements.

2.3.2. Accuracy analysis. In order to perform an accuracy analysis of a short baseline of GNSS system, the Base base station is moved vertically through the stand. The accuracy test datum of the short baseline is shown in Table 1. Note that, the Spider is set to calculate the coordinates of the GPS1 point based on the Base point. In fact, the Base point is the moving point instead of the GPS1 point. Thus, the elevation of GPS1 has risen. The Base point is supported by the centering tripod, and the moving distance is measured by the tape measure along the periphery of the centering rod. Therefore, the actually moving distance is greater than 0.1 m. It can be seen from the Table 1 that the short baseline solution of GNSS system is accurate and reliable and meets the monitoring requirements.

Table 1. Short baseline monitoring data.

| Illustration                              | Average distance | Ellipsoidal height of GPS1 |
|-------------------------------------------|------------------|----------------------------|
| Initial value                             | 36.756m          | 107.873m                   |
| Base point drops by 0.01m                 | 36.756m          | 107.882m                   |
| Base point drops by 0.05m again           | 36.753m          | 107.933m                   |
| Initial value after reset                 | 36.703m          | 107.935m                   |
| Base point extends 0.1m along the baseline| 36.810m          | 107.933m                   |

3. Measurement on different stages

3.1. Project overview
The monitoring program of the GNSS system on different stages has been studied based on the breakwater project in Lian Yu-gang Port. The breakwater project of Xuyu Port in Lian Yu-gang is 10 km offshore. It is located in the typical open sea area with a low beach and great waves. There are no buildings or control points nearby. Thus, it is necessary to set up a GNSS deformation monitoring system to monitor the construction and operation phases of the breakwater. The bucket foundation is applied in this engineering practice, of which the construction process is:
- Pre-fabricate the bucket foundation on the land;
- Then, hauling and shipping the structure;
- Sinking the foundation with negative pressure;
- Structures are casted-in-place offshore;
- Operation period.

3.2. Measurement of the GNSS system during operation period
The stability and accuracy of the GNSS system is demonstrated by short baseline tests. Figure 5 illustrates the monitoring program of the GNSS system during operation period. Firstly, a base station is set up in a relatively stable area close to the monitoring bucket on the land, while a monitoring station is set up on the monitoring bucket. Both base and observe stations are equipped with solar power, communication module of wireless bridge (using radio or 4G communication according to actual conditions), antenna, etc. Moreover, the stainless steel mounting bracket is adopted to place the GR10 mainframe, communication module and power supply into a stainless steel waterproof case. Then, a GR10 monitoring station is placed on the testing bucket. Finally, the data is transmitted to the monitoring center through the wireless bridge transmission system to solve, of which the solution is a quasi-dynamic mode. In the meantime, the displacement speed of the pontoon is synchronously calculated.
Since the station is installed at the top of the bucket, it should be as possible as close to the center of the bucket to reduce the difference in settlement due to the tilt of the float. The GNSS base station, also known as the continuous operation station, is the base framework for surface displacement monitoring of the whole project. Generally, a GNSS base station can cover monitoring points within 10 km. In order to ensure the stability and reliability of the monitoring system, the base station needs to be regularly combined with the national control point for joint measurement to achieve the uniformity of the monitoring coordinates and the project coordinates. Meanwhile, the displacement of the calibration base point is checked. The base station of the in-situ test was built near the department of port project, where the site was stable with an average annual subsidence and displacement of less than 3 mm. The field of view is wide and the height of obstacles in the field should not exceed 15°. There is no metal or other obstacles or large-scale water surface that strongly reflects radio waves, and its signal utilization rate is above 90%. Figure 6 indicates the field installation of the GNSS system.

3.3. Measurement of the GNSS system during construction period

The design mentioned above can meet the static displacement observation requirements of the breakwater structure during operation. However, the displacement observation of the structure is dynamic measurement during the construction phase, and the accuracy of 10 mm + 1 ppm (rms) can be achieved when using the real-time dynamic difference method. Since the in-situ test is nearly 10 km offshore, it is difficult to achieve the required accuracy of 10 mm. Thus, different solutions should be adopted during the sinking by the negative pressure. The breakwater project of Lian Yu-gang Port consists of hundreds of buckets, and the bucket that has been sinking and stable can be regarded as the base station of the GNSS system. Thus, the cumulative error caused by the proportional error of 1 ppm (rms) km in the nominal accuracy of the ranging can be avoided. The arrangement of deformation monitoring points under the sinking condition with negative pressure is shown in Figure 7. The construction dynamic displacements of ET4 and ET5 are measured by using the already stabilized ET3 barrel as the temporary base station.
4. Analysis of observations

4.1. Displacement observations of structures during the floating period in open sea

In order to ensure the full reflection of the displacement of the testing barrel during the floating and sinking period, the deformation and inclination monitoring of the GNSS are both carried out. Note that, the inclination monitoring can also verify the reliability of the displacement monitoring. The system collects the dip value every five minutes, while the GNSS deformation monitoring system performs a sedimentation measurement every minute. As shown in Figures 8 and 9, the trajectory curve of the barrel during the floating period and the trend of inclination angle are plotted against the time. The stability and displacement variation of the barrel during the floating period can be understood macroscopically.

![Figure 8. Inclination angle of bucket during floating period against time](image)

![Figure 9. Hauling track of bucket during Floating period.](image)

The bucket is bottomless with a cover. Its center of gravity is on the upper side, while the floating center is lower. Thus, it is necessary to strictly maintain airtightness during the process of airbag handing and floating to ensure deformation and stability of the structure. It can be seen from figure 8 that the inclination of the bucket during the floating period fluctuates, but the overall change is little. The maximum inclination angle is -1.45° and the minimum value is 0.3° (where positive values indicate a bias toward the sea and negative values indicate a bias towards the port side). Results indicate that the bucket is relatively stable during the floating period. Figure 9 reflects the plane trajectory of the bucket during the floating period. It can be seen that during the period that the bucket moves from the pre-fabrication plant to the wharf through the high-pressure airbag and is transported by the floating dock to the installation position, the displacement track is dense, which proves that the bucket is pulled by the positioning ship to the specified coordinates after waiting for a period of tidal water and then installed with negative pressure. The air tightness and stability during the floating period are very well, and the displacement variation of the bucket is in the control.
4.2. Displacement observations of structures during the sinking period with negative pressure

The major requirement for ensuring the bucket stability during the sinking period with negative pressure is to control the inclination and sinking speed of the bucket. In addition, the requirement that ensure the bucket vertical and sinking to the design elevation should be satisfied to avoid the great internal force resulting in steel yield and cracks in concrete. As shown in Figures 10 and 11, datum of the inclinometer and GPS are plotted against time, which can indicate the variation of the bucket in the sinking progress with negative pressure.

![Figure 10. Inclination angle of bucket during sinking period with negative pressure against time](image)

The test results present that the average inclination angle of the bucket during sinking period is about -2.741°, of which the range is -10.78° to +2.33°. It finally stabilizes at -3.24° (the positive value indicates the bias to the sea and the negative value indicates the bias to the port side). When the bucket sinks, the slope of vertical variation gradually decreases, especially after the bottom of the bucket inside soils. It can also be seen that the inclination angle of the bucket reached the maximum at 24:00 of July 3. In the meantime, there is an inflection point in the vertical variation trajectory of the bucket, due to end and friction resistances increasing after the bottom into soils for a certain depth. Then, the vertical displacement of the bucket gradually becomes stable, which indicates that the bucket is installed successfully. In general, the variation of inclination angle of the bucket is small during the sinking period. When the bucket is vertical and sinks to the design elevation, the bucket is relatively stable.

4.3. Displacement observations of structures during operation period

Figure 12 presents the variation curve of the displacement and settlement of the bucket. It can be found that the displacement of the bucket varies periodically with the wave, while the vertical settlement and horizontal displacement are very small. From the end of the sinking until the end of May 2017, the cumulative settlement of the bucket is about 2.29cm, and the horizontal displacement
changes little, which is about 1.04cm in the north-south direction and about 0.26cm in the east-west direction.

![Figure 12. Variation of the displacement of the bucket](image)

Based on the monitoring datum, the displacement of the bucket along the axis of breakwater is much smaller than that perpendicular to the axis, and vertical and horizontal displacements gradually become stable after the end of the sinking. Since settlement monitoring is very important for data analysis, the in-situ test also developed a photoelectric encoder monitoring system that is consistent with the GNSS monitoring system, which also validates the feasibility of the GNSS system for structural measurements in open seas.

5. Conclusions
This paper studied the deformation measurement technology of structures in open sea based on the breakwater project in Lian Yu-gang Port. The GNSS displacement monitoring system is successfully applied to stability control of the construction and the post stability of structures in open seas.

The GNSS system can solve the many difficulties, such as abominable environment, no control points nearby, difficulty in data transmission and no conditions for manual monitoring. However, it is necessary to formulate different monitoring schemes according to actual working conditions, and reasonably adjust the observative stations, base stations, data transmission systems and power supply systems in the GNSS displacement monitoring system.

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