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Research Paper

Investigating the Applicability of GNSS Technology for Monitoring Horizontal Displacement of Wharf Structures

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ABSTRACT

Wharves, vital components of maritime infrastructure, are intricate structures typically anchored by robust pile foundations. These essential facilities face substantial environmental and operational challenges, particularly in deep-water settings where forces are amplified. To maintain structural integrity and ensure safety, precise monitoring of horizontal displacement is of paramount importance. This comprehensive study delves into the application of cutting-edge Global Navigation Satellite System (GNSS) technology for tracking wharf movement. Researchers employed both static and kinematic GNSS techniques to capture detailed displacement data across various time scales, from short-term fluctuations to long-term trends. By meticulously analyzing the collected information, experts can identify subtle displacement patterns, evaluate structural behavior under different conditions, and make informed decisions regarding maintenance and repairs. The findings of this investigation clearly demonstrate the effectiveness of GNSS as a highly reliable and accurate tool for wharf monitoring. This advanced technology offers port authorities and engineers a powerful means to safeguard these critical maritime structures, ensuring their longevity and optimal performance in the face of challenging environmental and operational demands.

1 Introduction

Structural monitoring is a crucial component aimed at tracking and supervising the operational status of structures during construction and operation phases. A structural monitoring system incorporates various types of sensors serving diverse monitoring objectives. Among these, Global Navigation Satellite System (GNSS) sensors are frequently employed for continuous real-time displacement monitoring of characteristic points or periodic monitoring. While traditional methods such as the application of total stations in monitoring lateral displacement offer high accuracy, they are significantly limited in practical applications due to stringent requirements for line of sight between measurement points, substantial susceptibility to weather conditions, and the inability to conduct continuous real-time monitoring. The GNSS positioning

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method offers several advantages over traditional methods using total stations, such as the ability to measure continuously 24/7, reduced susceptibility to weather conditions, and the capability to perform continuous real-time measurements with high accuracy [1, 2].

In transportation infrastructure, wharf structures represent a type of concrete bridge with a beam structure supported by a pile foundation system. These structures are subject to various load types, including dead load, live loads from cargo and vehicles operating on the bridge, and impact loads from docking vessels. Furthermore, due to the characteristic of wharf structures being constructed in areas with unstable geological foundations caused by fluctuations in sedimentation and erosion from water currents, these structures are regularly subjected to load testing, inspections, and periodic quality assessments to evaluate their structural stability during operation [3-6].

In the context of wharf structure monitoring, the observation of lateral displacements at specific points on the bridge is a critical task. This process aims to accurately and promptly determine displacement values along various axes, thereby assessing the structure's stability during construction and operation [5-7]. This study examines and analyzes the results of lateral displacement monitoring of wharf structures using GNSS technology, based on practical applications in Vietnamese wharf facilities. Initially, periodic monitoring results using GNSS applied to a wharf structure of a thermal power plant are processed and analyzed for lateral displacements of measurement points across different cycles, comparing these with accuracy requirements and evaluating the structure's lateral displacement. Subsequently, GNSS technology employing the Real-Time Kinematic (RTK) method is investigated for its application in continuous displacement monitoring of a major wharf facility in Vietnam, assessing the accuracy of the monitoring method and the feasibility of establishing a continuous monitoring system for port structures.

2 GNSS Positioning Methods

In Vietnam, the Global Navigation Satellite System (GNSS) is increasingly developing and being utilized effectively with high accuracy, particularly in establishing control networks, mapping, and structural monitoring. This is due to its superior characteristics, such as ability to determine coordinates of points from base points without line-of-sight requirements; rapid measurement with high accuracy, less dependent on weather conditions; measurement results can be calculated in global or local coordinate systems and are recorded in digital format, facilitating easy import into mapping software or database systems etc. Two relative positioning methods using GNSS are commonly employed in geodetic surveying in general and structural monitoring in particular: static relative positioning and kinematic relative positioning [1].

2.1 Principles of GNSS Static Relative Positioning

This measurement method is typically applied in establishing geodetic control networks for construction projects or periodic structural monitoring. It utilizes multiple receivers placed at base points and points to be measured, simultaneously collecting satellite signals for a specified duration (measurement session). Subsequently, the collected data is post-processed to calculate the coordinates of the measured points. Currently, at a given measurement point, GNSS receivers can simultaneously receive signals from numerous satellites, thereby continually improving the accuracy of measurement results, potentially achieving millimeter-level precision.

2.2 Principles of GNSS-RTK Kinematic Relative Positioning

The GNSS-RTK (GNSS-Real Time Kinematic) positioning method is based on the principle of GNSS relative positioning. In this approach, a base station is established at a known control point, while one or more rover stations are placed at points to be determined. The base and rover stations are interconnected via 4G telecommunications (commonly used today) or radio waves, and simultaneously receive signals from satellites in real-time. The base station receives satellite signals, processes them, and determines its instantaneous coordinates, comparing them with known coordinates to calculate correction values. These correction values are then transmitted to the rover stations via 4G or radio methods. Fig. 1a illustrates the fundamental principle of the GNSS-RTK kinematic positioning method. The GNSS-RTK positioning principle applied in Structural Health Monitoring (SHM) systems for cable-stayed bridges typically involves a base station constructed near the bridge structure and fixed rover stations placed at characteristic points requiring monitoring on the bridge, such as at the top of towers, at the midpoint of bridge spans, and at the top of piers. The GNSS receivers (sensors)

are connected to data collectors via cables, and the measurement data is managed within a unified system. Fig. 1b depicts a schematic diagram of GNSS-RTK monitoring for a cable-stayed bridge with two tower piers.

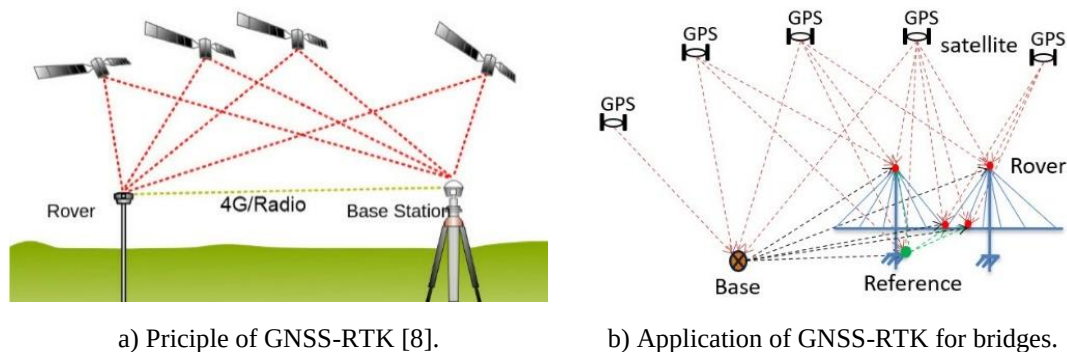


Fig. 1 – Principle of GNSS relative positioning

3 Lateral Displacement Monitoring of Wharf and Harbor Structures

Wharf and harbor structure monitoring is a systematic process of observing, measuring, and recording changes in geometry, deformation, displacement, and other technical parameters of maritime structures and their surrounding environment over time. Two primary monitoring methodologies are employed: periodic monitoring and real-time monitoring.

Periodic monitoring involves conducting measurements at predetermined intervals. The results from different monitoring cycles are compared and analyzed to calculate the changes in observation points, thereby assessing alterations in structural conditions. This method's advantages include ease of implementation using traditional measuring equipment, simplicity of measurement techniques, and low cost. However, it cannot determine instantaneous structural changes under external forces, and the monitoring data is discrete.

Real-time monitoring has been implemented in several large-scale, specialized projects. A Structural Health Monitoring (SHM) system, as previously mentioned, comprises various types of sensors such as strain gauges, temperature sensors, wind speed meters, and rain gauges, installed at characteristic locations of the structure. This system operates continuously in real-time, acquiring monitoring data at high frequencies. Long-term continuous monitoring data can be utilized for in-depth analysis and assessment of the structure's health condition and lifespan.

3.1 Characteristics of Periodic Lateral Displacement Monitoring

The primary objective of periodic lateral displacement monitoring for wharf and harbor structures is to determine the planar coordinates (X, Y) of observation points affixed at characteristic locations across different monitoring cycles. This data enables the calculation of component displacements (along each axis) and total displacement values.

Based on the monitoring objectives, the tasks involved in lateral displacement monitoring of port and harbor structures include:

- **Establishment of a control network:** This comprises a minimum of two high-order control points constructed outside the structure's perimeter to ensure they remain unaffected by the structure's displacement. These base markers must be robustly constructed, typically as deep-set benchmarks, to guarantee stability throughout the monitoring process. It is advisable to establish at least three markers forming a triangular network to assess the stability of base markers during each measurement cycle.
- **Creation of a monitoring network:** This network consists of observation points selected at characteristic locations of the structure (areas with high displacement risk), marked by fixed benchmarks that move in tandem with the structure. Typically, steel markers are used, firmly anchored to the bridge structure. The distribution of observation points depends on the structural characteristics and type of wharf or harbor. Given that wharf structures often have short spans supported by pile systems, for industrial transport piers, observation markers are

usually evenly distributed along the length of the structure. For ship berths, markers should be installed at locations of potential ship impact and mooring points.

- **Monitoring cycles:** The number of cycles and the interval between them are determined based on the construction phase or operational stage.
- **Measurement process:** This is conducted on-site for each monitoring cycle. Each cycle requires the design of a measurement session, typically lasting 2 hours. The number of sessions depends on the quantity of receiving equipment available. Crucially, the measurement scheme for each session must be consistent across all cycles to ensure uniformity in measurement accuracy.
- **Data processing:** This is performed after each monitoring cycle. Using standard GPS/GNSS data processing software, the procedure follows a specific sequence: baseline solution computation, network quality assessment, and network adjustment. The result of network processing is the coordinates (X, Y) of all observation points

3.2 Characteristics of Real-Time Lateral Displacement Monitoring

The principle underlying this method is the application of real-time kinematic (RTK) GNSS positioning to continuously monitor the lateral displacement of wharf and harbor structures. The primary objective of continuous monitoring is to determine the local lateral displacement values of the structure in real-time, enabling visual representation and in-depth analysis of the structural conditions of the wharf and harbor.

Based on the monitoring objectives, the tasks involved in real-time monitoring include:

- **Establishment of base stations:** Depending on the design documentation and topographical and geological reports, base stations are positioned to ensure the following factors:
 - + Stability without displacement during the monitoring process.
 - + Optimal geometry and distance to rover units for best measurement results.
 - + Convenience in management, operation, and utilization. To meet these requirements, GNSS base stations are typically located adjacent to the bridge management unit's office. When constructing the base station, its foundation piles are usually drilled deep into the bedrock at an appropriate distance.
- **Establishment of monitoring points (rover stations):** GNSS receivers are fixed at characteristic locations of the wharf structure with high risk of displacement due to various load factors. As these are installed on the port structure, where operating conditions are complex with numerous mechanical equipment, the receivers fixed at monitoring points require protective systems.
- **Connection system between base and monitoring stations:** This includes various connection protocols such as fiber optic cables or wireless connections (WiFi, 3G, 4G). Currently, 3G/4G wireless connections are widely used and effective in practice.

During the monitoring process, data is measured continuously in real-time. Depending on accuracy requirements, receivers can adjust signal reception frequency as appropriate. Data conversion systems are then used to transfer the data to computer devices. This continuous monitoring approach allows for real-time tracking of structural movements, enabling immediate response to any significant displacements and providing a comprehensive dataset for long-term structural health assessment.

4 Case Studies of GNSS Application for Lateral Displacement Monitoring of Wharf Structures

4.1 Periodic Lateral Displacement Monitoring at the Coal Wharf of Van Phong 1 Thermal Power Plant Project

4.1.1 Description of Wharf Infrastructure and Monitoring Points

The Van Phong 1 Thermal Power Plant Project is a Build-Operate-Transfer (BOT) initiative situated in Van Phong Bay, Ninh Hoa district, Khanh Hoa province. The project encompasses multiple component complexes, among which the

wharf complex is tasked with receiving coal-carrying vessels and transporting raw materials to the plant for operational purposes. The wharf complex comprises a jetty and an approach bridge, as illustrated in the accompanying figure.

The coal import wharf's dimensions are 297.5 meters in length and 27 meters in width. The structural composition of the coal unloading jetty consists of a reinforced concrete beam system and reinforced concrete slabs supported by a foundation of D1000 steel pipe piles. The approach bridge extends 1148.9 meters in length, with an average width of 5 meters. Its structure is composed of reinforced concrete beams and deck slabs, also supported by D1000 steel pipe piles.

The lateral displacement monitoring of the wharf complex was conducted over five cycles to facilitate project evaluation and acceptance. The interval between each monitoring cycle was one month. The monitoring system comprises:

- Three reference points, of which two (PAC1 and PBM5) are situated in proximity to the wharf complex and have been established as stable points to support bridge monitoring and other surveying tasks.
- A control network consisting of eight points (AT1, AT2,..., AT8) distributed equidistantly along the length of the approach bridge.
- Six points (CUJ1, CUJ2, ..., CUJ6) distributed evenly around the perimeter of the jetty.

Fig. 2 illustrates the location of the wharf infrastructure and the positions of the monitoring points.



Fig. 2 – Location of the Coal Wharf of Van Phong 1 Thermal Power Plant Project and monitoring points

4.1.2 Measurement and Data Processing for Monitoring

The monitoring network for the wharf infrastructure was surveyed using relative static positioning method. The equipment employed was the GNSS E300 Pro dual-frequency receiver, which offers a horizontal static measurement accuracy of $2.5\text{mm} + 0.1\text{ppm}$. For each cycle, five observation sessions were conducted, with each session lasting 120 minutes. The data collected from each cycle was processed using specialized software. To ensure consistency, the network configuration used in the adjustment process remained constant across all five cycles.

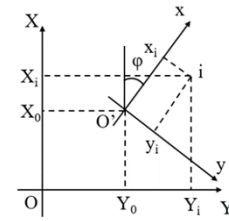
The coordinates of the monitoring points from each cycle were transformed into the bridge's coordinate system to facilitate the assessment of point displacements along the characteristic directions of the bridge. In this system, the x-axis represents the longitudinal direction, while the y-axis represents the transverse direction of the approach bridge or jetty. The coordinate transformation was accomplished using the Helmert transformation method. The principle of this transformation method is as follows:

Consider a point i with coordinates in both the OXY and $O'xy$ coordinate systems. The relationship between these coordinates according to the Helmert transformation method is expressed as

$$\begin{cases} X_i = X_0 + m \cdot x_i \cdot \cos\varphi - m \cdot y_i \cdot \sin\varphi \\ Y_i = Y_0 + m \cdot y_i \cdot \cos\varphi + m \cdot x_i \cdot \sin\varphi \end{cases} \quad (1)$$

where:

- (X, Y) are the coordinates in the OXY system
- (x, y) are the coordinates in the O'xy system
- (X_0, Y_0) represent the translation parameters
- m is the scale factor; α is the rotation angle between the two coordinate systems



Principle of coordinate transform

4.1.3 Displacement Results of Monitoring Points

The monitoring results from cycle 1 were selected as the baseline for calculating displacement values in subsequent cycles. The displacements of points along the longitudinal and transverse directions of the bridge were calculated using the following formula

$$\begin{cases} \Delta X_i = X_i - X_1; \\ \Delta Y_i = Y_i - Y_1; \end{cases} \quad i = 2 \div 5 \text{ (cycle)} \quad (2)$$

Tab. 1 presents the displacement results of the points across different measurement cycles. The displacement values at cycle 5 compared to cycle 1 represent the total displacement of the points up to the end of cycle 5.

Fig. 3a illustrates the displacements of the approach bridge points considered along both the longitudinal and lateral directions of the bridge, while Fig. 3b depicts the displacement results for the jetty.

Table 1 – Result of monitoring displacements along to longitudinal and lateral directions

Point	Cycle 2-Cycle 1		Cycle 3-Cycle 1		Cycle 4-Cycle 1		Cycle 5-Cycle 1	
	$\Delta X(m)$	$\Delta Y(m)$	$\Delta X(m)$	$\Delta Y(m)$	$\Delta X(m)$	$\Delta Y(m)$	$\Delta X(m)$	$\Delta Y(m)$
Coal Unloading Jetty								
CUJ1	-0.020	-0.008	-0.010	-0.019	-0.017	-0.001	-0.012	-0.005
CUJ3	-0.009	-0.004	-0.005	-0.002	-0.003	0.005	-0.002	0.003
CUJ4	-0.002	-0.014	0.001	-0.010	0.005	-0.003	0.010	-0.005
CUJ5	-0.004	-0.017	-0.002	-0.014	0.002	-0.008	-0.002	-0.011
CUJ6	-0.010	-0.002	-0.003	-0.011	-0.006	0.009	0.000	0.001
CUJ8	-0.019	-0.007	-0.007	-0.014	-0.015	-0.006	-0.008	-0.012
Access Trestle								
AT1	0.002	0.004	0.005	-0.002	-0.013	-0.004	-0.009	-0.005
AT2	0.002	0.003	0.003	-0.003	-0.012	-0.003	-0.006	-0.003
AT3	0.000	0.003	0.004	-0.001	-0.008	-0.001	-0.003	0.000
AT4	0.002	0.007	0.008	0.002	-0.009	-0.003	-0.004	-0.004
AT5	-0.001	0.001	0.004	0.000	-0.007	-0.005	-0.003	-0.003
AT6	-0.002	-0.005	0.011	-0.005	0.001	-0.009	0.005	-0.009
AT7	0.000	0.001	0.010	0.002	0.002	-0.008	0.006	-0.011
AT8	-0.004	0.000	0.010	0.003	0.001	-0.007	0.005	-0.008

Tab. 2 presents the design displacement values and the maximum allowable displacement limits for the approach bridge and jetty structures.

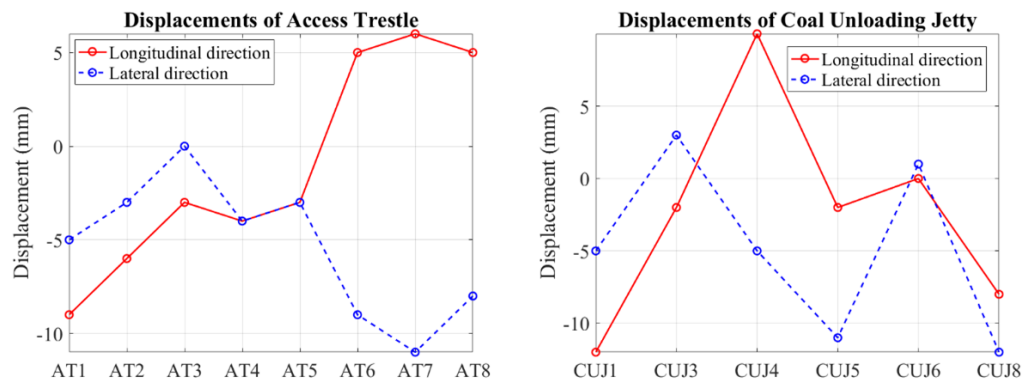
The results of the overall displacement monitoring indicate that:

- Regarding the horizontal displacement of the wharf, the maximum displacement value is 12mm and the minimum is 1 mm. Meanwhile, the maximum horizontal displacement of the approach bridge is 11mm and the minimum is 0 mm (no displacement).

- In the longitudinal direction of the bridge, the maximum displacement value of the wharf is 12 mm and that of the approach bridge is only 9 mm. This can be explained by the fact that the approach bridge has one end fixed to the shore and the other end connected to the wharf, resulting in a lower potential for longitudinal displacement compared to the wharf.
- This analysis indicates that the observed displacements of the wharf infrastructure are well within the designed and allowable ranges, suggesting that the structures are performing as intended and maintaining their structural integrity.

Table. 2 - Design Displacement Values and Displacement Limits

No.	Item	Results of displacement calculation, (mm)	Allowed horizontal displacement ($L/300$), (mm)	Height of the structure, L (m)
I	Coal Unloading Jetty			
	- Platform	35	100	30.00
	- Mooring Dolphin	86	100	30.00
II	Access Trestle	49.77	90	27.00

**Fig. 3 – Displacements of wharve along to longitudinal and lateral directions**

4.2 Real-Time Displacement Monitoring of Tan Thuan Wharf, Ho Chi Minh City

4.2.1 Description of Wharf Infrastructure and Establishment of Monitoring Points

Tan Thuan Wharf, situated on the bank of the Saigon River, was constructed and commenced operations in 2000. The key specifications of the jetty include: 203.4 meters length with 5 segments, 32.2 meters width. According to the most recent official declaration, the jetty is authorized to accommodate the container vessels up to 20,000 DWT and general cargo vessels up to 30,000 DWT. As per the technical standard TCCS 03-2010/CHHVN [9], the maximum allowable lateral displacement for the jetty structure is 327.00 mm. Theoretical calculations indicate that for a ship with a deadweight of 60,000 DWT, the expected lateral displacement is 8.4 mm.

4.2.2 Establishment of Real-time GNSS Displacement Monitoring System for the Wharf Jetty

The continuous displacement monitoring system for Tan Thuan Wharf jetty was established following a comprehensive approach:

- A site survey ensured optimal installation locations with clear sky views for satellite visibility, continuous power supply, and security measures.
- Critical monitoring points were selected based on structural analysis and maritime safety plans for 60,000 DWT vessels with reduced load, focusing on areas susceptible to lateral displacement from ship-induced forces.

- The system employs CHC i50 dual-frequency GNSS receivers operating in Real-Time Kinematic (RTK) mode, continuously collecting data at 1 Hz. This setup demonstrated stable operation throughout the experimental period, accurately reflecting point displacements under various conditions, including no load and large vessel mooring scenarios.

Data was transformed to align with the jetty's longitudinal and transverse axes for analysis. Fig. 4 shows an example of the location of GNSS receiver on the target bridge, while Fig. 5 describes the real-time measured displacements of a monitoring point. The Root Mean Square Error (RMSE) of displacements was also calculated by following fomula

$$RMSE = \pm \sqrt{\frac{[vv]}{n-1}} \quad (3)$$

where: v is the difference between the monitoring data and the mean value; n is the length of the data.

Notably, the observed displacements in both directions and under different loading conditions were significantly smaller than the allowable design limits, confirming the structure's integrity and operational safety within design parameters.



Fig. 4 – Location of Real-Time GNSS monitoring point at the target wharf

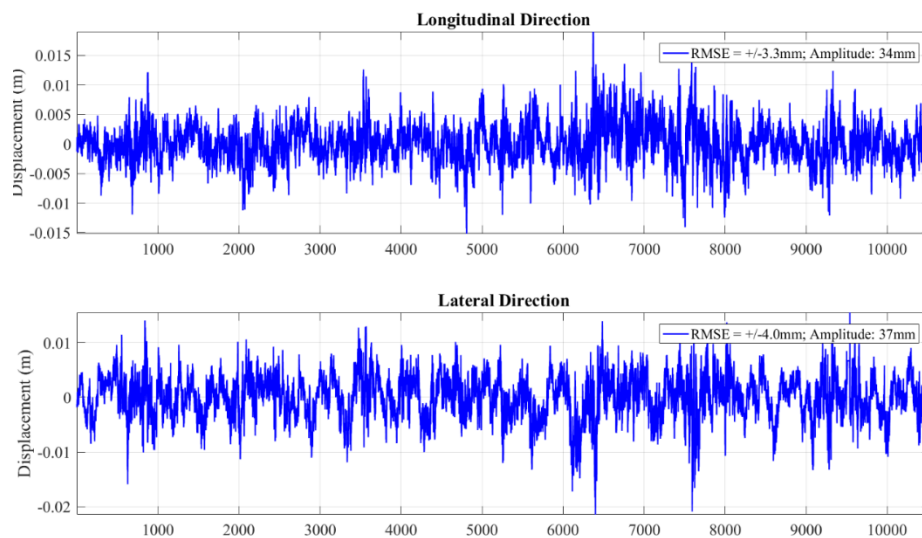


Fig. 5 – Real-time horizontal displacement of the target wharf observing by GNSS-RTK

Moreover, the horizontal displacements of the target wharf were also observed and analyzed due to a heavy ship coming to moor. Fig. 6 shows the wharf displacements in three periods: before the ship's arrival (the blue line), during the ship's mooring (the dashed red line), and after the ship's departure (the black line). The RMSE of the displacement series in these three periods were also calculated for comparison. It can be seen that there is no significant difference in the trend of the monitoring displacements among the observation periods. Additionally, the RMSE values also indicate that there are

only minor differences between the non-mooring ship case and the mooring ship case. Therefore, the target wharf was assessed to be capable of serving a ship with a deadweight of approximately 60,000 DWT.

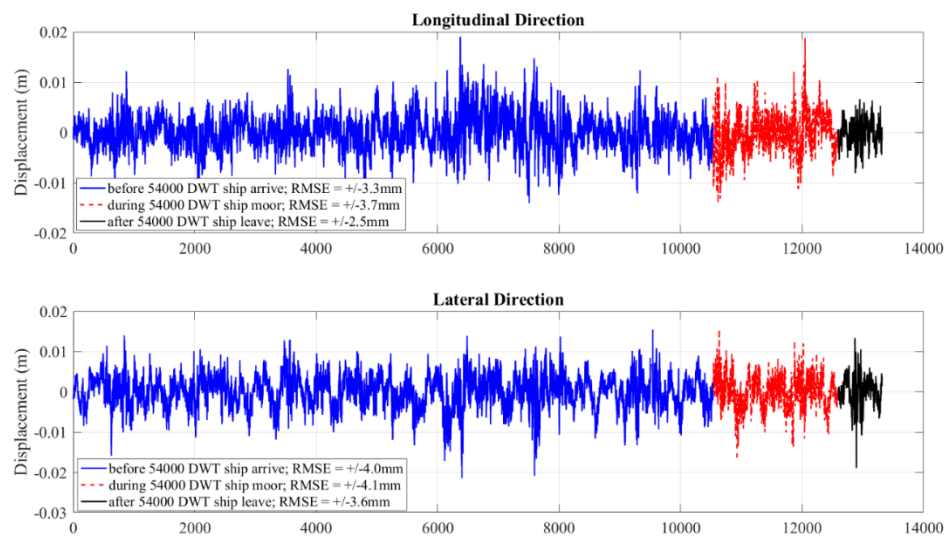


Fig. 6 – Real-time horizontal wharf displacement induced by heavy ship mooring

5 Conclusion

The experimental research results presented in this paper demonstrate that:

GNSS satellite positioning technology application in monitoring displacements and quality control of port jetty structures ensures required accuracy and high efficiency.

The accuracy of lateral displacement monitoring for port jetty structures using GNSS, whether in periodic or continuous mode, achieves millimeter-level precision. This enables the detection of structural displacements under various loading conditions.

However, the experimental conditions for establishing the continuous monitoring system for the port jetty were limited. The system lacked integration with other types of monitoring sensors, which would have allowed for a more comprehensive and accurate analysis of the port facility's working conditions.

This conclusion highlights the effectiveness of GNSS technology in structural monitoring while acknowledging the potential for further improvements through sensor integration for more comprehensive structural health assessment.

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