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The efficiency of single base and network RTK
for Structural Health Monitoring

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Abstract: With the developing technology and increasing construction, the importance of structural observations, which are of great significance in disaster management, has increased. Geodetic methods have been preferred in recent years due to their high accuracy and ease of use in Structural Health Monitoring (SHM) Surveys. In this study, harmonic oscillation tests have been carried out on a shake table to determine the usability of the Single Base and the Network Real-Time Kinematic (RTK) Global Navigation Satellite Systems (GNSS) method in SHM studies. It is aimed to determine the harmonic movements of different amplitudes and frequencies created by the shake table with 20 Hz multi-GNSS equipment. The amplitude and frequency values of the movements created using Fast Fourier Transform (FFT) and Time Series Analysis have been calculated. The precision of the analysis results has been determined by comparing the LVDT (Linear Variable Differential Transformer) data, which is the position sensor of the shake table, with the GNSS data. The advantages of the two RTK methods over each other have been determined using the calculated amplitude and frequency differences. As a result of all experiments, it has been determined that network and single base RTK GNSS methods effectively monitor structural behaviours and natural frequencies.

1. Introduction

Structural Health Monitoring (SHM) is the monitoring, damage assessment strategy and identification process for important engineering structures. It is essential to monitor important engineering structures, detect changes, and take necessary precautions in case of a possible disaster. Detection of these changes in the buildings and making the required reinforcements can only be achieved with a systematic building health monitoring application. Operational safety and availability of an engineering structure depend on admissions during the building's construction, the observation during the construction and the operation, and the implementation of emergency plans in case of identification of erratic behaviour (Im et al., 2013).

There are many different methods and equipment used in SHM surveys. But, today, the high-speed Global Navigation Satellite Systems (GNSS) techniques are frequently preferred for the detection of dynamic deformations and determination of structural vibrations in structures such as dams, towers, high-rise buildings and long-span bridges (Wells et al., 1987). At this point, high accuracy is achieved by using static, kinematic, Real-Time Kinematic (RTK) and Precise Point Positioning (PPP) GNSS methods in determining the structural behaviours (Akpınar and Aykut, 2017).

GNSS methods for structural observations and damage detection have become widespread since the 90s of the twentieth century. There are many studies on real-time and post-process GNSS methods, especially in long-span suspension bridges and high-rise buildings. In 1995, a study was conducted by Lovse et al. (1995) to determine the structural vibrations of the 160-meter Calgary Tower under the wind load in Alberta, Canada, two GNSS antennas were placed at the top of the tower, and a GNSS receiver was placed at the reference point. The data have been collected with a 10 Hz sampling frequency for 15 minutes using a differential GNSS measurement method. As a result of the analysis, it has been determined that the tower oscillated with an amplitude of approximately 5 mm in the east-west directions and about 15 mm in the north-south directions and with a frequency of 0.3 Hz in both directions. Thus, it is seen that the natural frequencies of high buildings such as the Calgary Tower could be determined by the GNSS measurement method. In 1998, Hartinger and Brunner (1998) determined the landslide in Styria with a plus-minus 2 mm accuracy. It has been shown that relative displacements can be detected by GNSS technology with mm precision. In a 34-story building in San Francisco in 2002, Çelebi and Şanlı (2002) have reported that high-rise buildings' structural vibrations can be determined with a 10 Hz GNSS receiver. And they have stated that GNSS is a more promising technology than the accelerometer widely used in determining displacement changes. Erdoğan's (2006) study demonstrates the Bosporus Bridge's action-reaction in case of continuous monitoring with geodetic measurement.

As a continuation of this study, the behaviour of the bridge under the influence of different loads has been explained by monitoring the movements of that bridge during the Eurasia Marathon in 2005 with the use of RTK GNSS. It has been seen that the frequencies of the bridge deck during the marathon process were concentrated between 0–0.5 Hz and 0.75–1 Hz. Li et al. (2006) have been monitored the structural behaviour of the 108-meter steel tower in Tokyo with a system in which they integrated the accelerometer into

a 20-speed GNSS. They have compared the results with Fast Fourier Transform (FFT) and finite element methods and obtained consistent results. [20]Meng et al. (2007) have been compared the displacement values obtained from the accelerometer with the values obtained from the 10 Hz GNSS in the study they conducted at the Nottingham Wilford bridge. It has been reported that the displacements obtained from GNSS are more accurate than the accelerometer. There are also current studies on real-time and post-process GNSS methods in bridges and tall structures (Park et al., 2008; Moschas and Stiros, 2011; Yiğit et al., 2010; Gorski, 2017; Xu et al., 2017). In addition, many shake table tests have been carried out to simulate building movements, create high oscillations that the structure may encounter, and detect them with GNSS hardware. In [30]Wang et al. (2012) study, the tests performed with the 3-axis shake table and the 1 Hz GNSS results related to the 2010 Chile earthquake have been included. In their study, the results of the GNSS and accelerometers that they mounted on the 3-axis shake table have been compared under the specific harmonic motion of the shake table. As a result of comparing GNSS (10 Hz) with an accelerometer (100 Hz), they have reported the great potential of GNSS in determining horizontal displacements. Akpınar and Aykut (2017) have compared Network RTK methods with various tests they performed with the shake table. Within the scope of the shake table tests, they have been made GNSS measurements by connecting to CORS, İSKİ and YLDZ networks. The displacements have been compared from GNSS with LVDT results, and sub-cm accuracy has been received. As a result of their studies, it has been reported that the network RTK GNSS methods can be used in SHM studies by using appropriate sampling intervals. More studies can be found in these articles (Önen et al., 2014; Nie et al., 2016; Dindar et al., 2018; Paziewski et al., 2018; Oku Topal and Akpinar, 2022).

In this study, the usability of the Single-Base RTK method and Network RTK method started to be used actively in engineering studies by introducing fixed GNSS networks such as Continuously Operating Reference Stations (CORS-TR) and ISKI-UKBS, in SHM studies have been investigated. There are three main techniques used in broadcasting corrections and point coordinates in RTK positioning, which can be used effectively and practically in SHM. These are Virtual Reference Station Method (VRS), Field Correction Parameters Method (FKP), and Main-Auxiliary Reference Station Method (MAC) techniques. In this study, RTK GNSS measurements obtained by the movement of the shake table have been examined by Fast Fourier Transform Analysis and Time Series Analysis methods. The results of these three Network RTK (NRTK) GNSS methods have been analyzed, and the advantages and disadvantages of the methods compared to each other have been determined. In addition, the YLDZ station was used to compare single base RTK GNSS measurement results with NRTK results. Unlike previous studies, the sufficiency of NRTK GNSS methods in detecting periodic movements has been determined by comparing methods both within and between processes.

2. Single base RTK GNSS

There must be at least two receivers for classical or single base RTK measurements. The first is the base receiver, whose fixed coordinates are known. The other is the rover

receiver, whose coordinates are determined instantly. Thanks to the communication link between the two receivers, like radio waves or GSM links, the corrections are sent to the rover receiver (Aykut et al., 2015).

The YLDZ single base RTK station (YLDZ) has been operating by the Department of Geomatic Engineering since July 2012. YLDZ is located on the roof of Yıldız Technical University Faculty of Civil Engineering (Fig. 1). There is no physical obstacle creating any multipath effect. Aero Antenna AT 1675-120 SPKE Choke Ring GNSS Antenna and Spectra Precision Ashtech Proflex 800 GNSS Receiver installed on the pillar. Proflex 800 offers effective and reliable results in positioning. Thanks to the Z-Blade technology in the receiver, all GNSS signals are used equally without any clustering, and reliable and fast RTK solutions are offered. AT1675-120 choke ring antenna is capable and equipped to eliminate the multipath signal error that may come from any source very well (Fig. 1). Therefore, it provides measurement accuracy with an accuracy of below cm (Gülal et al., 2015).

Fig. 1. YLDZ GNSS Station (Karabulut et al., 2021)

3. Network RTK GNSS

The primary constraint in the single base RTK GNSS method is a maximum 15 km limitation between two receivers. In the Network-RTK measurement technique, corrections are made not by a single reference station but by a system consisting of multiple reference stations. The method's most significant advantage is that the 15 km working area limit required to obtain cm accuracy is pulled to a 100 km base distance (Yıldırım et al., 2011). The 100 km limit in this method provides fast and accurate ambiguity resolution. The most efficient way to increase the accuracy of corrections is to increase the number of stations (Aykut et al., 2015). The main methods used to determine corrections are MAC (Main Auxiliary Concept), FKP (Flächenkorrektur parameter) and VRS (Virtual Reference Stations) methods.

The VRS (Virtual Reference Station) method is based on the determination of the position of mobile receivers concerning a virtual reference station created using data of reference stations covering the working area. In the VRS method, it is assumed that there

is a virtual station without equipment installed on it only a few meters away from the roaming receiver. With this method, even if there is a malfunction in the operation of any reference station in the network, the necessary GNSS corrections can be calculated using other station data. In this way, some systematic effects (troposphere, ionosphere, antenna phase centre, orbit, etc.) in the measurements of the travelling receivers are significantly reduced. Thus, unlike the classical RTK technique, it increases the distance between the mobile receivers and the reference stations and increases the system reliability. With this method, even if there is a malfunction in the functioning of any reference station in the network, the necessary GNSS corrections can be calculated using other station data (Arslan et al., 2002).

The basic principle in the corrections used in FKP (Field Correction Parameters Method) is the same as that used in the VRS method. In the FKP method, which is the German translation of FKP (Flächen Korrektur Parameter), surfaces are used as a reference when calculating the correction parameters. In this method, it is possible to transfer the data from the reference stations to the browsing receiver by knowing the approximate location of the browsing receiver. Since the ionospheric effects change in short time intervals, the correction parameter in the method consists of ionospheric and geometric components. The geometric part includes orbital errors and tropospheric time delay. The rover receives the required network correction from one of the nearest fixed stations. In one-way communications, this station is determined by the control centre. In one-way communication, since the user must choose the closest station himself, one-way communication is rarely used in this method. This situation affects the result accuracy of the method (Eren et al., 2009). For this reason, it is preferred more rarely than the other two methods.

The basic principle of the MAC Method is based on determining the location of the mobile receiver within the network, which consists of one master station and several auxiliary stations. The critical point of this method is that most of the calculations are made in the mobile receiver. The base station does not have to be the closest to the receiver in this method. The critical point is that observations were made on the identical satellites as the receiver. The primary function of the main station is to broadcast correction information. If the main station cannot fulfil its role, one of the auxiliary stations undertakes the task. In the MAC method, correction data of all error sources are transmitted to roaming receivers. As a result, system integrity is established, the time to lock on satellites and start the measurement is shortened, and phase uncertainty solutions are made faster and more accurately. Therefore, the accuracy of positioning increases (Kahveci and Yıldız, 2001).

The NRTK system used in Turkey is the CORS-TR / TUSAGA Active system, with 150 stations across the country (Gülal et al., 2013). Some other networks work in the Network-RTK technique, not nationally but regionally. For example, the ISKI-UKBS network, which has ten fixed stations covering the whole of Istanbul, is one of these local networks. In our study ISKI-UKBS network has been used to compare VRS, FKP, and MAC methods.

UKBS system consists of 10 fixed reference stations (Fig. 2). The absolute accuracy of the precise coordinates of İSKİ-UKBS fixed reference stations is 2 mm on average, and

the relative accuracy is 2 cm on average. According to these results, the UKBS network can be used in engineering measurements studies and navigation in RTK applications (Gülal, 2009).
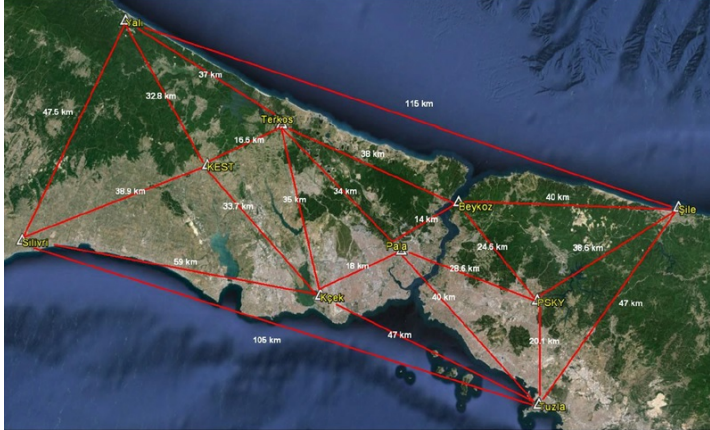

Fig. 2. ISKI-UKBS reference stations network (UKBS, 2022)

4. Materials and methods

Spectra Precision GNSS Receiver (SP80) has been used for shake table tests carried out in the backyard of the YTU Department of Geomatic Engineering. Many harmonic oscillation tests have been carried out on the shake table at different periods to detect whether structural vibrations can be determined with a single base and Network RTK GNSS. GNSS data have been collected for the moments when the shake table oscillates at specified amplitudes and frequencies and is stationary. The amplitude and frequency results obtained by analyzing the collected data have been compared with the shake table position sensor (LVDT). For each of the VRS, FKP, MAC and YLDZ methods, GNSS data has been collected with a sampling rate of 20 Hz for ten minutes, with the first and last 4 minutes being still and 2 minutes moving Table 1.

Table 1. All events equal observation times and the same frequencies on the shake table

GNSS	Stationary	Motion	Stationary	Duration
VRS	4 min	2 min (5 Hz)	4 min	11.00–11.10
FKP	4 min	2 min (5 Hz)	4 min	11.10–11.20
MAC	4 min	2 min (5 Hz)	4 min	11.20–11.30
YLDZ	4 min	2 min (5 Hz)	4 min	11.30–11.40

There are shake tables that can oscillate in one, two and three axes, and the QUANSER Shake Table II (Fig. 3) is preferred in the tests and has a displacement capability of 9.5 cm

in a single axis. The maximum working speed of the shake table is 400 mm/s, and its total stroke is 190 mm. LVDT sensors, integrated into the hardware and provide exact location information, measure with 50 samples per second (50 Hz) with an accuracy of 0.0006 mm. A software program manages the electric motor that can produce the vibrations of the table. In this way, harmonic movements of desired amplitude and frequency can be created. The harmonical motions are determined as a sinusoidal wave function defined by its frequency, amplitude, and the number of cycles (Yiğit et al., 2018).
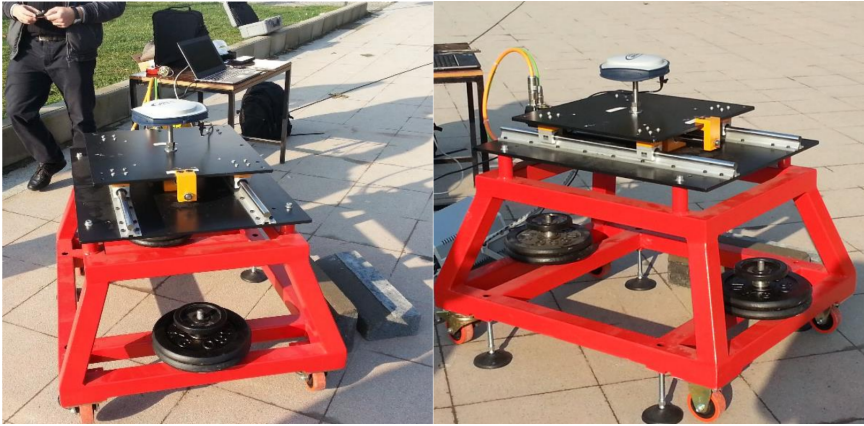

Fig. 3. The Shake Table (Oku Topal and Akpınar, 2022)

Time Series Analysis is a method in which trend, stochastic and periodic components are analyzed in signals and is widely used in SHM studies. Besides, spectral analysis methods are used to obtain frequency and amplitude information about movements. Amplitude and frequency values have been determined by applying time series analysis and the Fast Fourier Transformation technique to GNSS and LVDT data obtained.

The first process of the time series analysis is to display the series graphically. Then, some filtering operations determined regarding the characteristic of the series are applied (Erdoğan, 2006; Yiğit et al., 2010). The next step in the analysis is to eliminate existing trends in the series. The trend component representing the long-term changes in the series is defined by the function given in the expression below:

$$Y(t_i)\text{Trend} = \sum_{k=1}^{m} C_k t_i^{k-1} . \tag{1}$$

Depending on the degree of the function used, $(C_k = 1, \ldots, m)$ takes values (Erdoğan and Gülal, 2013; Gülal et al., 2013). De-trended series graphs are created by separating the calculated trend components from the series (Fig. 4). After that, the amplitude and frequency values for comparison should be calculated by the spectral analysis method.

FFT is used to move the series defined in the time domain to the frequency domain (Erdoğan, 2006). The basic principle of the FFT is based on the separation of the signals that form the series. In the Fourier technique, as in the time series analysis, the series

must be separated from the trend component. A function with a period T is expressed in the FFT as the sum of the sin and cos functions.

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos \frac{n\pi x}{L} + b_n \sin \frac{n\pi x}{L} \right) \qquad (2)$$

$f(x)$ is the representation of Fourier sequences. The a_n and b_n values expressed in Eq. (2) are defined as the Fourier coefficients of the $f(x)$ function, and L is the length of the discrete signal. In the range $[0, L]$, where the array can be expanded into a Fourier series, the function must be continuous and have finite maximum and minimum points. Provided in this way, Fourier sequences converge to $f(x)$ wherever the function is continuous. Since the Fourier transform is calculated for N discrete frequency values, a total of N $(k = 0, 1, \ldots, N-1)$ complex Fourier Transform values are obtained. The frequency, amplitude, phase, and power spectrums of a signal can be easily determined from the complex numbers obtained from the Fast Fourier Transform (Erdogan, 2006).

De-trended graphs and amplitude and frequency values obtained due to time series and FFT analyses applied to both GNSS and LVDT data will be examined in the results and discussion section.

5. Results and discussions

Before the measurements, the shake table was oriented approximately to the north, and it was tried to ensure that the coordinate changes were in a single direction. Based on previous tests, it has been requested that the shake table oscillates with a frequency of 5 Hz and an amplitude of 20 mm to compare the RTK methods. Still, these initial values varied according to the oscillation capacity of the shake table. Measurements have been carried out with the assumption that RTK GNSS measurement methods could detect even the motion at high oscillations of 5 Hz with high accuracy and detect low oscillations of 3, 2, 1, 0.5 Hz. Data has been transferred with a 20 Hz sampling frequency during the measurement. In the time series analysis, GNSS data converted to UTM Gauss Kruger coordinates has been analyzed since time-dependent graphs of the series should be created first. By taking the coordinates of the midpoint of the shake table as the reference value, the time series analysis of the calculated displacements has been made by creating the coordinate differences of all points according to this value. Then, a trend component analysis of each series was made, and de-trended time series was created. Finally, the amplitude and frequency values of the movements have been determined by applying FFT analysis to the series. The same procedure has been used for the VRS, FKP, MAC, YLDZ measurement results, and LVDT displacement data.

Figure 4 and Figure 5 show all methods' LVDT and GNSS derived displacement time series. It can be seen that GNSS displacements show good agreement with the LVDT results. It is seen that the de-trended graphs created after the removal of the trend component detected in the series are more compatible with the LVDT displacements. However, the FFT method must examine each event's peak frequency and amplitude

values to determine this agreement in more detail. The frequency analysis methods have also been applied to the LVDT results. After creating the de-trended time series, the amplitude and frequency values to be used as references have been calculated. The 5 Hz, harmonic oscillation data of all 3 Networks and one single base RTK method have been analyzed by time series and fast Fourier analysis. The amplitude and frequency values are expressed in Table 2. It should be noted that the graphics used in Figure 5 were sampled to 20 Hz since the time series became illegible due to the 50 Hz high frequency of LVDT, but the FFT analysis was continued over the 50 Hz series.
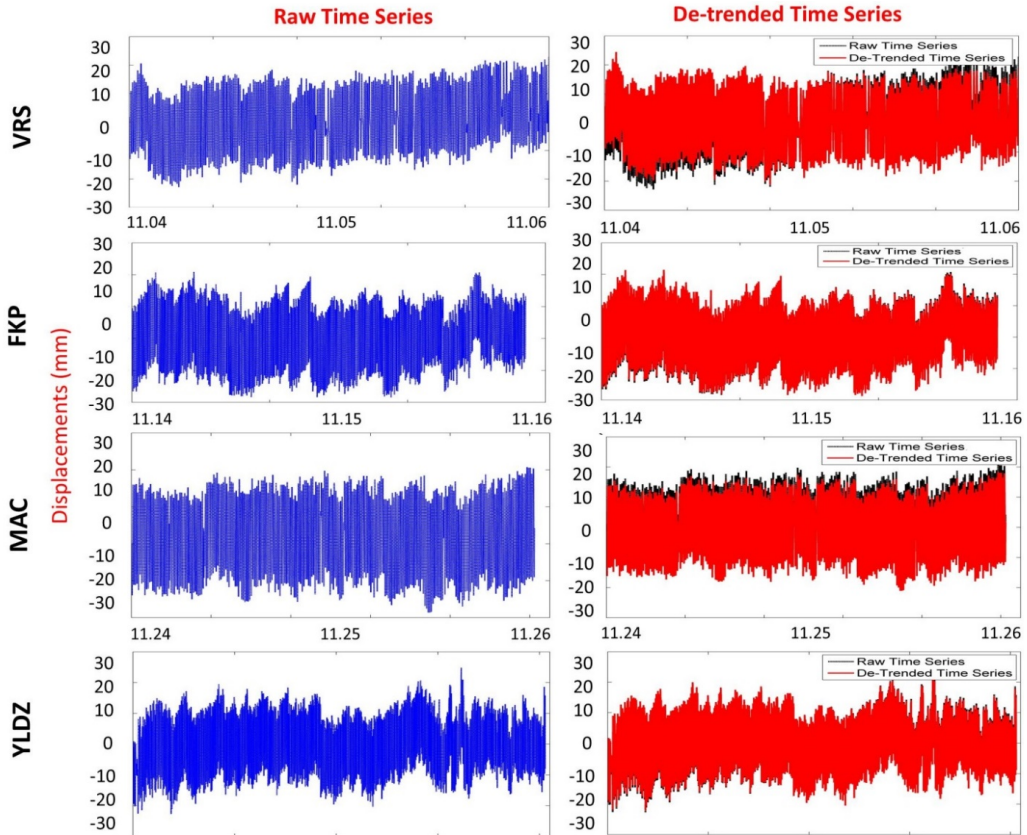

Fig. 4. Raw and De-Trended Time Series of GNSS (VRS, FKP, MAC, YLDZ) Displacement

Four different RTK GNSS measurement methods have been used. It has been investigated whether these methods could be used to determine the structural behaviors with the help of the LVDT measurements. When Table 2 is examined, it is seen that frequencies could be detected with high accuracy in all four measurement methods. To determine the amplitudes, the measurement methods gave consistent values within themselves. When the differences are examined, it is seen that the best results from Network RTK GNSS methods are obtained with VRS and MAC methods. Compared to the other two methods, lower accuracy is obtained from the FKP method with the highest difference value. In
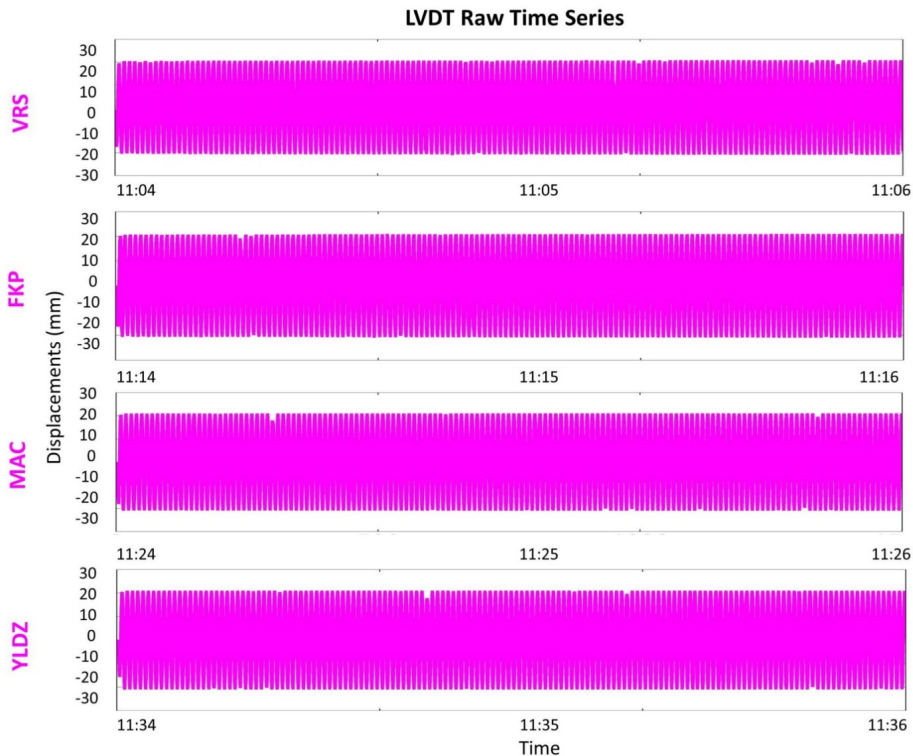
Fig. 5. Raw time series of LVDT displacement corresponding to GNSS (VRS, FKP, MAC, YLDZ) measurements

Table 2. Peak amplitude and frequency differences between GNSS and LVDT values

Methods	GNSS		LVDT		Differences	
	Amplitude (mm)	Frequency (Hz)	Amplitude (mm)	Frequency (Hz)	Amplitude (mm)	Frequency (Hz)
VRS	14.6	5.00	16.1	5.00	1.5	0.0
FKP	15.0	5.00	17.0	5.00	2.0	0.0
MAC	15.0	5.00	16.4	5.00	1.4	0.0
YLDZ	13.8	5.00	13.1	5.00	–0.7	0.0

addition, when all processes are examined, it is seen that the best result is obtained from the YLDZ station, which is a single base RTK method. This is because this station is close to the test point (Fig. 6). Since the differences between the LVDT and GNSS amplitudes calculated as a result of harmonic tests are a maximum of 2 mm, it can be said that the relative accuracy of the measurement methods is relatively high. The maximum natural frequencies of 15–20 story high buildings are 0.5–1 Hz. (Yiğit et al., 2010) For long-span suspension bridges such as the Bosporus Bridge, 1.2 Hz is the maximum natural

frequency (Erdoğan, 2006). The 5 Hz oscillation frequency determined with a sampling interval of 20 Hz with high accuracy by RTK measurement methods has shown that the RTK-GNSS techniques could be preferred in the SHM studies.
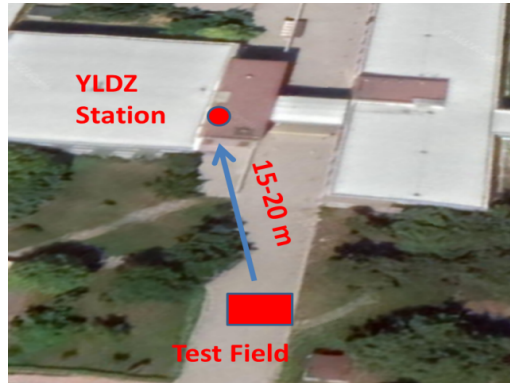

Fig. 6. Position of the shake table test area and YLDZ reference station

The other reason for the sub-cm accuracy offered by the YLDZ station is its SNR and multipath values. The Signal to Noise Ratio (SNR) measures receiver tracking performance or compares signal intensities between channels and satellites (Bilich et al., 2007). In open-sky conditions, the SNR should be higher than 42 dB-Hz. Due to signal power loss from reflection, SNR is often reduced by at least 5 to 10 dB-Hz under multipath conditions (Uaratanawong et al., 2020). Multipath in the vicinity of GNSS stations, caused by diffuse or specular reflections, is a significant source of cm-level positioning. SNR values, which are impacted by the actual intensity of the broadcast signal, space loss, atmospheric influences, antenna gain pattern, and other factors, can be used to detect and mitigate carrier phase multipath problems (Rost and Wanninger, 2009). It is known from previous studies that the SNR values of the YLDZ station are 40–50 dB Hz on average and do not fall below 30 dB Hz, and the multipath values are zero (Karabulut et al., 2021). Based on these results, the YLDZ station provided high accuracy in the single-base GNSS results (Karabulut et al., 2021).

Data were collected during the RTK measurements in no-motion (stationary) time with GNSS for four minutes after the oscillations started and ended. When the table is stationary, Root Means Square Errors (RMSE) values are calculated. And the RMSE results of the stationary time have been used as a reference for the internal accuracy of the measurements. When Table 3 is examined, it is seen that the lowest RMSE belongs to the VRS method, and the highest RMSE belongs to the FKP method. When the single base

Table 3. Root Mean Square Error of stationary time

Stationary	VRS	FKP	MAC	YLDZ
RMSE (mm)	2.0	2.8	2.3	1.8

and network RTK methods are compared, it is seen that the lowest RMSE is obtained from the YLDZ station. It is seen that the accuracy of the results for the stationary time and the accuracy of the results for the harmonic motion are consistent.

As can be seen from these results, using NRTK GNSS, higher accuracy can be obtained from VRS and MAC solutions as expected (Fig. 7). When comparing single base and network RTK solutions, it is seen that the YLDZ station provides solutions with higher sensitivity than others. Additionally, when the RMSE for the stationary time is examined, it is seen that the VRS value is 2.0 mm, MAC value is 2.3 mm, FKP value is 2.8 mm, and YLDZ value is 1.8 mm, as expected. Since the RMSE for stationary times should be below, the best results were obtained from the YLDZ station with a low RMSE of 1.8 mm.
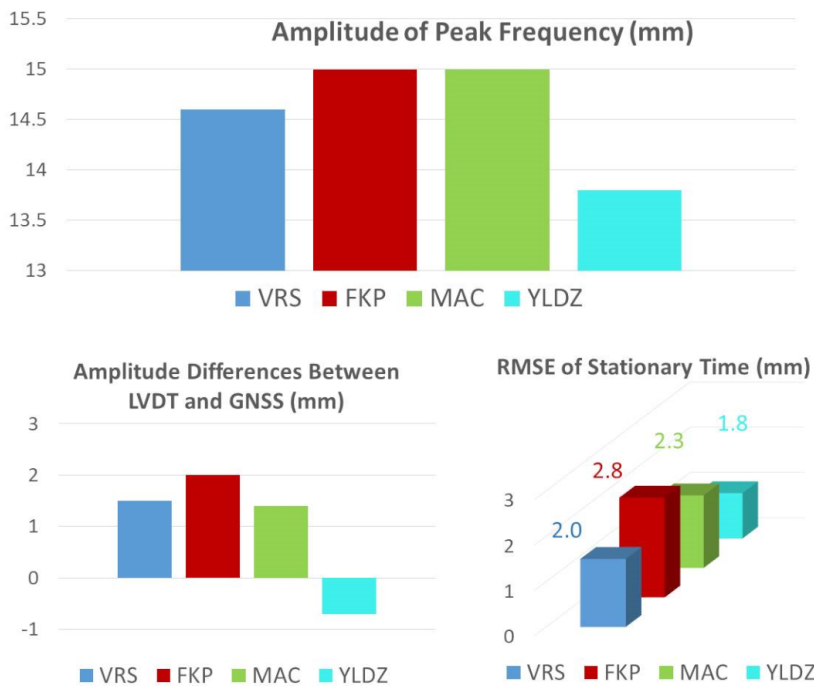

Fig. 7. Amplitudes and amplitude differences of peak frequencies obtained from FFT spectra for GNSS solutions and RMSE of stationary time

Figure 8 shows the LVDT and GNSS Fast Fourier Transform (FFT) spectra. When Figure 8 is examined, it is seen that all 4 GNSS methods give results consistent with LVDT. It is seen that the peak frequency and amplitude values of the harmonic movement are determined with very high accuracy. However, all four displacements have some low-frequency components in the GNSS results. The primary source of this noise appearing in the FFT spectrum is white noise. Besides, the differences and low-frequency components shown for the GNSS can be attributed to multipath, random noise of the carrier phase, and higher-order ionospheric errors (Oku Topal and Akpınar, 2022).
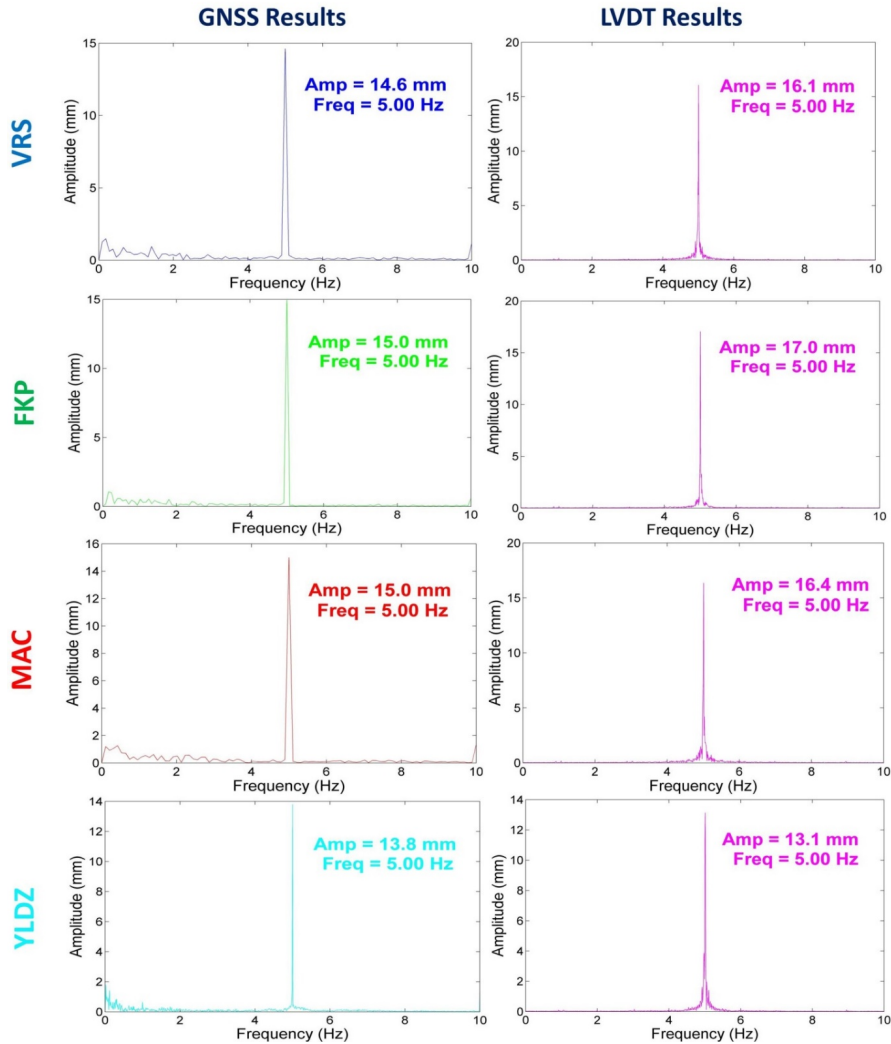
Fig. 8. Vibration responses of GNSS (VRS, FKP, MAC, and YLDZ) and corresponding LVDT FFT spectrum

6. Conclusions

Considering the study results, it can be said that the behaviors of large engineering structures can be defined accurately and in detail by using appropriate geodetic measurement equipment. By analyzing the measured observation data in the frequency and time domain, meaningful information about the natural behaviors of the structures could be obtained.

The amplitude and frequency values determined by applying the same analysis procedures to RTK GNSS and LVDT measurement data have been determined as 1.5 mm for VRS, 2 mm for FKP, 1.4 mm for MAC and –0.7 for single base RTK methods. Although

frequencies could be detected with high accuracy in all measurement methods, some differences have been detected in the calculated amplitudes compared to the LVDT results. However, these differences are extremely low, calculated as a maximum of 2 mm. In this study, the relative accuracy of all four methods has been determined as below cm. In addition, rmse values were determined when the shake table was stationary. Since these values for stationary times are a maximum of 2.8 mm, it can be said that the absolute accuracy of the measurement methods is relatively high.

The natural frequencies of large engineering structures are in the range of 0.5–1 Hz. Determining 5 Hz oscillation frequency with high accuracy and RTK measurement methods has shown that the RTK-GNSS method can be used effectively in SHM studies.

In conclusion, The Single base and Network-RTK GNSS methods are effective methods that provide high accuracy in determining the natural frequencies of engineering structures. Based on the results of all tests, it can be said that three Network RTK GNSS techniques are effective in SHM studies. Also, The Single base RTK has better results than Network RTK due to the proximity of the measurement area to the reference station (YLDZ).

Author contributions

Conceptualization O.T.G. and A.B.; methodology development O.T.G. and A.B.; writing original draft: O.T.G. and A.B.; writing – review and editing: O.T.G. and A.B.

Data availability statement

The data used in the study are available from the corresponding author upon reasonable request.

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