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A General Review on Application of GNSS for Structural Deformation Monitoring

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Abstract
Engineering structures need to be timely monitored for identifying any sort of deformation. Conventionally employed surveying techniques such as Total Station survey, Precise leveling are more labor intensive and computationally tedious. In recent times, GNSS based positioning method has been identified as a major substitute of conventional techniques in order to monitor both horizontal as well as vertical displacement of engineering structures even in real time. However, various modes within GNSS positioning and other factors limits the attainable accuracy level in deformation monitoring. Therefore, in this article a comparative study on different modes and other alternative techniques is made and aims to summarize the key concepts, historical experiments and current innovative trends within GNSS based deformation survey.

Keywords
deformation, monitoring, GNSS, structure

1. Introduction

One of the major concern after construction of engineering structures is to ensure their sound structural integrity and serviceability. However, with due course of time and their usage, all of the structures are subjected to some kind of structural deformations. Deformations in engineering structures can be attributed to various internal and external factors which are not constant in nature. Conventional geodetic survey techniques such as Electronic Distance Measurement (EDM), Theodolite, Total station, Precise levels were commonly employed for determining horizontal and vertical displacements of the major structural components until the very beginning of 1980's [1, 2]. However, such techniques were subjected to be more intensive regarding both time and labor with extensive data processing requirements. After the advent of Global Navigation Satellite System (GNSS), it has surfaced out as an effective tool for deformation monitoring in structures. GNSS is a space geodetic technique of positioning which consists network of interconnected points through linear and/or angular measurements.The system provides redundant observations that are used in statistical evaluation and error detection [1]. Advantages of GNSS positioning system over other conventional techniques include high accuracy, simultaneous 3D positioning, long-term stability, full automation, all weather observation and absolute measurement outputs [1–5]. Comparison between precise conventional and modern GPS method in different literature has outlined relevance of GPS in structural monitoring. In modern times, more precise camera and 3D laser scanner are also developed. However, their use are limited as they suffer the limitation of decrements in accuracy with the increasing sight distance [5]. A study has been carried out by [6] in Italy for monitoring of Cantoniera dam, where displacements from GNSS based survey were compared with displacements from Pendulum observations. It was observed that in the cross-crest direction of the dam, displacements from both GNSS and Pendulum observations described same oscillations with coherent amplitudes. Also, along the direction of crest, GNSS could detect the displacement at the millimeter level thereby proving the reliability of GNSS for deformation monitoring.

This study emphasizes on summarizing the general concepts behind GNSS positioning and its application in monitoring of structural deformation. Also various issues of GNSS monitoring system are briefly introduced and aims to explore the key concepts that may further revolutionize the monitoring mechanism with the aid of GNSS technology.

2. Deformation Analysis

Most of the deformation analysis involve strain analysis and determining deformation parameters through initial study which is strictly related to displacement. Thus, at the first it is essential to have a well-established strain-displacement relations [3]. However, its major prerequisite is a known displacement function representing deformation of the object. Displacement function can be expressed as,

$$d(x,y,z,t-t_o) = (u,v,w)^T$$

where, d is the displacement of a point (x,y,z) at time t (with respect to a reference time t_o) and u,v,w are components of the displacement function in the x,y,z directions, respectively [2].

Displacement, in simple words, is the difference in the Cartesian Coordinates of the same point at different times [3]. Whether measured as absolute or relative, displacements in structure components can be monitored through either of the two methods [2] .

Coordinate Differencing In this method, cartesian coordinates are obtained from two independent surveys which are then arithmetically differentiated to determine displacements. [2].

Measurement Differencing This method involves observing changes in measurements for two epochs of observation. Change in the position are revealed by comparing measurements to previous surveys. [2].

In a geodetic network, conventional deformation analysis is based on difference in coordinates between two epochs of observation. Occurrence of displacement is examined via statistical tests. For conventional deformation analysis, implementation of global congruency test is done to examine whether the displacement between two epochs are significant or not. This requires setting up of two hypothesis; Null and Alternative as:

Null Hypothesis: $H_o : E(x_1) = E(x_i)$

Alternative Hypothesis: $H : E(x_1) \neq E(x_i)$

where E stands for expectation. Redundant observations from GNSS are processed for least square positioning solution between two epochs. According to Gauss-Markov model, if there is any change within the coordinates of the corresponding points according to expectations between two epochs, they form the null hypothesis and is tested against the alternative. It is also to be noted to have the same datum between two epochs. It is managed by taking the approximate coordinates of the identical stations as the same in both epochs [3]. If not, there exists numerous methods of localization for deformation analysis in the literature. However, S-transformation method is the one usually employed. S-transformation is an operation employed for datum transformation without the necessity of new adjustment computation. In other words, S-transformation computes the unknown parameters and their co-factor matrix in order to transit from one datum to the other. [1].

It has been well stated fact from above discussion that the foundation of GNSS in structure deformation monitoring lies in deriving the displacement of the monitoring points with respect to three conventional directions.

3. GNSS Positioning

GNSS is an umbrella term that denotes global collection of satellite based navigation system with satellites generally adopting medium altitude earth orbit (MEO) configuration. Such system provides precise navigation and timing solution services either on global or local basis. Besides, there are also few augmentation systems which are employed to improve the performance of GNSS by providing differential correction data and integrity information. In recent times, GNSS positioning has achieved highly improved performance and has also seen growth in the data sampling rate.There exists different modes and constraints of GNSS positioning that influence the accuracy and survey requirements. Therefore, it is essential to have prior knowledge of such constraints to achieve desired level of accuracy for structural monitoring.

Since an unit bit/chip of PRN code in code phase measurement measures about 300 m in distance while a complete cycle of carrier signal measures 19 cm long, we can get centimeter level accuracy in carrier phase mode and is thus superior to code phase measurement technique. In relative (differential) positioning mode, the two receivers record very similar errors (biases), and since the base position is known, corrections can be generated that can be used to improve the solution. Thus, relative carrier based positioning is employed for major projects requiring high accurate results. Furthermore, carrier based relative positioning can be obtained basically in two modes; Static and Kinematic, whose characteristics are summarized in Table 1.

Table 1: Major Modes for GNSS Positioning [5]

Solution Mode	Remarks
Static	Relative positioning technique which employs two or more stationary receivers simultaneously tracking the same satellites and requires post-processing of observed raw data
PPP	Determines solution using carrier phase observations as well as precise ephemeris and clock bias afforded by ground tracking stations
RTK	Determines real time coordinates of measurement points using correction data broadcasted by base station
PPK	Provide more accurate results but its limitation lies in the increased convergence time to obtain accuracy at cm level
NRTK	Removes the limitation of baseline length between base and rover but requires installation of CORS station making the system costlier

PPP: Precise Point Positioning, RTK: Real Time Kinematic, NRTK: Near Real Time Kinematic, PPK: Kinematic Post Processing

3.1 Direct Displacement Computation

All the above discussed modes used positioning service at a single epoch. However, relative change; dynamic monitoring of displacement could also be directly determined through some non-positioning approach. One of the direct displacement detection method is Signal Processing Method (SPM) [4]. Based on double-difference observations, it determines the displacement of the monitored point in both horizontal and vertical directions between two adjacent epochs. This method requires at least four common satellites in consecutive epochs and can be implemented in both single and multiple frequency receivers. The implementation of SPM method is shown in flowchart as below [4].

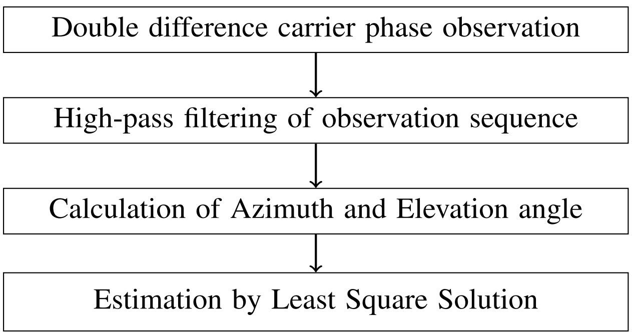

Figure 1: Methodology for Direct Displacement Computation [4]

It was also observed that the method could provide reliable and consistent displacements with PPP and RTK. Unlike other positioning methods, this method is not sensitive to the length of the baseline between rover and reference stations. The major advantage of this direct method lies in the application of high pass filtering which removes the long term trend of noise that improves the solution in comparison to other previously described positioning approaches. In comparison to traditional method SPM method loses information about absolute position and thus has limited use in monitoring of long-term deformation [4]. Various studies regarding implementation of different positioning modes of GNSS for deformation monitoring will be discussed in the following subsection.

3.2 Comparative Study

As stated earlier, deformation monitoring could be performed either in static or kinematic mode of positioning. With reference to various literature, it has been disclosed that new experinments primarily incorporated kinematic mode of GPS survey as static method although being accurate, was unable to fix integer ambiguities and required very long session of observation. Regarding this, a study was conducted by [7], where a comparison between post-processed static data and RTK observation was done for long-term deformation estimation. It was observed that such long-term estimate with static mode was found to contain frequency dependent noise arising from various sources which demonstrated limited application of static positioning in deformation monitoring. With the advancement in both hardware and processing technologies, the capability of GPS was expanded and used to assess dynamic behaviors and oscillations of large engineering structures.

Immediately after the advent of GPS, Post-Processing Kinematic (PPK) technique was employed for monitoring Calgary tower of Canada in 1993.

Observation revealed accuracy for PPK technique was ±5 mm and ±10 mm in horizontal and vertical direction respectively [8]. Similarly, in 1995 Pacoima Dam located at California was observed by employing PPK method from continuous GPS data of three years time period. Although, it was initially intended for employing real time kinematic techniques, with the limitation of telemetry techniques for data transmission real time kinematic was not employed. The major concern was to evaluate damage of the dam in response to two of the significant earthquakes of 1971 and 1994 [9]. The initial GPS observation system of the dam by PPK method employed dual frequency GPS receiver operating with P-Code. Solutions obtained from daily analysis of GPS data showed East-West displacement of center of dam at an amplitude of 17 ± 2 mm which complemented with the results of conventional surveying measurements which recorded the displacement of about 15mm. [9].

Likewise, two of the relative post-processed observation technique; DGPS and PPP were compared for assessing their accuracy in positioning solution. [10] conducted an observation separately for two bridges in Mexico. DGPS method was implemented in Juarez bridge and PPP method was implemented in El Carrizo bridge. Observations showed semi-static and dynamic displacement upto the level of 10 cm in Juarez bridge where DGPS method was employed. In the contrast, for El Carrizo bridge the displacement was observed to be at the level of 10 mm when processed through PPP method.

A recent study on cantilever beam structures located at the Campus of Gebze Technical University was carried out by where the ability of high-rate PPP was assessed to measure dynamic oscillation of the structures in vertical dimension. Further, a comparison was made with the results obtained from high-rate PPP and those obtained from post-processed result of kinematic relative method in three domains; Time, Position and Frequency. The study demonstrated that the overall difference between high-rate PPP and relative kinematic positioning was generally below ±10 mm. Thus, it was also concluded that high-rate kinematic PPP method could be used to capture natural frequency in vertical dimension for engineering structures [11].

One of the first attempt of deformation monitoring of bridges through real time kinematic GPS survey was performed for Humber Bridge in UK using a receiver which was capable of operating in dual frequency mode [12]. Data collected at a sampling rate of 1 HZ demonstrated deflection in vertical direction to be about 300 mm which is shown in Figure 2. This eventually supported the feasibility of kinematic GPS technique for studying deflection of large suspension bridges [12]. In order to evaluate the performance of initial GPS montiroing against new simulation models,same bridge was re-observed by designing a Finite Element Model. A Finite Element Model of Humber bridge developed at Brunel University facilitated the comparison of FEM derived results with that obtained from GPS observation. The observation was found to be consistent with vertical vibration frequency of 0.117 Hz . [13].

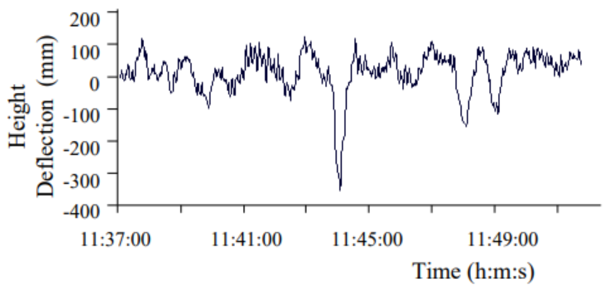

Figure 2: Deflection in Height of Humber Bridge Kinematic Survey [12]

In recent times, the concept of NRTK positioning method has gained prime focus in deformation monitoring whose reliability has been already demonstrated by many literature. The first observation using NRTK method was performed by [14] for Wilford bridge in UK. In this study, vertical movements recorded by both NRTK and accelerometer were compared. Observations

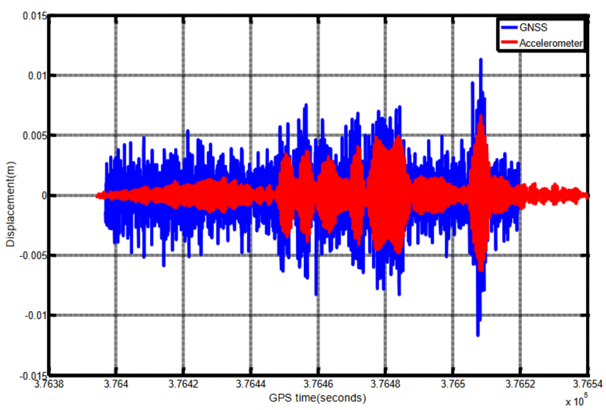

Figure 3: Vertical Deflection Observed By NRTK GNSS (Blue) & Accelerometer Observations (Red) for Wilford Bridge [14]

identified accuracy of the bridge response to few millimeters level although there existed some difference in recorded amplitude as shown in Figure 3. Also, [15] studied the performance of NRTK technique for monitoring real-time displacements and the study indicated that real-time horizontal displacement upto 6mm could be determined. Similary, vertical displacement in real time could be detected upto 10mm.

4. Application of GNSS in Deformation Monitoring

As GPS can provide positioning solution in all the three dimensions, both horizontal and vertical displacements of different engineering structures can be monitored by employing GPS. An apt example of structural monitoring was performed for Koyna Dam in Maharashtra. [16] examined the stability of Koyna Dam in response to 7.8 Magnitude earthquake. For the analysis, continuous GPS data 2.5 hrs before and 2.5 hrs after the earthquake were observed. Observations captured 2.3 cm displacement in the North-West direction. Again, a displacement of 2.1 cm in the opposite direction (southeast) was observed which concluded the stability of dam. This study upholded the advantage of GPS technology over conventional methods in structural deformation monitoring.

Apart from evaluating accuracy of horizontal displacement, assessment of vertical displacement remains crucial as the GPS provides its weakest solution in vertical component. In this regard, [17] monitored vertical displacement of Forth road bridge

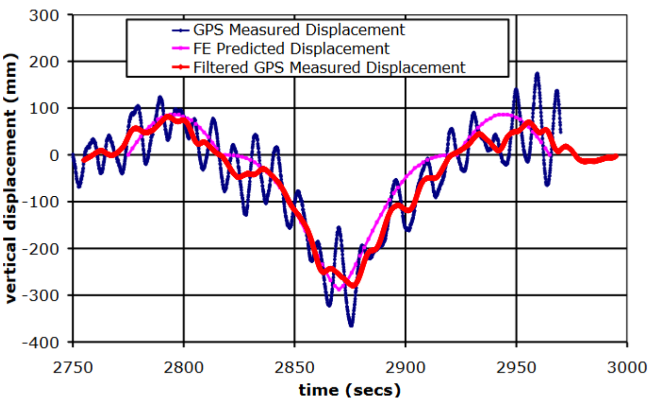

Figure 4: Comparison of Height Deflections from GPS & FEM Model for Forth Road Bridge [17]

in the UK during the year 2005. Data were collected at minimum rate of 10 Hz using four types of GPS recievers over an observation period of 46 hours. The vertical displacement results obtained for the midspan from GPS observations were compared with displacements from Finite Element Method (FEM) and was found to agree with the prediction of FEM model which is shown in Figure 4. And hence it was concluded that GPS could provide observation for magnitude and frequency of bridge's deflection in 3D positioning mode.

To evaluate the modern trends, monitoring of vertical displacement for the same bridge was again performed by [18] by obtaining vertical deformation time series of the bridge tower with 33 months of data provided by GNSS.

Table 2: Comparison of Vertical Deformation from GVD & TED Model for Forth Road Bridge in the UK [18]

Component	Amplitude (mm)	Phase (°)
GVD	9.2 ± 1.8	268 ± 12
TED	9.3 ± 0.6	240 ± 4

Such GNSS vertical Deformation (GVD) time series was compared with time series simulated by thermal expansion model (TED) with the support of 15-month meteorological data. The estimated annual amplitudes and phases of the two time series were observed which were found to be consistent with each other as tabulated in Table2. In order to make an application for structural health monitoring in real time, a web application was developed as a part of the project GeoSHM funded by ESA for three long-span bridges; Forth Road Bridge in Scotland, Erqi Bridge in Wuhan, China and Zhixi Bridge in Yichang, China. The key sensor module comprised of Leica GNSS receivers with high performance and low-cost Panda GNSS receivers. This web application aimed at providing real time communication platform between users and the GeoSHM system that enabled user to have real time deformation information of the bridges [19] . An interface of the application for Forth Road bridge is demonstrated in Figure 5.

[20] conducted a study to employ high-precision global positioning systems for monitoring the displacement of tall buildings under the action of wind. Performance of GPS was then evaluated against the motion obtained from simulation. Results were observed to have error less than 10% when compared

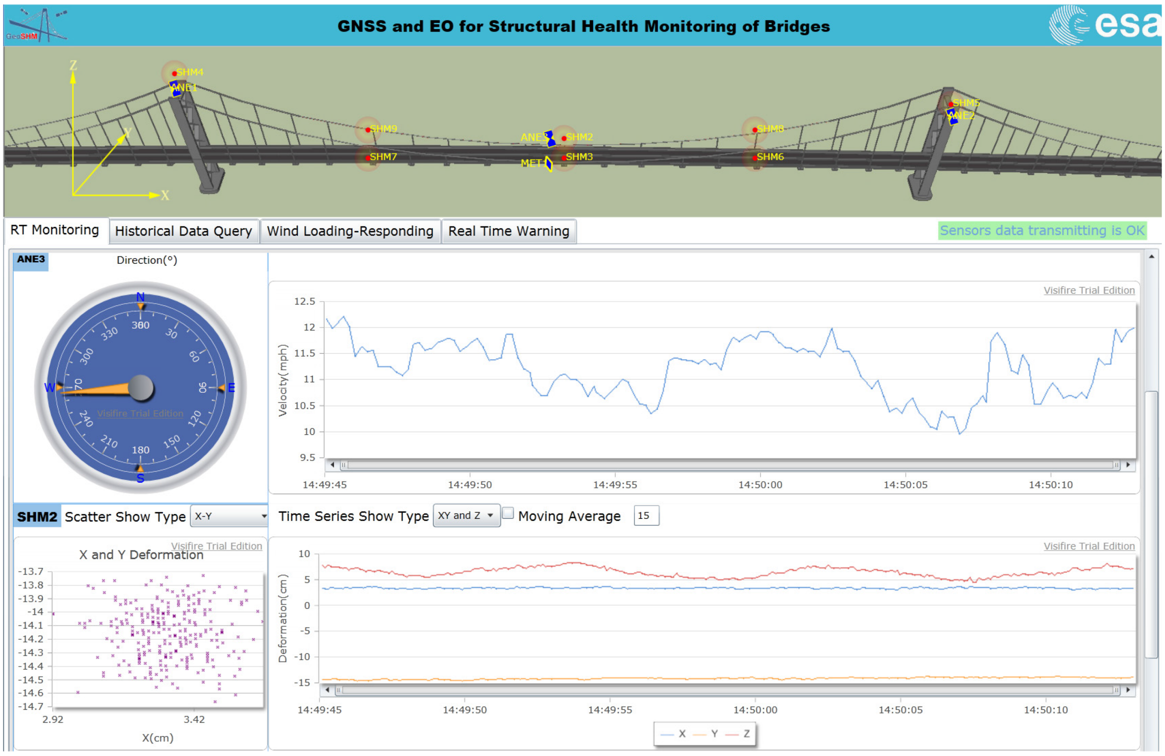

Figure 5: An Interface of the Web Application for Forth Road Bridge, Scotland [19]

with the simulated motion of building due to wind. And thus concluded GPS to be a highly reliable sensor for monitoring total structural displacements.

[21] in Northern Australia conducted a study for a cable-stayed bridge over the River Tama by employing GPS technology. Observations showed longitudinal displacement of 17.2 mm on the tower structure and of 54mm in height on the main span of the bridge. Also, estimates derived from GPS were found to correlate well with the predicted model response from SPACE GASS structural analysis software suite. Again, deformation monitoring conducted at the reservoir dam in China by [22] obtained a smoother deformation time series than in North and East direction and concluded the presence of higher noise level in the deformation results of vertical direction. This made to a conclusion that more precise results can be obtained for horizontal dimension than for vertical in deformation monitoring.

5. Discussion

One of the major constraint in GNSS based monitoring system is the large cost associated with the hardware components. This can be addressed by incorporating multi-antenna system in which multiple GNSS antennas are connected to a single receiver. [23] devised a GPS Multi Antenna System (GMAS) and conducted experinment to monitor Xiaolangdi dam using dual-frequencies GPS receivers. Ambiguties were then resolved by double-differenced carrier phase measurements and the obtained results were compared with standard data from traditional surveying. From experinment, the number of required receivers had been significantly reduced and also the accuracy after post-processing was observed around 1-2 mm. However, as the data of multi-antenna GNSS system are not collected continuously, this system has its limited applicability and is incorporated only for long term monitoring of displacement [5].

It has been already observed that the weakest component of GNSS based positioning is the vertical component. Thus, GNSS could be complemented with other sensors and survey techniques to increase the accuracy to monitor vertical displacement. In recent times, Robotic Total Station (RTS) has been established as one of the accurate methods for positioning service. A comparative study for vertical displacement time series was conducted by [24] and observed Robotic Total Station to have more accuracy than GPS time series. The observed time series are demonstrated in Figure 6 and 7. Finally, the combined observation depicted an improved solution of 1-4 mm and 5-10 mm for static and dynamic displacement respectively.

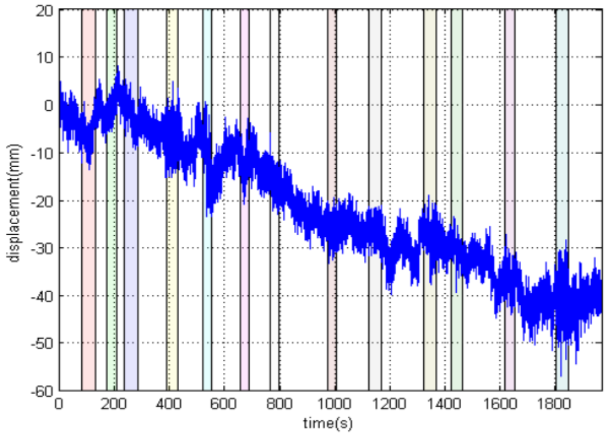

Figure 6: GPS Based Time Series for Vertical Displacement [24]

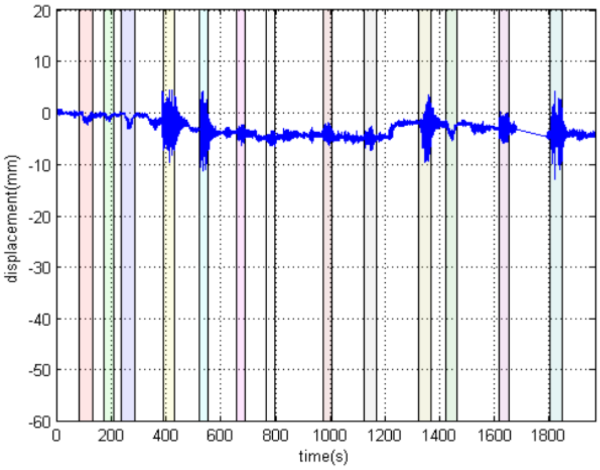

Figure 7: RTS Based Time Series for Vertical Displacement [24]

However, it is to be noted that RTS system although being accurate cannot describe the oscillation cycles precisely. The limited accuracy of GPS can be increased by applying proper filtering technique to remove long-term noise. Therfore, appropriately filtered GNSS observations still possess strong potential in structural monitoring applications when complemented by RTS based observation.

Furthermore, GNSS based system can also be integrated with Inertial Measurement Unit (Accelerometer) system. Prevailing GNSS system has its advantage of identifying structural response of low-frequency vibrations whereas accelerometer system can identify response of high-frequency vibrations at a high data sampling rate of 1,000 Hz [5]. A research conducted by Univeristy of Texas, USA by integration of GNSS and accelerometer system for structural monitoring revealed that the integrated system could provide long-term monitoring of deformation at a accuracy of millimeter level [5]. Observations of GNSS based system can also be augmented by implementation of Pseudolites. Pseudolites act as an augmentation system for satellite geometry by generating a local ground-based signal which is alike GPS [5]. An experinment conducted using pseudolites with GPS signal for a footbridge in UK demonstrated improved accuracy over displacement measurement by 41, 31 & 6 % respectively along E-W,N-S and elevation directions respectively [25].

Similarly, while employing GPS monitoring system for structural dynamics, the sampling rate of the system is the crucial factor. GPS monitoring system with higher sampling frequency is found to have advantage compared to instruments with lower sampling frequency. [26] conducted a comparative study by employing two GPS measurement system with of low and high sampling frequency GPS measurements, 1 and 20 Hz, respectively and monitored structural movement in the time and frequency domain. Observations concluded that measuring system with lower sampling rate can be used to monitor semi-static behavior in time domain (displacement) while instruments with higher sampling rate are effective for monitoring dynamic behavior of structures in frequency domain (oscillation).

Furthermore, while implementing relative kinematic positioning, most usually single baseline solution model has been incorporated by existing GNSS system. With the increasing length of baseline, the accuracy and reliability can be degraded and also the mathematical correlation between the baseline is neglected in single baseline solution (SBS) model. For large scale monitoring projects, often multiple reference stations are to be setup and there exists the concept of multiple baseline model. [27] conducted a comparative study between single baseline solution (SBS) and multi baseline solution (MBS) model and observed that MBS model can increase the accuracy by reducing the RMS of positioning upto 56.9, 60.4 & 58.4 % along North, East and Height components respectively.

6. Conclusion

With the discussions from above sections, it has been evident that GPS technology offers great advantage for monitoring structural displacements. Regarding the different modes of positioning, it is concluded that only carrier based precise relative technique can provide sufficient accuracy for health monitoring of engineering structures. Furthermore, post processing of data allow for highly accurate solution and its better analysis. Thus, it is suitable for long-term deformation survey. On the other side, RTK and NRTK techniques are very important for short-term deformation survey where real time monitoring is required. Also it is observed that GNSS based monitoring incorporates comparatively low accuracy for monitoring along vertical component. It is also to be noted displacement obtained in terms of GPS co-ordinate may not be accurate enough to reveal the structural behavior when prior filtering is not considered for the raw data. [10]. Furthermore, there are a lot of technical issues and factors which are associated with GNSS monitoring survey that limits its accuracy. Such factors include satellite geometry, effects of multipath, low sampling rate, cycle slips, etc. Accordingly, proper mechanisms should be incorporated while designing the monitoring system that helps to mitigate these limitations.

To sum up, GNSS is an accurate and efficient method for deformation monitoring of large engineering structures and promises more precise monitoring when aided by modern supplementary methods.

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