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The Current and Future Trends on Structural Health Monitoring Scheme in Malaysia

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***Abstract*- Aging of our national structural inventory and the fact that many artificial structures are carrying greater average loads than predicted during their designing stage, have significantly increased the need to monitor their health and stability performance. In order to ensure the safety and serviceability of these structures as well as to prevent disastrous consequences due to the structural displacement, periodic monitoring and in-depth analysis of their structural behaviour based on a large set of variables contributing to the deformation are highly demanded. Deformation in which refers to the changes of a deformable body undergoes in its shapes, dimension and position can be detected and monitored using several platforms and approaches. In addition to the discussions on the conventional geodetic techniques such as accelerometer, close range photogrammetry and laser interferometer, this paper highlights the current and the future trends in structural health monitoring studies such as the use of total station, modern Global Positioning System (GPS) techniques and terrestrial laser scanning method. Based on series of observation campaigns conducted at various large scale engineering structures (e.g. breakwater, wide span bridge and high rise building), further discussion includes the suitability and the practicality of these techniques for structural health monitoring in Malaysia.**

Keywords: large engineering structures, structural health monitoring, techniques

I. INTRODUCTION

Structural health monitoring refers to the act of observing changes of a deformable structural body undergo in its shapes, dimension and position. Also referred to as structural deformation monitoring, the need for an effective monitoring scheme on large engineering structure such as dams, wide span bridges, highways and high rise buildings are often arises from awareness and concerns among contractors, professionals, consultants and even public associated with structural integrity, durability and reliability. In most cases, the displacements of large engineering structures are generated by the lateral forces imposed by the strong winds, the extreme temperature variation, the load changes and the earthquakes excitation. Deformation happens in two conditions: the absolute displacement and the relative movement. Several important procedures such as the data snooping, the variance ratio test, the stability conformation and the deformation allocation test are needed to detect certain deformation. To ensure the safeties and serviceability of these manmade structures as well as to prevent disastrous consequences due to structural displacement, the periodic monitoring and the in-depth analysis of their structural behaviour based on a large set of variables contributing to the deformation are highly demanded. Structural displacement can be monitored using several techniques. These techniques can be divided into the geotechnical methods and the geodetic survey methods. As far as the geodetic survey methods are concern, these techniques include total station, close range photogrammetry, very long baseline interferometer, satellite laser ranging and Global Positioning System (GPS). The survey methods can be further subdivided into the survey network method and direct measurement methods. There are two types of geodetic method known as reference (absolute) and relative network. In addition to the discussions on the conventional geodetic techniques such as accelerometer, close range photogrammetry, laser interferometer and total station. this paper highlights the future trends in deformation studies such as the use of modern GPS techniques and terrestrial laser scanning method. Based on series of observation campaigns

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conducted at various large engineering structures, further discussion includes the suitability and the practicality of these techniques for structural health monitoring in Malaysia.

II. CONVENTIONAL METHODS

A. ACCELEROMETER

Accelerometer is a common instrument used by the structural engineer. It detects structural displacement using frequency shift methods that infer damage by analyzing the frequency response of a structure. One of the limitation to this instrument is it requires a direct contact with the structure. In order to link the accelerometers to a central recording unit, it also requires a very tedious wiring work in which contributes to a great possibility of damage, installation error and a high cost in maintenance. Calibration of these instruments with respect to temperature is necessary for accurate results, especially when the temperature varies throughout their network. Despite of its capability to accurately detect vibration frequencies up to several hundred Hertz or even higher, accelerometer is facing a major problem to accurately detect 'very low' vibrations (i.e. structural movements that happen slowly) in which are evident for long span structures [1].

B. CLOSE RANGE PHOTOGRAMMETRY

Photogrammetry allows the use of photographs to determine displacements over long period of time. This technology can be used to measure, document, or monitor almost anything that is visible within a photograph. In addition to the distance of the camera from the subject, the use of photogrammetry method depends on the scale of the object being measured. Close Range Photogrammetry (CRP) is one of the photogrammetry approaches that have an object-to-camera distance of less than 300 m. As far as CRP is concern, the most important equipment required for this method is the digital sensor which comprise of the digital camera of various forms, costs, resolutions and formats, the Charge Couple Device (CCD) camera, and the video camera. In addition to the Intelligent Camera (INCA) developed by the Geodetic Service Inc (GSI), compact camera can also be used for CRP. The precision attainable with compact digital cameras however, are only 1: 20 000 which is in the order of two-third (2/3) of that achievable with SLR digital camera [2]. Though CRP can be applied especially when a prompt analysis is required, it is suggested that CRP is not an effective approach when the accuracy of the measurements need to be at the highest level. Due to complex and difficult conditions surrounding, it is also not always possible to use CRP alone in structural health monitoring as CRP needs to be integrated with other auxiliary instruments.

C. LASER INTERFEROMETER

Laser interferometer measures the variation in distance between the interest point and the reference point. To obtain distance to the interest point, a prism or reflective film need to be mounted on the structure. Variation in distance can be measured and be further analyzed to determine dominant frequencies and corresponding amplitudes throughout the observation. This method has the advantages of high accuracy, but it is difficult to fix the interest point when vibration of the structure is too big. Moreover, laser interferometer is also quite expensive. Apart from its limitation to detect 3D displacement, automation is also a major problem whenever this method is being used. Real time measurement to the interest point need to be made manually by at least two personnel since it cannot be automated. Another major drawback of this method is laser interferometer is climate dependent. As it is difficult to conduct a measurement during rainy condition due to interference on the line of sight, it is suggested that in most cases, laser interferometer is not rather suitable for continuous monitoring of manmade structures in Malaysia

III. CURRENT METHODS

A. TOTAL STATION

Total Station is originally a combination of digital theodolite and electronic distance measurement (EDM) instrument. This instrument is capable of providing easting and northing coordinates height differences and horizontal distances. Nowadays, some total stations have a memory card and Bluetooth connection capabilities to record data directly to the data recorder or notebook for further processing. Robotic or motorised, reflectorless and target recognition total station is yet another recent advance in total station technologies. Even though it is currently being used for periodical (repeated) structural health monitoring scheme, the most common limitation is the pointing error and inter-visibility requirement between stations. Total station also requires redundancy in measurement to detect the possibility of human error. As it is also weather dependent instrument, the use of total station is not quite suitable as regards to the tropical weather condition in Malaysia. It is also requiring a clear line of sight between the reference stations and the structures of interests. Given clear line of sight is achievable, the estimated accuracy of total station method is 5 mm horizontally and 10 mm vertically.

B. GLOBAL POSITIONING SYSTEM (GPS)

GPS technology is a satellite-based navigation system that permits users to obtain their 3D position (X, Y, Z or latitude, longitude and height), velocity information and time in common reference system 24-hour a day. GPS can also directly derive 3D displacement without any need to go through integration process to obtain distance or displacement. GPS combines high accuracy of the results with the possibility of surveying continuously in all weather conditions and the ease of the equipment installation. As it capable of obtaining results in real time, GPS holds promise as an essential way for a continuous and

automated structural health monitoring, especially when swift results could save lives and property. GPS does not require a clear line of sight like laser interferometer, EDM or Total Station. Several studies have been conducted to simulate the use of GPS for structural health monitoring [3], [4], and [5]. GPS receivers with sampling frequency ranges from 10 Hz to 20 Hz are currently available from several manufacturers. For the purpose of structural health monitoring, GPS need to be performed either episodically (epoch intervals) or continuously measurement. Differential GPS carrier-phase approach is also needed to attain accuracy in positioning up to only few millimetres. In general, there are two ways of using GPS for structural health monitoring. The first is using Static technique while the other is using Real Time Kinematic (RTK-GPS).

The principle of Static GPS observation technique is having at least two receivers where one being placed at known location whiles the other at the interest point for a certain period of time. However, in order to attain a good accuracy level in measurement, allocation of both reference and interest points need to be decided carefully. It is highly recommended that the relative distance between the stations (reference and target points) is less than 10 km, the Dilution of Precision (DOP) should be less than 6, and the associated effect of atmosphere and orbital errors are expected to be at or below millimetre level. Clear sky visibility from more than 10 degrees above the horizon is also required in order to reduce the multipath errors.

Currently, instead of using episodically approach, continuous monitoring methods have been increasingly used for structural health monitoring. Here, the utilization Real Time Kinematic GPS (RTK-GPS) technique is crucial as it capable of providing 3D coordinates with a precision of 2 cm ± 2 ppm. In principle, the RTK-GPS hardware configuration consists of at least two GPS receivers (reference station and rover station), radio-communication device and a handheld survey data collector/computer. For structural health monitoring, as long as the interest point can receive both signals transmitted from at least five satellites and the differential signal from the reference benchmark, RTK-GPS technique can be effectively deployed.

IV. CASE STUDIES

A. USING TOTAL STATION

Breakwater structural monitoring campaigns were previously conducted using Leica™ TPS 400 total station at Pengkalan Laut 1, Tanjung Gelang, nearby Kuantan Port, Kuantan [6]. Since total station is only capable of measuring points from an approximate of 1 to 4 km, only three concrete monuments (base stations) can be established close to the breakwater structure. A total of two epoch with an interval of approximately two months (26 December 2006 and 28 February 2007), were carried out at 12 control stations during this campaign. Least square adjustment (LSA) and statistical tests were applied during data processing. Table 1 tabulates the output of the computation.

Station	ΔX	ΔY	Disp. Vector	Fcom	Ftab	Status
1	-0.0013	-0.0005	0.0014	0.01	5.85	Stable
2	0.0016	0.0007	0.0017	0.01	5.85	Stable
3	-0.0003	-0.0002	0.0004	0.00	5.85	Stable
4	0.0031	0.0257	0.0259	0.02	5.85	Stable
5	0.0028	0.0147	0.0149	0.02	5.85	Stable
6	-0.0012	0.0113	0.0114	0.03	5.85	Stable
7	0.0015	0.0084	0.0086	0.02	5.85	Stable
8	0.0010	0.0004	0.0011	0.01	5.85	Stable
9	-0.0002	0.0012	0.0012	0.01	5.85	Stable
10	-0.0005	0.0008	0.0010	0.01	5.85	Stable
11	0.1990	0.1064	0.2257	0.02	5.85	Stable
12	-0.3145	-0.1648	0.3551	0.08	5.85	Stable

Table 1: Single Test Point Result.

Displacement vector can be defined as length of the displacement in error ellipse. Fcom on the other hand is the Fisher value computation obtained from LSA whereas Ftab is the Fisher value taken from the degree of freedom and confidence level. As shown in table 1, total station provides deformation analysis to only horizontal (X and Y) displacement. Providing that value of Fcom is less than Ftab, conclusion can be made that the breakwater structure was in stable condition.

B. USING STATIC GPS

Two episodically campaigns using Static GPS technique at KOMTAR building in Penang for deformation monitoring study has been conducted by [7]. KOMTAR which is the tallest building in northern Malaysia is located at George Town at 245 meter high (65 floors). By using three units of Leica™ System 300 dual-frequency receivers, the first campaign was conducted in November 2000 while the latter was in February 2001. Two Department of Surveying and Mapping Malaysia (DSMM) 1st. order GPS stations, namely TLDM (P314) and Kg. Penaga (P288) were used as the reference stations. Six interest points namely KT1 - KT6 were measured throughout the process. As GPS provides deformation analysis to both horizontal (X and Y) and vertical

(Z) displacement, congruency test at a significance level of 0.05 were then conducted to determine whether structural displacement is occurred significantly between the two campaigns (see table 2). Again, providing that value of Fcom is less than Ftab, conclusion can be made that the breakwater structure was in stable condition.

Station	ΔX	ΔY	ΔZ	Disp. Vector	Fcom	Ftab	Status
KT1	-0.0288	-0.0053	-0.0217	0.0364	0.21	4.51	Stable
KT2	-0.0301	0.0094	-0.0222	0.0386	0.36	4.51	Stable
KT3	-0.0985	0.0211	-0.0215	0.1030	3.08	4.51	Stable
KT4	0.0031	-0.0099	0.0468	0.0479	0.71	4.51	Stable
KT5	-0.0431	0.0136	-0.0233	0.0508	1.13	4.51	Stable
KT6	0.1682	-0.0318	0.0239	0.1728	2.61	4.51	Stable
P314	-0.0284	-0.0204	-0.0509	0.0618	3.70	4.51	Stable
P288	0.0292	0.0032	0.0179	0.0344	0.69	4.51	Stable

Table 2: Single Test Point Result.

C. USING SINGLE BASE RTK-GPS (CASE 1)

Three days of continuous RTK-GPS monitoring campaign have been conducted by [8] on a 30-stories high rise building namely Sarawak Business Tower located at Stulang Laut, Johor Bahru. During this campaign (21 December 2004 until 23 December 2004), two dual frequency GPS receivers namely Leica™ System 500 with RTK communication facilities (i.e. radio modem and antenna) were used. One GPS control point (B1) has been established from two GPS reference stations: J416 and JHJY. Using RTK-GPS technique at 1 second of sampling rate, one interest point (R1) was placed at the top of the building. Based on the dynamic variation of R1 position in Northing, Easting and Ellipsoidal Height components (see figure 1), the attainable precision of R1 is about 1.5 cm for horizontal and 4 cm for vertical component respectively. However, due to loss of lock for certain epochs during the observation periods in which one of the limitation of RTK-GPS, the value is occasionally reached up to 3 cm horizontally and 5 cm vertically. A statistical test was then conducted to ensure the stability of the building. Based on the result, no deformation on this structure is detected throughout the observation campaign.

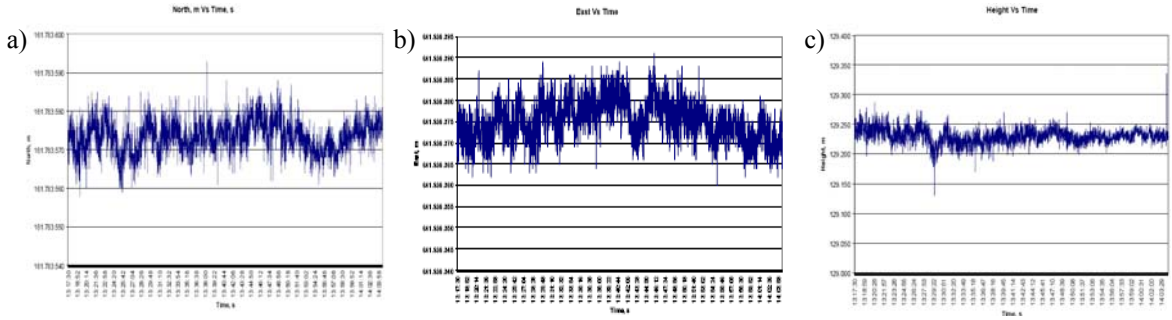

Figure 1(a, b, c): The Dynamic Variation of R1 Position in (a) Northing, (b) Easting and (c) Ellipsoidal Height.

C. USING SINGLE BASE RTK-GPS (CASE 2)

At a total length of 13.5 km in span, Penang Bridge is currently the longest bridge in Asia and third longest in the world. Situated in the northern region of Peninsular Malaysia, continuous RTK-GPS observation campaigns were made to monitor the stability of the Penang Bridge [8]. One GPS control point (master station - P3) was firmly established at the rooftop of Block D of N-Park Condominium near the bridge. This station is tied to two DSMM's 1st. order GPS stations, namely TLDM (P314) and Kg. Penaga (P288). Again using Leica™ System 500 receivers with RTK facilities, 15 interest points were measured throughout the campaign. Validation on the correlation between the quality of RTK-GPS data and the number of satellites during the campaign were firstly made. Figure 2 shows the 3D RTK-GPS data quality of one interest point (PP1) ranging from approximately 10.30 am to 10.50 am and the number of satellites during observation.

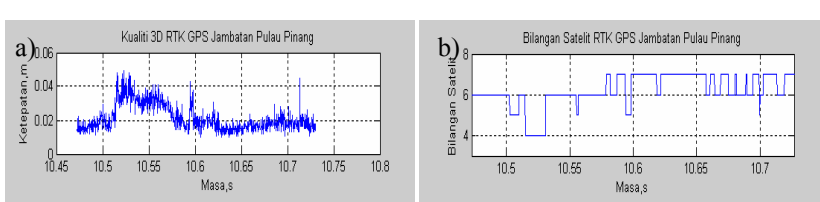

Figure 2: Correlation between (a) RTK-GPS 3D Data Quality and (b) Number of Satellites.

From Figure 2, it is clear that RTK-GPS 3D data quality increases when the number of satellites increases. Variation in number of satellites was due to the radio signal jamming between P3 and PP1 and the multipath effect as a result of heavy traffic and also due to big-sized vehicles disturbances. It is also noted that the vibration caused by the traffic might significantly induces frequency changes. The Fast Fourier Transformation (FFT) is one of the analysis methods that can be used to ensure the quality of RTK-GPS data. The use of FFT is to determine the amplitude of each frequency change. Another method known as Wavelet Transformation (Daubechies) was also been applied during data analysis. This Wavelet Transformation provides two functions. The first function is to eliminate noises in signal data based on 'threshold' value before retransforming the data (free of noises). The second function is to determine frequency changes along the timeline in order to detect any 'frequency breakdown'. Figure 3 shows the example of frequency changes for Northing, Easting and Height components of PP1 ranging from 10.30 am to 10.50 am respectively.

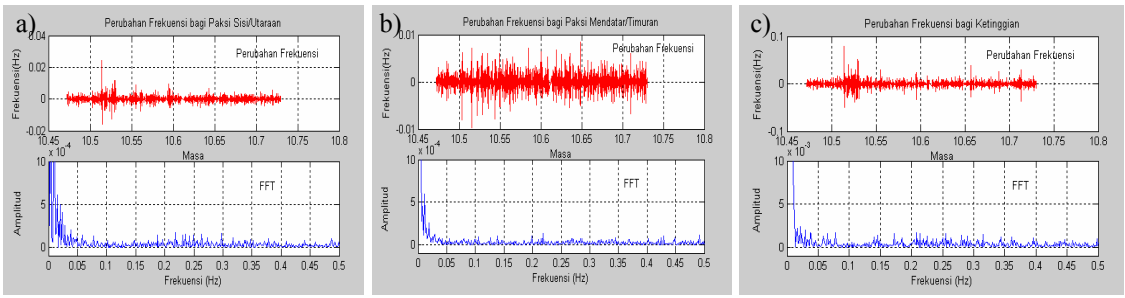

Figure 3 (a, b, c): Frequency Changes of (a) Northing, (b) Easting and (c) Height Components.

In most cases, there were some sudden changes or fluctuations in the frequency on the RTK-GPS Northing and Height component. As these two components are more sensitive to vibration, the Easting component tends to be consistent throughout the observation periods. The occurrence periods of sudden changes at both RTK-GPS Northing and Height components are identical at 10.31 am to 10.32 am. The magnitude of changes for Height component range from -0.05 Hz to 0.09 Hz with the amplitude (shown in FFT) of 0.002 m. Magnitude of changes for Northing component on the other hand, range from -0.018 Hz to 0.022 Hz, with the amplitude of 0.005 m.

V. FUTURE TRENDS

A. RTK-GPS NETWORK

One significant drawback of single base RTK approach is that the maximum distance between the reference and the rover receivers must not exceed 10 kilometres in order to be able to rapidly and reliably resolve the carrier phase ambiguities. Here, the single base type of RTK, tethered as it were to the vicinity of a single reference station and the progressive degradation of results over distance due to systematic errors (distance-dependent biases) has given way to concept of Network RTK. Though not wholly dependent on cellular communications, the move from single-base RTK and radio has been coincident with the move towards network RTK and cellular packet data for primary transmission or corrections This technique is called Network-RTK and is used in DSMM projects, known as MyRTKnet. In MyRTKnet, the virtual reference stations (VRS) further simplifies the usage for the surveyor in the field, since the VRS corrections are treated as corrections from a single reference station. MyRTKnet infrastructure offers the flexibility of enabling both RTK and DGPS operations. MyRTKnet provides high performance solution for real-time data collection needs of Malaysian users. The network, which includes the provision of redundancy at the data collection, transmission and processing layers, has a high degree of service reliability.

The preliminary test of using MyRTKnet infrastructure was carried out at two EDM pillars in Seremban, Negeri Sembilan with difference initialization process, using Topcon^{TM} Hyper Ga GPS receiver. The analysis of the RTK data for two epoch campaign was done by comparing the true values (provided by the Geodesy Section of DSMM) and the processing results. In conclusion, the differences between the observed data and true value are not more than the tolerance 3 cm for horizontal component and 6 cm for vertical component (as in KPU Circular No 1/2008). The result shows that the MyRTKnet is very reliable and more flexible compared to single base RTK, and therefore can be used in the near future for geodetic survey work, including structural monitoring scheme.

B. TERRESTRIAL LASER SCANNING

In the opinion of the authors, could be considered a fascinating challenge: can be used Terrestrial Laser Scanning (TLS) techniques for monitoring displacements of structures. Many instruments and surveying methods have been applied so far in order to continuously access the safety of this kind of large engineering structures. However, the common characteristics of all approaches are the possibility of measuring with high accuracy displacements of a small number of points, if compared to the size of a large structure. The number of control points is even smaller if an automatic measurement system is applied (i.e. when using robotic total stations or GPS methods). On the other hand, laser scanners are capable to acquire a very huge number of points, so that the control could be extended to the whole structure instead of being limited to a few points. This fact is

particularly important, because in many sites to find some stand points for the instruments might be very complex due to local topography of the ground. These imaging systems provide a user with a dense set of three dimensional vectors to unknown points relative to the scanner location. The volume of points and high sampling frequency (a full scan can be captured in few minutes) of laser scanning offers users an unprecedented density of spatial information. For this reason, there is enormous potential for use of this instrumentation in monitoring applications where such dense data sets could provide great insight into the nature of structural deformations for risk assessment, change detection and structural model validation. However, there are two main problems that can be encountered in this approach: (i) the accuracy and the stability of geo-referencing, which is fundamental to make comparisons between different multi-temporal scans; and (ii) the computation of deformation based on the acquired point-clouds [10].

IV. CONCLUSION

An effective continuous monitoring of engineering structures may lead to the early detection of changes of the structures' response to traffic load, temperature and wind load. It is thus an important step towards increasing safety and life-time of the structures. With recent advances on GPS receiver's technology and data processing software during the past decade, the accuracy of positioning is improving distinctly up to only few mm by using a differential GPS carrier-phase approach. Compared to other conventional method, GPS especially through the advent of RTK-GPS network (VRS technique), is capable to overcome the limitation of single base RTK. Here, considering on the reliability of MyRTKnet on providing a dependable positioning accuracy, it is suggested that VRS-RTK can be well-implemented in high accuracy applications including. structural health monitoring scheme. Finally, with a limited control survey of precise targets using GPS and total stations, multiple scans of terrestrial-based laser scans can be registered together to form one cohesive 3D model. This model overlay the different period of deformation data for estimating the changes of the structural behaviour.

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