Study on Issues of Tilt-meters and Utilization of GPS in Bridge Monitoring System (BMS)

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ABSTRACT:

Efficient construction of a Bridge Monitoring Systems (BMS) is typically achieved using a wide array of sensors. Currently bridge construction is developing at an unparalleled speed in comparison to previous ones in terms of both the performance role and project scale. To effectively operate BMSs to match this pace of bridge construction, it is necessary to consider the performance roles of monitoring sensors. This research investigates tilt-meters that monitor the absolute inclination angle that are used for assessing the inclination of the pylons of in-service bridges and the pylons and deck of bridges under-construction. It is an unfortunate reality that regulations regarding the number and location of tilt-meters are currently not well formulated in most countries with rapid bridge development. In such situations, the location and number of tilt-meters are being operated at the personnel's discretion on each construction site. In this research, the minimum number of tilt-meters required for each type of bridge is derived. Data collected through tilt-meters is compared with tilt estimation based on collected Global Positioning System (GPS) data. Current BMS have entered a new phase with the availability of high-precision satellite-based sensor technology. BMS based on Global Navigation Satellite Systems (GNSS) technology are widely spreading. As long as the required system accuracy is achieved, it is thought that this system exhibits outstanding performance in terms of efficiency and interoperability compared to previous BMS. In this research, comparative research was conducted by collecting both GPS and tilt-meter data. On the basis of the results of this comparative study, GPS appears to be a more worthy approach for bridge monitoring systems to assess the inclination angle of a bridge's structure in terms of both efficiency and accuracy. Finally, the expected efficiency with regards to monitoring inclination of the pier and deck was described.

1. INTRODUCTION

Generally, engineering research considers economic values in terms of practical use and the degree of contribution that will be counted towards scientific advancements. However, there is a clear difference between general engineering and engineering applied in BMS. Unlike general engineering, BMS must consider an additional crucial factor along with the two previously mentioned factors; namely, safety. This is because in the case of bridge-collapse accidents, the impact will be immense and will likely lead to the loss of human lives. Additionally, economics wise, such projects are very costly. In the case of the recently built Incheon Bridge, the total cost reached 0.8 billion pounds; hence, economic loss will be just as substantial if problems occur. Thus, the construction of BMS and the research that follows should always emphasize the importance of securing safety prior to any other factors. Optimal BHMS (Bridge Health Monitoring Systems) performed to actively bridge maintenance must be specific systems that can provide the most reliable information possible that can account for some factors, such as traffic control and determination of repair time, by monitoring a bridge's deformation as changed by lapse of time and installing at the expected damage points or key parts of bridge. Therefore, securing the usability, safety and design life of bridge can be achieved because the risk factors of such structures can be determined in advance, and early countermeasures devised through maintenance systems. Securing the safety of bridges begins with the installation and appropriate operation of sensors that enable efficient monitoring systems. The results obtained from these sensors can be used as the basis for safety evaluations; therefore, sensors installed directly on bridges, and the efficient operation of such devices, play an absolutely crucial role in bridge monitoring system. This study investigated effective operation methods for tilt-meters used in constructing monitoring systems for cable-supported bridges that are currently under-construction and in-service. It also introduces a monitoring system that uses GPS-based satellite systems applied commonly in recent BMS, and through comparison studies evaluates the applicability and capability of GPS in replacing or assisting current tilt-meter-based systems in the future.

2. THE ROLE OF TILT-METER MONITORING AND EXPECTED EFFICIENCY

2.1 Necessity of monitoring Pier inclination

BMS uses data obtained from various sensors as a basis for the basic monitoring of bridge behaviour, and, in turn, evaluates a bridge's degree of safety. Failures in bridge safety monitoring that lead to accidents such as the collapse of a bridge are directly related to the usage and role of these sensors. Bridge-collapse accidents for both under-construction and in-service bridges often occur due to careless maintenance of pier inclination, mode shape of bridges, deflection of slaves and stress changes. In terms of the causes of such accidents, tilt-meters are responsible for monitoring the inclination of the pier and the deflection of girders. Thus, monitoring the inclination angle (tilt-angle) of each member must be performed in effective BMS.

2.2 Role of tilt-meters

Although data obtained from sensors installed directly on bridges differ according to each sensor's characteristics, they are primarily divided into two types: sensors for displacement analysis and sensors for acceleration analysis for grasping natural frequency. Generally, operating monitoring systems use extracted displacement and acceleration as important measurements, and these observations are used in primary analysis data to assess the external load applied on a bridge and evaluate the degree of influence such external load has on the bridge. Sensors such as accelerometers, installed on each member, are used to extract acceleration data, thereby yielding the natural frequency. [6], [7] Assessment of the natural frequency enables the monitoring of stiff changes of each member and allows damaged points of the bridge to be identified so that repair and maintenance for the required sections can be scheduled. [8] Using this method, the analysis of mode shape is possible, and long term monitoring of this nature can be very critical in terms of effective bridge operation. As previously mentioned, sensors installed on the bridge, along with sensors used for displacement observations, are undoubtedly the most important components in the effective and efficient use of BMS. In the case of tilt-meters, they monitor the change in inclination of under-construction and in-service piers, and also check the amount of girder deflection for bridges that are under construction. For bridges under-construction, these devises identify the behaviour at the pier that are connected via girders that uses stay cables; in the event of abnormal activities causing excessive inclination, alarms are set off to ensure the safety of both workers and of the bridge itself.

Figure1. Installed tilt-meter at pier

2.3 Expected efficiency of monitoring the inclination angle

To ensure the safety of the bridge, data obtained from tilt-meters require consistent monitoring. The expected effects of such procedures are as follows.

2.3.1 Provision of data required for the structural analysis of finite element model adjustments: Tilt-meter provides data that is used for adjusting the finite element model by comparing the measured inclination and the calculated angle of the pier. Using the adjusted outcomes of the finite element model, the structural tolerance limit from the point where tilt-meter is installed can be calculated.

2.3.2 Acknowledgement of pier inclination characteristics – Provision of data to be considered when examining potential bridge damage in future: Tilt meter provides data that can be used when examining potential bridge damage in the future by using structural tolerance limits and other databases.

2.3.3 Technology development of structural analysis: The provision of data is required for the development of techniques in structural analysis. The reasons for changes in inclination and the degree of change in inclination of pier are as follows: reduction in the stiffness of the pier, reduction in the stiffness of the mould, changes in cable tension, changes in temperature, and changes in traffic load. All of these factors can be used to investigate such relations in structural analytical ways can be provided as required information for research. Such objective accumulation of long-term data is necessary. If the relationship between change in inclination of the pier and the reason for such change can be correctly identified using structural analysis, it should be of great use in maintenance of structures.

3. ISSUES OF TILT-METERS AND THE PURPOSE OF THIS RESEARCH

The reason for installing tilt-meters on the pier or deck of bridges is to eventually come up with a calculation of the amount of inclination of the member. Therefore, a conversion formula that converts the inclination obtained from tilt-meters into deflection (meter-unit) is required. The deflection formula can be calculated by multiplying the measured inclination (tilt-angle) and the measured distance, or by using the successive integration method. The method of multiplying the inclination by the distance becomes more accurate if the quantity of sensors used is sufficiently high. However, as the number of tilt-meters increases, the cost efficiency drops; furthermore, if installation error or device error occurs at the initial measurement point, such error may influence the final measurement point. Thus, currently, a conversion calculation method for inclination monitoring is often used in tilt-angle integration through the method of successive integration. This method determines the degree of displacement formula according to the shape of the member and the form of load, and uses the degree to determine the necessary number of measuring points.

4. DEDUCTION OF THE OPTIMAL NUMBER OF TILT-METERS

4.1 Displacement Function Theory

In the beam theory function, the relationship between the form of load and the tilt-angle function is as follows. [4], [9]

$$EI\dot{y} = \theta,\ EI\ddot{y} = -M,\ EI\dddot{y} = -V,\ EI\ddddot{y} = q \qquad (1)$$

The above function shows that the member where uniformly dis tributed loads are the main form of load is typically expressed in the form of a cubic function. Such cubic equation forms can als o be expressed as follows, and to determine each unknown cons tant, the values of the four points must be known.

$$\theta_{(x)} = ax^3 + bx^3 + cx + d \qquad (2)$$

The deflection formula can be calculated by taking the first inte gral of above equation.

$$\upsilon_{(x)} = \frac{a}{4}x^4 + \frac{b}{3}x^3 + \frac{c}{2}x^2 + dx + e \quad (3)$$

Generally, the tilt-angle (degree) and the amount of tilt (meter) of the cantilever beam at the support are assumed to be 0; hence, *d* and *e* in the above equation are eliminated. Because there are three unknown constants (*a, b, c*), if the tilt-angle of three points can be calculated, the displacement function of the member can be found and can be used as a basis for determining the overall displacement behavior of the member.

4.2 The case of deck of bridge during construction (In FCM method)

When constructing the upper part of the FCM (Free Cantilever Method), tilt-meters installed on the deck of the bridge are used to calculate the managing deflection of the member that may occur during construction. Generally, the inclination function of the upper part of the bridge in the FCM construction method can be expressed as a cubic expression with regard to parameter x in terms of length (assuming cantilever beam):

$$\theta(x) = ax^3 + bx^2 + cx + d \quad (4)$$

Because the support of cantilever beam can be assumed to have no deflection, x=0 and θ=0; therefore, d=0, and to solve the equation above with 4 unknown values, at least three points (excluding the top point) must have tilt-meters installed. If the location and the measured value of the three points of installed tilt-meters can be expressed as, constant a, b, and c can be calculated as shown below.

$$\begin{aligned} \theta_1 &= ax_1^3 + bx_1^2 + cx_1 \\ \theta_2 &= ax_2^3 + bx_2^2 + cx_2 \\ \theta_3 &= ax_3^3 + bx_3^2 + cx_3 \end{aligned} \quad (5)$$

Equation (5) can be expressed in the form of matrix as shown below.

$$\{\theta\} = [X] \cdot \{C\} \quad (6)$$

$$\begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{pmatrix} = \begin{bmatrix} x_1^3 & x_1^2 & x_1 \\ x_2^3 & x_2^2 & x_2 \\ x_3^3 & x_3^2 & x_3 \end{bmatrix} \cdot \begin{pmatrix} a \\ b \\ c \end{pmatrix} \quad (7)$$

Constants a, b, c in equation (7) can be determined by inverse matrix.

$$\{C\} = [X]^{-1} \cdot \{\theta\} \quad (8)$$

Equation (8) derived from constant found in equation (9) is calculated as follows.

$$v_{(x)}mm = \int \theta(x)dx = \frac{a}{4} \cdot x^4 + \frac{b}{3} \cdot x^3 + \frac{c}{2} \cdot x^2 + e \quad (9)$$

Using equation (9), if support is assumed fixed, v=0 when x=0

$$v_{(x)}mm = \frac{a}{4} \cdot x^4 + \frac{b}{3} \cdot x^3 + \frac{c}{2} \cdot x^2 \quad (10)$$

Using the above equations, the overall displacement of the member and the calculation of the inclination of the pier of cable-stayed bridges can be determined.

5. LIMITATION OF USING TILT-METER

The calculation of the displacement (deflection) using to the method explained above has the advantage of determining displacement using a measured point as the basis. However, the use of the displacement function theory above is only possible when a beam is loaded uniformly and distributed loading is dominant; if the form of load on the member changes, tilt-meters must be installed to suit the change in degree of formula. In fact, there are various types and forms of load that apply to each member, and different lengths of member and construction methods are used to accommodate such different lengths and directions. Thus, to calculate an accurate functional formula, a precise structural calculation must be performed, and the event of possible deflection due to loads such as temperature loading or wind loading must be taken into account. Additionally, increases in the degree in the functional formula leading to additional numbers of tilt-meter required may lead to installation errors or errors in the sensors themselves, causing a serious number of accumulated errors in the final outcome. In addition to the technical limitations mentioned previously, there are still problem that can occur in the sensing site. In terms of bridge management technology, even in developed countries such as Korea and those in the EU, regulations and legislation related to overall sensing are still not systemized. Furthermore, the number and installation location of sensors is arbitrarily determined by workers or system operators without the consultation of defined protocols. Therefore, the use of the necessary number of sensors can enhance across-the-board operation BMS in terms of sensing.

6. UTILIZATION AND APPLICATION OF GPS TO BRIDGES

As mentioned previously, sensors currently installed for bridge monitoring are faced with limitations in terms of the application and effectiveness of such systems in current long sized bridges, which are developing rapidly in terms of both size and function. GNSS system-based receivers have been considered as a breakthrough to overcome the limitations of such sensors. This is because they exhibit numerous desirable functions that outweigh their high cost. The use of GPS only requires one device installed for analyzing the movements of the pier in three-dimensional position estimates, allowing the accurate calculation of the tilt of the pier or deflection of the deck, making it a very stable monitoring system in terms of effectiveness and the accuracy of its calculations. It is a capable of delivering the outcome directly in the form displacement analysis figures without the inconveni conversion process, making effective fieldwork collaborat possible between the workers and the monitoring operator. T section presents research into the application of GPS in t angle monitoring. Monitoring of the tilt-angle of the pier of b in-service and under construction bridges was performed. Th results were investigated by comparing them with existing t meters already installed on site.

6.1 Assessment of the Inclination Angle of Und Construction Piers

Piers are one of the bridge members that exhibit relatively la deflections by external environmental factors and global bri deformation. In the case of bridges under-construction, beca the amount of deflection may be bigger than that of in-service bridges, this is very important factor in terms of securing the safety of the structure and the workers. The reasons for monitoring the pier inclination of bridges under-construction are to verify the accuracy and stability of the bridge. In addition, it is possible to prevent advanced damage caused by unequal movement of the piers or girders. For this research, tests were conducted on a cable-stayed bridge with 2 piers and a mid span of 800 m. Two piers were distinct from the west and east by their construction location; in this research, only the west pier was analyzed.

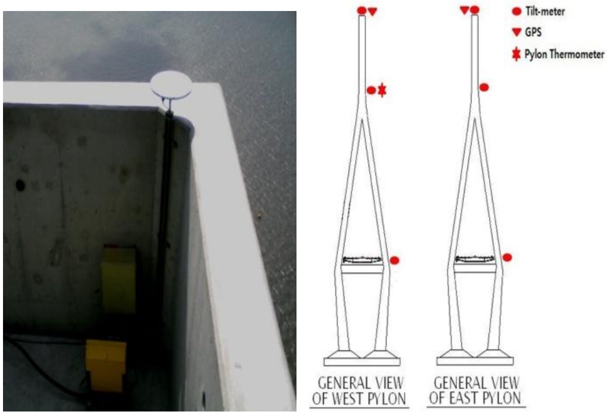

Figure2. Installation of sensors

6.1.1 Data Analysis of Tilt-meter:

The inclination of the west pier was analyzed using data collected from tilt-meters. This observation session lasted approximately 50 days, from the 1st of May to the 19th of June. The raw data obtained via tilt-meters is represented in units of degrees, and the sampling rate was 10 minutes. These data were converted to deflections using the distance unit by deflection equations introduced in section 4. The equation constructed by the three tilt-meters has three unknowns and can be converted into a quadric equation by the first integration to convert the deflection equation. Because the inclination at the point of support can be assumed to be zero, this quadric equation can be solved using three inclinations obtained from tilt-meters. First, Figure 3 below describes the analysis results of data collected by tilt-meters and is represented by three colours that correspond to the analysis of different locations. As expected, according to the installation location, the amount of inclination would clearly exhibited differences.

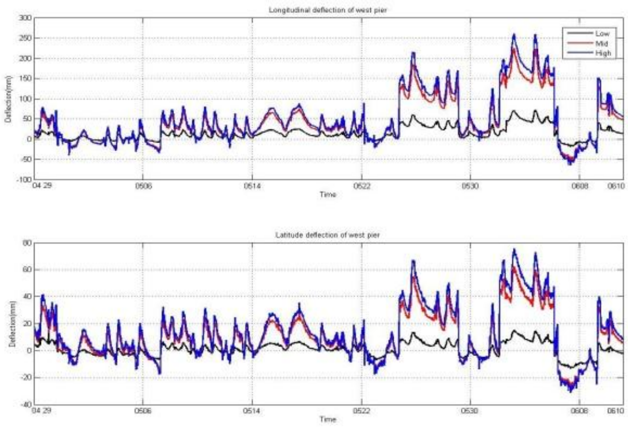

Figure3. Analysis of tilt-meters

As can be seen from figure 3 above, the longitudinal deformation of the pier to the under-construction bridge was 280~313% bigger than that of the latitude direction. Furthermore, the Standard Deviation (STD) is also larger by 2.7 times. The piers of bridges under-construction were being supported by only cables at the statue, which was not connected main segment. The unexpectedly large deflection may have occurred due to inequality of the moment caused by the use of various construction equipment and external loading. Therefore, continuous monitoring with regards to pier inclination is necessary for securing bridge safety.

6.1.2 Comparative Research on GPS and Tilt-meters:

In current large structure monitoring systems, such as those used on bridges, GNSS is widely utilized. This feasibility of such systems has been proven by previous research.[2],[3] However, it is difficult to determine the application of such systems for under-construction bridges. The application of GNSS-maintained requirement accuracy can provide many benefits to the monitoring systems of under-construction bridges. In this chapter, comparative reserch between GPS and tilt-meters is presented. For this investigation, two GPS recivers with 10 Hz sampling rates were installed at the top of the pier. Because the GPS and tilt-meters are set up in similar locations at the top, data measured by both sensors can be directly compared. The comparative research was performed by selecting a specific period that was judged to have stable GPS data collection. The entire observation session lasted for ten hours from the 29th of April. These GPS data were processed using a single baseline processing technique at a reference station 3 km away. Figure 4 below shows the results of analysis in both directions (Longitude and Latitude), and Table 1 presents a summary of the statistics for this result.

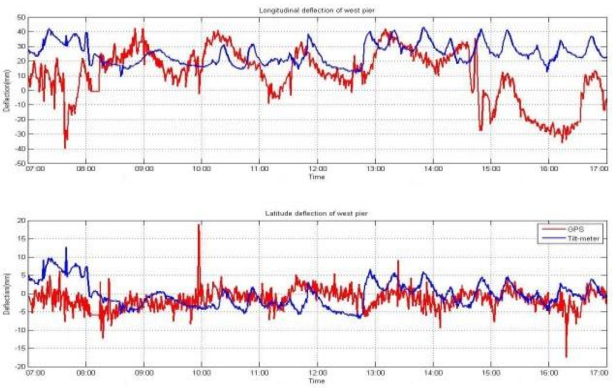

Figure4. Deflection of longitudinal and latitude directions

As shown in the figure above, the pier inclination in the latitude direction was bigger than that of the longitudinal direction. This is because the main deformation of under-construction bridges occurs in the longitudinal direction.

	Longitude(mm)			
	Mean	Max	Min	STD
GPS	24	43	9	18
Tilt-meter	11	43	-40	7
	Latitude(mm)			
	Mean	Max	Min	STD
GPS	-1.694	18.91	-17.5	2.7143
Tilt-meter	-0.421	12.6	-6.8	3.469

Table1. Statistics for both devices

The results of analysis of the tilt-meters (converted from inclination angle to deflection) and GPS were compared directly using the graph and table. As can be seen from results above, the results of the tilt-meter analysis were more stable than that of GPS. Although the GPS analysis in the latitude direction is more stable than that obtained using tilt-meters, the main point of monitoring with regard to pier inclination is to focus on the longitudinal direction; this is because the movement of longitudinal direction is more affected by overall bridge movement. From the graph above, it can be seen that there are many fluctuations in the GPS analysis, and the standard deviation of the GPS analysis is bigger than that of tilt-meters by a factor of approximately 2.45. It is assumed that this result is closely related to the site of the under-construction bridge. Various construction equipment, such as tower cranes and the construction site itself, create a multipath environment. These can directly affect the GPS positioning solution. In general, the monitoring of inclination angle with regard to pier or girder relies on terrestrial surveying such as total station or levelling in the construction field. However, this method is restricted by the available measuring period due to the effect on temperature and exposed to limitation in terms of the durability. GPS can overcome the limitations that characterize terrestrial surveying. However, the environments of under-construction bridges may cause some critical problems in terms of GPS surveying. This is deeply related to the required accuracy, which is typically regarded to be at the sub-centimetre level. It is thought that these limitations can be overcome through modelling of multipath environments that may frequently occur at the sites of bridges under-construction and integration with other GNSS systems. The reason environmental factors were not analyzed is that pier inclination was more shown to be more affected by construction procedures. Therefore, it is not easy to identify the deformation effect resulting from environmental factors.

6.2 Analysis of the inclination angle of the pier in an in-service bridge

A comparative research test was conducted at the SeoHae cable-stayed bridge. Because a BMS is under operation at the SeoHae cable stayed Bridge, it was relatively easy to collect data. Data collection was conducted using sensors that were already installed in the pier on the 25th July 2010 for approximately 10 hours. Figure 5 below shows the installation sites of sensors on the pier.

Figure5. Tilt-meters and GPS

As mentioned previously, at least three tilt-meters are required to efficiently monitor the inclination angle of the pier of cable-stayed bridges. Three tilt-meters were already installed on this bridge. However, in the case of GPS, if one GPS-receiver is installed at the top of pier, the three dimensional position estimates can be assessed because the inclination angle is zero at bottom of pier. Moreover, its position estimates are represented as meter-unit displacements. From this data, it is possible to monitor the inclination angle of the pier. Although this must be quite efficient in terms of sensor installation and data management, the most important factor, the accuracy of the sensors, is first considered. To this end, comparative research between the two sensors was conducted to assess accuracy. The Figure 6 below depicts the location of the sensors.

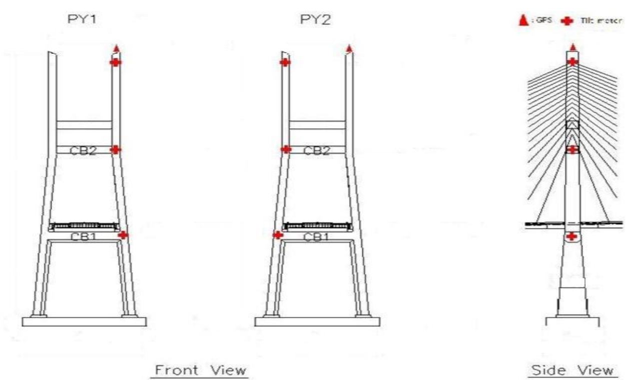

Figure 6. Location of sensors

6.2.1 Data Analysis on Pier Inclination: In this bridge, th piers are defined as number one and number two fc convenience, and data analysis was performed at both piers fc this research. Before the full-scale analysis on inclinatio deflection was performed, we determined whether or not th initial inclination angles achieved from tilt-meters converged t structural analysis. The structural analyses are as follows: [5]

- Structural analysis to longitudinal direction: -3346 ~ +455 μradian

- Structural analysis to latitude direction: -1554 ~ +1554 μradia

The results above reveal that the inclination angles fit th desired range. Figure 7 below shows the data analysis estima using tilt-meters through both piers. These outcomes are a expressed as inclination deflections. The data are representec different colors on the graph according to their installat location. The outcome of these analyses revealed that deflection of pier 2 exhibited more fluctuations. This was u for the data analysis of environmental factors that is presen in the next chapter.

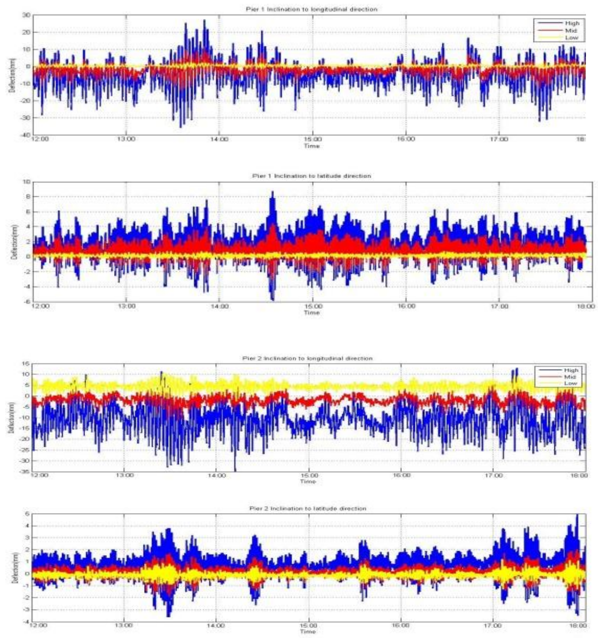

Figure7. Analysis results of tilt-meters and GPS

As in the previous experiment, comparative research was performed by sensors installed similar locations at the top. GPS receivers located on the bridge as a rover were employed using identical products produced by Trimble Navigation Ltd, and the antenna used was a NetR5 model. The antenna used at the reference station was a Zephyr Geodetic Model 2 model. Each receiver gathered data continuously at a rate of 20 Hz for the entire observation session.

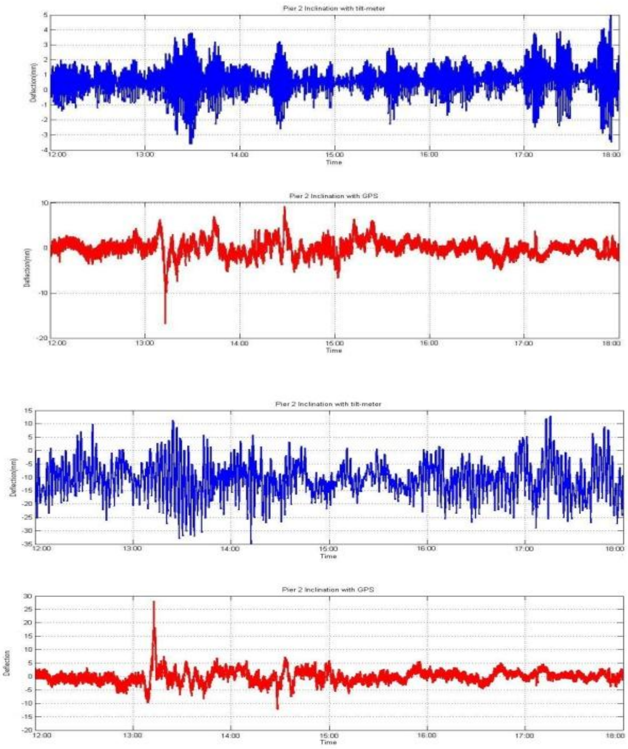

Figure8. Tilt-meter and GPS analysis

Table2 below is summarizes the statistics of the GPS and tilt-meter analysis. The values of means were significantly different while the values of standard deviation (STD) were similar. As can be seen from figures above, if the section that was contaminated by the multipath environment is excluded, it can be concluded that GPS displays more stable deflections in the rest of the bridge.

Longitude Deflection								
	GPS (mm)				Tilt-meter (mm)			
	Max	Min	Mean	STD	Max	Min	Mean	STD
PY1	26	-29	3.2	7.445	27.1663	-35.8876	-5.6883	8.3276
PY2	17	-12	1.8	2.15	12.9	-34.9	-11.5947	6.8692
Latitude Deflection								
	GPS (mm)				Tilt-meter (mm)			
	Max	Min	Mean	STD	Max	Min	Mean	STD
PY1	11	-12	1.3	2.74	8.7278	-5.884	1.2074	2.0462
PY2	9	-17	0.45	1.63	5	-3.6	0.5082	1.0069

Table 2. Comparatives research of both sensors.

Although the analysis outcomes achieved from both sensors exhibited non-similarity in the specific section, it can be concluded that the overall tendency was similar during observation session. Thus, GPS can assist the role of tilt-meters, or even replace these under conditions in which tilt-meters are unavailable in the future. Figure 9 below depicts on-hour the maximum deflections of piers on 14:00 25th of July 2010.

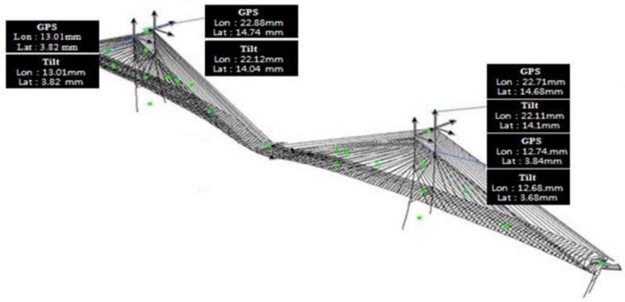

Figure9. Analysis results of tilt-meters and GPS

The primary purpose of this comparative research was to determine the capability of GPS to improve BMS. The results revealed that GPS can be fully performed in terms of the inclination monitoring of pier. However, it was observed that the accuracy of GPS must also be increased. In the result of GPS processing, there were a number of contaminated error sources that are expected in multipath environments. Therefore, research related to multipath environments should be considered in the future. Furthermore, the effects of multipath environments should be assessed. Such studies would likely increase the reliability of BMS based on GNSS. As a result, the overall application and serviceability of and monitoring systems can be substantially enhanced.

6.2.2 Environmental effects: Cable-supported bridges, such as suspension and cable-stayed bridges, exhibit continuous deformation or deflection of overall structure members throu various external loading. Particular attention must be paid periodical deformation by environmental factors for secur the safety of bridges. From such research, the correlat between these factors and deformation can be determined. T following investigation analyzed the structural deformat through wind and thermal loading, which both significar affect deformation. The currently available techniques focused on determining the location and degree of dam using the changed parameters of structures. Using th techniques, varied structural parameters estimated by measuring forced vibration or ambient vibration of structures can be calculated, and structural identification using changed parameters can be performed. There is an assumption that the changes in the parameters of structures is caused only by damage. In other words, changes to structural parameter caused by factors other than damage are minute, and can even be ignored. Thus, it is true that, in terms of environmental factors, only wind loading and earthquakes can affect the structures that are considered. However, there should be certain deformation resulting from external loading and changed temperature and humidity applied to large sized structures such as cable-stayed bridges. In the particular case of temperature, because this affects overall material characteristics, its influence should be cautiously analyzed in terms of bridge. Therefore, an analysis for monitoring changes in structural parameters with regard to changed temperature is described in the next chapter. This is because large sized bridges are frequently installed in hostile environments such as mountains and seas. Thus, changes in structural deformation caused by wind and thermal loading are more likely to cause direct damage to structures.

6.2.2.1 Wind Velocity and direction: Due to the all-round development of all fields of engineering, structural materials have been improved, and the expectations that the infrastructure service-using public have of technologies has increased. Because of these increased expectations, the span of bridges has become longer. To meet current demands, it is necessary to construct special bridges that are required high-technology, such as suspension and cable-stayed bridges. In general, in long span bridges high-strength steels or pre-stress concrete are used to reduce fixed loads. Using such materials, the thickness of the sections can be decreased, and the weight of such components can even be reduced. Due to such reductions in weight, long span bridges exhibit flexible characteristics and may easily be vibrated by dynamic loading such as wind. Therefore, the more the span of a bridge is lengthened, the more the safety of bridge is affected by wind resistance in comparison to shock-resistance. Therefore, when a long span bridge is developed, the determination of stability with regard to dynamic wind loading should represent a dominant factor in the bridge design. In cable-supported bridges that have lightweight cables, flexibility is increased and the natural frequency is lower. Therefore, such bridges may exhibit noticeable vibration when exposed to relatively low wind speeds. This effect can lead to structural fatigue result in discomfort to the public using the bridge. Moreover, vibration at high-wind speeds can be primary cause of structural collapse. Therefore, the effect of wind on long-span bridges must be investigated. [1] The purpose of wind vane and wind gauge installations is to measure the size and occurrence of the possible maximum wind when cable support bridges are constructed. Measured wind is used to analyze the deflection of the members of a bridge. The correlation between wind effect and deflection of each member can be also obtained due to the occurrence of maximum wind. Using such methods, the safety of both the bridge and bridge users can be secured.

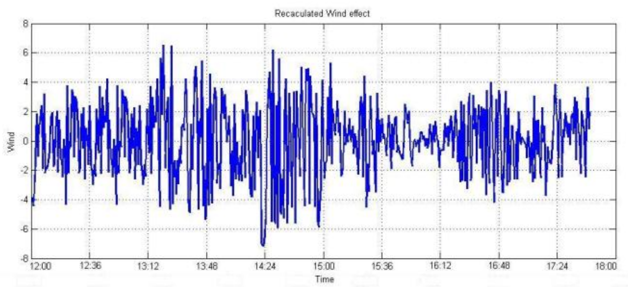

Figure10. Recalculated wind loading

Figure 10 above shows re-analysis results in which the effect of wind loading is only considered relative to the perpendicular direction of deck by calculating wind velocity and direction. F The strength of wind was first analyzed relative to the perpendicular direction of bridge deck by calculating an azimuth of bridge and the direction of wind. This investigation was conducted at pier 2, which was more susceptible deflection. The analysis session recorded the maximum wind during an approximately three hour period from 12:00 to 15:20 on the same day. Data collected during this period was used to investigate the correlation between the strength of the wind and the pier inclination.

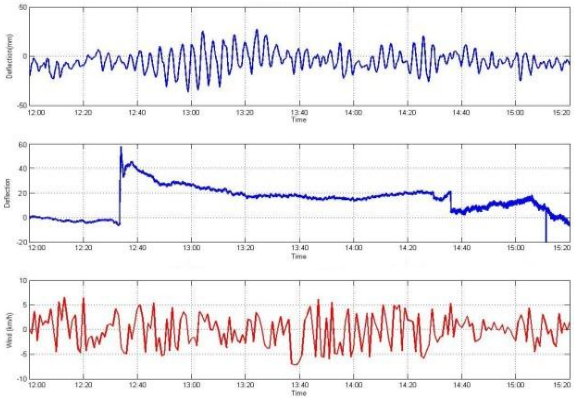

Figure11. Effect of wind on pier inclination

Figure11 shows the data analysis from both sensors and the recalculated wind effect during the detailed period. Table 3 below describes the statistic of data analysis and compares it with the data analysis of the total period.

Tilt-meter (mm)		
	Total period	Detailed period
Max	27.1663	27.1663
Min	-35.8876	-35.8876
Mean	-5.6883	-5.2606
STD	8.3276	9.7711
GPS (mm)		
	Total period	Detailed period
Max	58	58
Min	-23	-23
Mean	12	15
STD	2.91	11.1
Recalculated wind (km/h)		
	Total period	Detailed period
Max	6.5303	6.5303
Min	-7.1492	-7.1492
Mean	-0.1266	-0.2856
STD	6.5303	9.2359

Table3. Statistics of correlation research

This research regarded the early stage as equivalent to determine the effect of the strength of wind with regard to pier inclination. To facilitate a more precise analysis, the strength and direction of wind to random wind loading should be estimated more clearly.

6.2.3 Data Analysis for long-term monitoring :

Monitoring related to the inclination of the pier should be considered in terms of both short-term deflection induced by unexpected external loading and long-term deformation normally resulting from environmental factors. It is inevitable that excessive changes of pier inclination affect the amount of deflection and dynamic characteristics of result analysis; moreover, these unusual results could threaten overall bridge safety. The short-term monitoring investigated previously at a stretch of bridge and the long-term monitoring, which was performed over seven years and can be considered relatively long-term, were investigated in this chapter. Figure 10 below shows the monitoring results with regards to the inclination of pier performed over an approximately seven-year period.

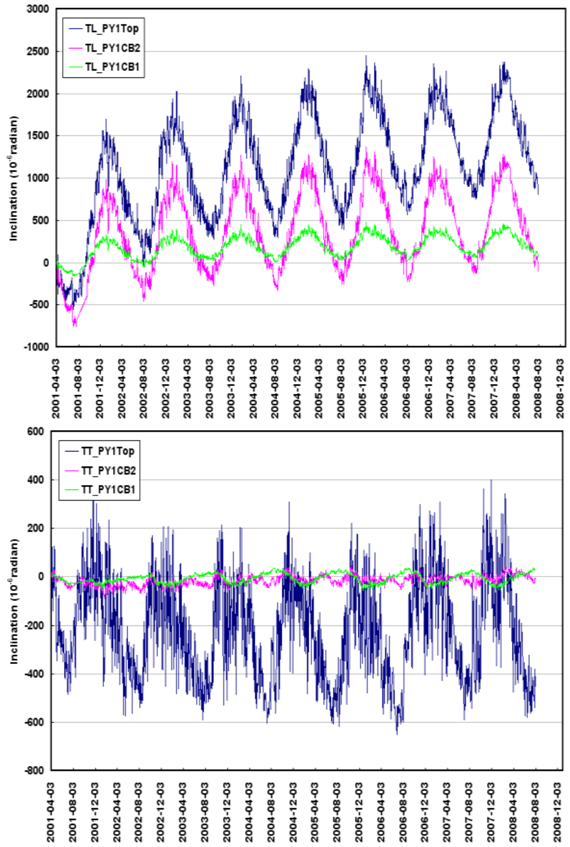

Figure12. Long-term monitoring analysis

As a consequence, it is possible to ascertain that longitudinal deflection has increased from the time the bridge was initially completed. On the other hand, the lateral deflection shows a more stable inclination. The deflection to longitudinal direction was analyzed as follows. Deflection monitoring of the pier typically occurred as a result of changes in temperature and creep and drying shrinkage. Based upon this, the investigation was conducted by sorted seasons that exhibit different temperature patterns. As can be expected, the piers exhibit different moving directions. Figure 12 below shows the moving direction of the pier due to seasonal change. In the summer, the pier was moved to an outside direction of the bridge, while it was moved to the inside in winter. Therefore, overall movement of the pier exhibited different dimensional movements according to the season.

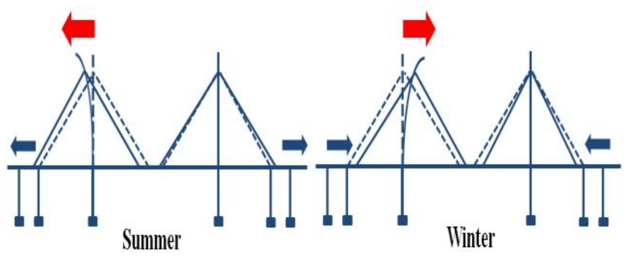

Figure13. Seasonal deformation direction of pier

7. INCREASE ON PRACTICAL VALUE OF GPS FOR SPECIFIC CONSTRUCTION METHOD

In terms of bridge construction, various methods have been developed and are being used over the course of this research. These can be separated according to the location, purpose, materials used and the superstructure type of the bridge deck. In this chapter, the ILM (Incremental Launching Method) construction method will be introduced. Superstructures are made in advance and are produced in segments at manufacturing facilities located on the tail of bridge deck and are. Generally, one segment consists of two or three separate pieces. These have the parallel compressive force that can be passed through the span of the bridge and then are imposed to pre-manufactured superstructures (segments) using the post-tension method. In the ILM method, each segment is pushed using special “pressing out” equipment in the longitudinal direction, after being exposed to pre-stress. The advantage of this method is expressed in economics and convenience by developing a PTRF Sliding Pad. Figure 14 below depicts a bridge deck being constructed using this method.

Figure14. ILM Construction Method

The method was introduced to restrict the usage of tilt-meters, which are installed for to monitor the inclination of the deck in this method. This means that tilt-meters are not suitable for this method in terms of real-time monitoring and maintenance. Thus, GNSS is the only alternative for monitoring the inclination of the deck during the construction of the bridge deck by this method. It is thought that a GNSS receiver installed at the end of a segment can monitor the inclination of the deck in real time. This can increase the practical value of GPS, and the monitoring limitations exhibited by this specific construction method can be solved. However, no reported field tests have been conducted thus far, and the required accuracy of GNSS is also under investigation; thus, both of these factors must be simultaneously considered.

8. CONCLUSION

This research investigated the optimal maintenance of tilt-meters, which measure the inclination of the pier and improve the applicability of GPS with regard to BMS. In an earlier study, the issues and limitations of tilt-meters were described. In current BMS, tilt-meters or terrestrial surveying equipment is/are commonly used for measuring pier inclination. In the case of tilt-meters, data obtained using such devices is initially represented as an inclination angle. This inclination angle is then converted to inclination deflection, which is displayed by the meter-unit. In this research, the optimal number of tilt-meters was determined. Based on these results, it is concluded that more efficient and stable data collection can be achieved in future monitoring systems. It is expected that this will contribute to the development of structural technology. Thus, GNSS, which has a great efficiency and superiority in terms of maintenance of sensors, comes to the fore as an alternative to current monitoring system. To assess the applicability of GPS, several tests were conducted in both in-service and under-construction bridges. The results from these are as follows.

1. In terms of bridges under-construction, comparative research was performed with regard to the inclination of pier by using both GPS and tilt-meters. The outcomes of tests conducted during approximately ten-hour periods were analyzed in both directions (i.e., longitude and latitude). In the longitudinal direction, tilt-meters exhibited more stable analysis results than GPS. In particular, the STD of tilt-meters was better by a factor of 2.54 in comparison to the STD of GPS. However, GPS exhibited better results in the direction of latitude. Even though the outcomes of GPS were better in the latitude direction, the accuracy of GPS should be increased in the longitude direction because the longitude direction is the main direction in the deflection monitoring of piers. It is expected that the reason GPS exhibited unstable outcomes is closely related to the environment of construction site. Construction equipment located on construction site may induce the multipath sources.

2. Ccomparatives research was also conducted on in-service bridges following the monitoring of pier inclination of bridges under-construction. It was conducted using relatively stable GPS data analysis compared to the monitoring of bridges under-construction. As the result of the comparative research, GPS was shown to enable more stable data analysis in the direction of longitude, while tilt-meters exhibited better outcomes in the direction of latitude. There was an apparent larger deflection of pier 1 out of the two piers tested. In the monitoring of pier inclination of an in-service bridge, a higher similarity of data outcomes estimated through both sensors was found relative the results obtained from monitoring an under-construction bridge. In other words, the construction-site environment is unfavourable for the operation of GPS. In addition, correlation research with regard to environmental factors was conducted in monitoring pier inclination. Wind loading data collected during the same observation session was investigated with regards to its effect on pier inclination. The detailed period in which the maximum wind was recorded was compared with the total period in terms of statistics such as STD and mean. As a result of this, the outcomes analyzed during the detailed period exhibited larger fluctuations than those of the total period. This indicates that wind loading affects the deflection of pier inclination. There is a known, commonly recorded significant difference in temperature between the summer and winter seasons. Correspondingly, the deformational direction of piers exhibited opposite moving directions upon changes of season. This is related to the deflection of the deck due to changes in temperature.

Finally, the applicability of GPS with regard to BMS was evaluated in this study. Because the applicability of GPS is clearly shown, the increasing accuracy of GPS is an essential priority due to the nature of BMS, in which the insurance of safety should be a primary focus. In particular, this should be more highly emphasized in the application to bridges under-construction. In the future, GNSS will become an important technology in the field of BMS due to its high reliability and convenience of maintenance.

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