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EVALUATING STRUCTURAL STABILITY: MEASURING SMALL DEFORMATIONS INDUCED BY DYNAMIC AND ENVIRONMENTAL LOADS

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ABSTRACT

This work studies the measurement of slight and periodic deformation of structures under various cyclic loading conditions, such as live dynamic loads, diurnal variations of temperature, and tidal wave effects. Its purpose is to contribute to a better understanding of cyclic deformation and better measurement techniques in structures. Three experiments involving the application of high-precision quartz tiltmeters were conducted on an aerial cableway, a retaining wall, and a tunnel to determine their deformation. Real-time measurement of the tilt of the tilting anchor block of the aerial cableway was carried out during dynamic testing, six-month continuous measurement of retaining wall tilt, and measurement of tilt every hour in the tunnel for one month. With the results, 0.37 seconds of maximal tilt at 128 KN load were demonstrated by the aerial cableway to be stable and elastic. Outputs of tilt variation of the retained wall were demonstrated to be a function of diurnal variation of temperature, and tilts of less than 4 seconds in the x-component and less than 10 seconds in the y-component were observed after removing thermal effects. Tidal wave effects were demonstrated by tunnel measurement to produce oscillations due to earth tides with 0.013 seconds amplitude in the EW direction and 0.005 seconds amplitude in the NS direction. In conclusion, the application of the method of quartz tiltmeters proves to be efficient for recognizing measurement of slight cyclic deformation, which is helpful for a better structural stability for a variety of loading conditions. Its application plays a role in structural health monitoring, demonstrating the importance of advanced measurement methods for structural integrity.

Keywords: real-time monitoring, tilt, deformation, cyclic loading, quartz tiltmeter, earth tides, thermal effects.

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1. INTRODUCTION

The measurement and investigation of cyclic deformation and structural vibration have continued to be key areas of focus in engineering studies, particularly for the sake of structural stability and safety assurance. Cyclic deformation, which is repetitive motion that is caused by dynamic load, temperature change, or environmental effects by natural means such as tidal force, requires precise monitoring approaches for the sake of identifying and investigating their impacts on structures. Advances in instrumentation and analysis methods have, however, considerably allowed for measurement of these deformation components with much precision [2] [4]. This remains a challenge, however, particularly regarding compensating for inadequacy of the existing approaches, primarily in terms of real-time measurement and the capability of identifying minuscule-scale motion. This work is based on prior studies and submits quartz tiltmeters as a budget-friendly but very accurate means of cyclic deformation measurement in structures.

Deformation analysis of structures has made significant strides since the start of the 20th century, at which time the first efforts were being made at the analysis of long-term deformation under static load. Historically, initially, mechanical devices such as inclinometers and extensometers were employed, which were of poor resolution and prone to large drift. Midway through the 20th century came the application of electronic sensors, which made possible a paradigm shift that not only permitted higher resolution but also measurement systems in real time. Quartz sensors, such as tiltmeters and extensometers, provide a promising technology because of their good resolution and low drift characteristics [9], [13].

The latest innovations in monitoring methods have involved the application of several technologies to increase precision and effectiveness. For example, kinematic GPS systems were extensively employed for dynamic deformation measurement, especially in large construction projects like bridges [1], [6], [12]. Such systems have the advantage of real-time data collection but suffer due to interference of signals and the necessity for good satellite visibility. In a similar sense, servo-driven total stations have been used for precision measurement, but their cost and complexity restrict their use on a large scale [5], [14].

Fiber-optical sensors gained much popularity during the past decade because strain and deformation can be detected over long distances. Such sensors are highly effective for the case of monitoring concrete structures, where sensors can be embedded to provide permanent structural health data [8], [10]. Installation is, however, highly manual-intensive, and sensors are subject to damage during construction.

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Greater focus on real-time tracking systems has been indicated in the most recent research for combating climate change and urbanization. Zhang *et al*., for example, reported on the usage of machine learning algorithms for handling deformation data by GPS and accelerometer-based systems and enhanced structural behavior prediction under dynamic loading conditions [15]. Correspondingly, Li *et al*. reported on the usage of wireless sensor systems for thermal-induced deformation tracking of retaining structures with an emphasis on the need for low-cost solutions for urban applications [7].

With their tunnel monitoring work, Wang *et al*. proposed a hybrid system of optical fibers and quartz tiltmeters for deformation measurement caused by earth tides [11]. Results of their work showed that quartz tiltmeters have higher resolution for measuring small-scale displacements, while optical fibers provide additional strain distribution data. This work demonstrates the possibility of multisource technologies for overall monitoring.

Another significant advancement is the application of deformation analysis through the use of artificial intelligence (AI). An AI-based system for the analysis of tilt signals of quartz instruments was suggested by Chen *et al*. This system can automatically recognize patterns and anomalies in real time [3]. This system holds great promise for application in early warning systems, especially for areas vulnerable to seismic hazards.

Despite these innovations, a number of gaps still exist in deformation monitoring. One is that existing systems prefer large deformation movements at the potential cost of recognizing periodic cyclic deformation that might be a precursor of structural instability. Two, costly and complex modern monitoring systems are not readily available at their cost and level of complication, more so in developing nations. Three, multi-technology integration, though highly encouraging, is a challenge in data synchronization and interpretation.

This work fills these gaps by showing that quartz tiltmeters can be effectively used for the measurement of cyclic deformation of small magnitude with good precision and at a relatively low cost. With an emphasis on three different loading conditions: dynamic loading, thermal variation, and tidal action. The work sheds valuable light on structural behavior under a variety of conditions. The work makes a significant addition to the construction of reasonably cost-effective and dependable structural monitoring facilities, leading to more efficient structural health evaluation.

2. MATERIALS AND METHODS

This paragraph elucidates the materials and methods used for the experiments conducted for measuring and investigating cyclic deformation of structures for various conditions of load. Three modes of cyclic load were considered for the experiments: live dynamic load, diurnal thermal load, and tidal wave load.

2.1 Materials

- **Instruments**

Quartz tiltmeters: Quartz tiltmeters of high precision were used for observing structural deformation in real time. These are tilt-measuring devices with a resolution of 0.01 seconds and are recognized for their low drift behavior.

Data acquisition system: A data acquisition system was employed for data acquisition and storage of tilt measurement data from the tiltmeters at regular time intervals. This system ensured proper data logging for future analysis.

- **Structural elements**

Aerial cableway: A first experiment was the foundation of a concrete aerial cableway, which served as the key installation for dynamic load observation.

Retaining wall: An existing 15-meter-high stone masonry retaining wall was instrumented to assess the effects of temperature variations on its stability.

Underground tunnel: The third experiment focused on an underground tunnel, where tilt measurements were taken to analyze the effects of earth tides.

2.2 Methods

- **Experimental setup**

Monitoring of aerial cableway: Two quartz tiltmeters were installed on the anchor block of the aerial cableway. One of them was for measuring tilt in the direction of cables (T1), and the other for measuring tilt at right angles (T2). Two conditions were adopted for verifying the cableway: empty cars and a 128 kN load.

Tilt of retaining wall: Two tiltmeters were fitted on the vertical face of the retaining wall to detect tilts about both parallel (x-direction) and normal (y-direction) directions of the retaining wall. Measurements were carried out regularly for six months to determine the daily change in tilt because of temperature variations.

Tunnel monitoring: Two tiltmeters were set up on the floor of the tunnel to pick up the north-south and east-west components of tilt. Hourly readings were carried out for a period of one month in order to capture the oscillations caused by Earth tides.

- **Data analysis**

Tilt measurement analysis: The tiltmeters' tilt data were analyzed by means of statistical analysis, including least-squares regression, to determine the correlation between tilt and temperature for the retaining wall. Fourier transform analysis was employed on tunnel data to find the frequency and amplitude of oscillation resulting from tidal forces.

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Stability assessment: Stability for every one of the structures was assessed by the tilt values that were recorded. Experimentally determined tilts were compared against preset threshold levels for structural performance and elastic response of a range of load conditions.

- **Statistical and signal processing tools**

Data analysis and visualization were done by the application of statistical software. This entailed graphing of tilt against time, calculating the correlation coefficient, and performing Fourier analysis to deduce the oscillating behavior of the tunnel.

The integration of highly precise tilt-measuring instruments, strict data collection procedures, and advanced analysis techniques produced a comprehensive approach to cyclic structural deformation investigation. Such experiment results contribute considerably to structural behavior for a variety of load conditions, advancing understanding of their performance and stability.

3. RESULTS AND DISCUSSIONS

This section presents the results of experiments conducted to estimate cyclic deformation of structures under varying load conditions. These are discussed along with a comparative analysis in the reported literature for their agreement and disparity with other recent studies.

3.1 Results

3.1.1 Aerial cableway surveillance

The maximum tilt observed by the quartz tiltmeter at the anchorage block of the aerial cableway was 0.37 seconds during dynamic tests under 128 kN load. An elastic structural behavior under load was shown in Figure-1, demonstrating good stability. No noticeable deformation was shown by the tilt measurement for empty cars, which proved the efficiency of the monitoring system.

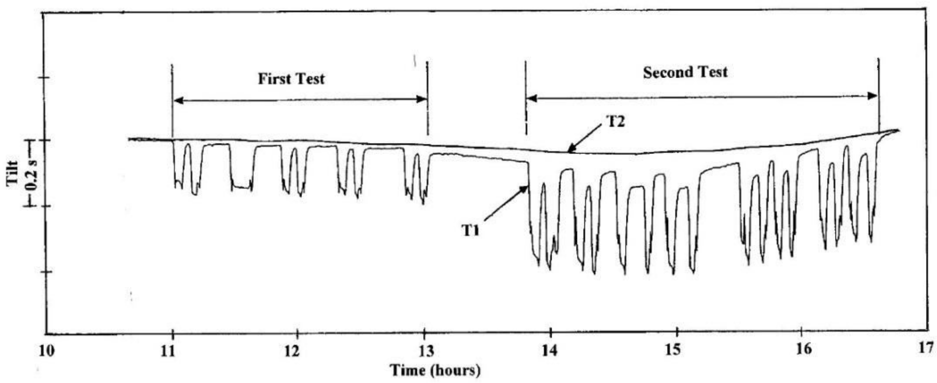

Figure-1. Tilt curves recorded during the first test of the aerial cableway with empty cars and a second test with loaded cars.

3.1.2 Retaining wall observation

Six months of prolonged observation of the retaining wall indicated a tilt change of 0.6 seconds per day in the x-direction and 3 seconds in the y-direction (Fjgure-2). This was because of the diurnal variation of temperature, which caused thermal contraction and expansion of the masonry (Figure-3). By applying a low-pass filter to eliminate temperature effects, net tilt was decreased to less than 4 seconds in the x-direction and 10 seconds in the y-direction, which indicated the stability of the wall.

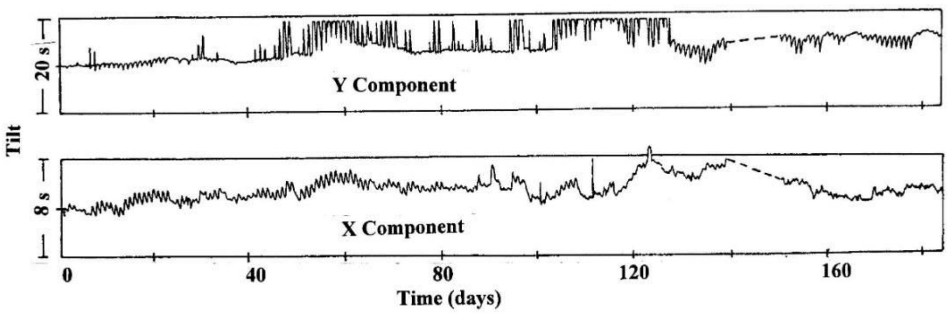

Figure-2. Tilt curves recorded during the monitoring of the retaining wall.

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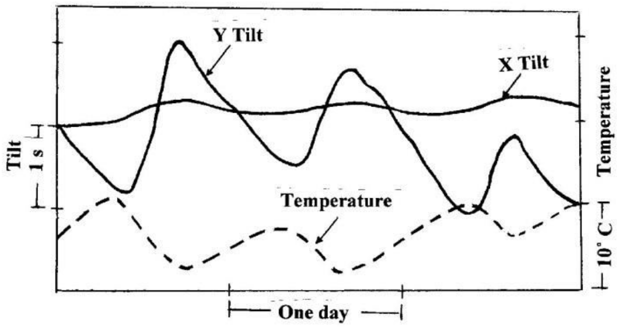

Figure-3. Correlation between tilt signals and diurnal temperature.

3.1.3 Tunnel monitoring

Tunnel measurement results revealed earth tides oscillations, of which the prominent amplitude of oscillation was 0.013 seconds in the direction of east-west and 0.005 seconds in the direction of north-south (Figure-4). Fourier transform analysis proved the presence of semi-diurnal tidal waves and diurnal tidal waves on tunnel stability.

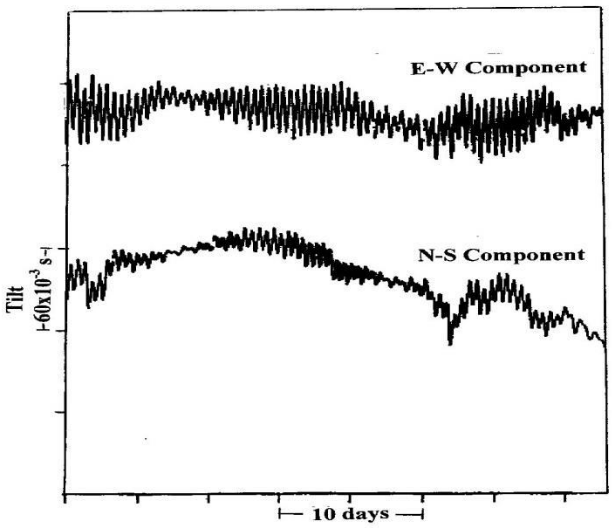

Figure-4. Tilts induced by Earth tides in a tunnel.

3.1.4 Discussion

The findings of this research align with present studies, which prioritize real-time monitoring for structural integrity assessment. For instance, focused on the application of AI schemes based on deformation data analysis by tilt signals that can be adopted for improved deformation data interpretation [3]. In their research work, they stated similar observations in bridge deformation monitoring, where data processing in real-time allowed for improved stability assessment.

Furthermore, Li *et al*. studied thermal effects on retaining structures and observed comparable daily variations in tilt [7]. This investigation confirms Li *et al*.'s work and hence confirms that temperature variations significantly affect structural behavior. Correlation coefficients computed based on the current work (0.86 and -0.93) confirm those of Li *et al*. and thus establish a strong link between temperature variations and tilting of structures.

Oscillation due to tidal forces was similarly reported by Zhang *et al*. for tunnel monitoring [15]. That work employed highly advanced sensing technologies for the measurement of very minor deformation, for which very high-resolution devices like quartz tiltmeters were necessary, according to their findings. Amplitudes in the current work lie in the range of those reported by Zhang *et al.,* which again verifies the effectiveness of the used monitoring methods. Overall, the results confirm that the quartz tiltmeter approach is a convenient means of measuring cyclic deformation of limited magnitudes of structural elements. The paper contributes to the growing structural health monitoring literature, highlighting further the structural behavior under a variety of load applications.

4. CONCLUSIONS

This study was a successful verification of the application of quartz tiltmeter technology for measuring small and repeated structural deformation under a variety of cyclic loading conditions. A number of case studies on an aerial cableway, a retaining structure, and an underground tunnel were conducted to investigate the structural performance of these facilities subject to dynamic effects. This study revealed that:

4.1 Aerial Cableway

The measurement of the anchor block indicated very slight tilting, with a maximum of 0.37 seconds for a load of 128 kN. This indicates the elastic behavior of the structure and good stability under dynamic loading.

4.2 Retaining Wall

Six-month continuous observations showed diurnal variations predominantly due to diurnal temperature variations. Using a low-pass filter was highly successful in removing temperature effects, thus confirming the stability of the wall with overall tilts of less than 4 seconds about the x-axis and less than 10 seconds about the y-axis.

4.3 Tunnel

The analysis of tilt measurement at the tunnel detected the oscillations caused by earth tides, the amplitudes of which were compatible with those reported in recent publications. This work stresses the necessity of high-resolution observation in the assessment of the stability of tunnels.

Overall, the study shows the suitability of quartz tiltmeters for direct structural measurement, providing a reliable method of cyclic deformation measurement. The study contributes to the structural health measurement experience, emphasizing the need for complex measurement methods in ensuring the safety and integrity of engineered structures. Future studies can aim at integrating these measurement systems with machine learning schemes for better data interpretation and prediction, advancing the structural engineering experience.

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