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TESTING PROCEDURES FOR THE MONITORING OF SEISMIC INDUCED VIBRATIONS ON A CABLE-STAYED HIGHWAY BRIDGE

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Abstract

The acquisition of structural response data during earthquakes is essential to confirm and develop methodologies for analysis, design, repair and retrofitting of earthquake resistant structural systems. Accelerometers are most commonly used to monitor structural systems during earthquakes but do not directly measure structural displacements. Geodetic techniques, including robotic total stations and Global Positioning System (GPS) technology, provide supplementary sensors by giving direct displacement information in real time. The paper reports on sets of experiments designed to examine the suitability of geodetic techniques for monitoring the dynamic response of control points on the deck of the Evripos cable-stayed bridge in Greece. Results from a robotic total station and GPS receivers are presented in conjunction with respective displacements derived from the permanent accelerometer network suite of the bridge, highlighting the advantages and disadvantages of each monitoring system.

1. Introduction

Many cable-supported bridges have been constructed around the world. Superb performance of cables in tension along with unique appearance and aesthetics are two important incentives for creation of these landmark structures. Despite the advantages associated with cable structures, there are several concerns for the use of cable-stayed bridges (the newer generation of cable-supported bridges) due to high stress concentrations in anchorage zones and susceptibility to high frequency induced vibrations. Low frequency vibrations (from wind and traffic loading) are generally confronted with continuously modified cable systems and local damage detection methods for wire break detection (eg Mehrabi et al., 1998; Suzuki et al., 1988). High frequency vibrations, such as those caused by seismic events, are more problematic.

Incidents of major damage in cable-stayed bridges (eg the Zarate-Largo bridges in Argentina, (Main and Jones, 1999)) highlight the need to develop monitoring systems and preventative measures. Continuous monitoring regimes on bridge structures can be approached either from the material or from the structural point of view. In the first case, monitoring concentrates on the behaviour of the local properties of the materials under load or ageing. In the structural approach, the bridge is observed from a geometrical aspect whereby the displacements of critical pre-defined locations are calculated. It is then possible to extrapolate the global behaviour of the construction materials to the whole structure. Historically, most research has been concentrated on material rather than structural monitoring, due to the availability of reliable strain sensors (Inaudi et al., 1996). The design of a comprehensive instrumentation system for long term structural monitoring of bridges remains a challenging research issue.

Large amplitude vibrations induced by weather conditions, traffic and other load forces are generally investigated during the design phase of a bridge. Analytical models derived from known material properties can confidently predict bridge vibration modes under most conditions. However, the likely impact of seismic induced forces on a structure is invariably less well known, predominantly because earthquakes have irregular recurrence intervals and varying force patterns. While accelerometers are traditionally used for safety monitoring of seismic and other hazards in large structures, they have a major disadvantage in that are unable to directly measure bridge displacements during a seismic event in close to real time. Further limitations on accelerometer monitoring are imposed by the high cost of equipment installation and maintenance. Advances in the use of modern surveying techniques, such as electronic distance measurement (EDM) and the Global Positioning System (GPS) offer an alternative method to augment existing monitoring regimes for relatively straightforward recovery of absolute displacements in a pre-orientated reference frame (eg Wieser and Brunner 2002; Roberts et al., 2001; Wong et al., 2001; Watson and Coleman; 1998; Santerre and Lamoureux, 1997).

The monitoring of structures during and after seismic events is of particular interest mainly because even relatively small but unexpected responses can have significant implications for a structure's safety. In this case, rapid access to data collected after a seismic event is critical to ensure public safety and reduce downtime for the structure in question. Geodetic monitoring can provide measurements of relative displacements in near real-time and help identify the dynamic characteristics of vibrating systems. The information collected on the response of the structure during and after seismic events can be used by building operators and structural engineers to detect changes in the structure's resonant frequency. This, in combination with structural drift estimates derived from the positioning data obtained by GPS or EDM may allow early detection of structural damage.

Previous work by Tsakiri et al. (2001) studied the implementation of a GPS-based monitoring system on the Evripos bridge in Greece. Further work in this area has shown that to provide complete information about the dynamic response of a structure during any potential seismic event, an integrated structural monitoring system comprising several sensors is preferable to single sensor systems. This paper considers implementation of a structural monitoring system, comprising a robotic total station and GPS receivers, for providing measurements of absolute displacements. The test site is the bridge over the Evripos Channel, on the island of Evia in Greece. It is located about 30km away in a north-easterly direction from the 55km long fault of Atalanti. This fault presents regular seismic activity causing high frequency (>3Hz) bridge motions. Issues regarding hardware configuration and data collection are examined. Results from high frequency GPS and EDM measurements (angles and distances), collected from predetermined critical locations on the bridge, are evaluated with respect to displacements derived from a permanent accelerometer network.

2. The accelerometer network of the Evripos cable-stayed bridge

The Evripos bridge in Greece connects the island of Evia to the mainland. The bridge measures 700m in length, with the main span being 215m long and 40m high. Since 1994, a permanent accelerometer network of 43 sensors has been operating on the bridge. The positions of the sensors are selected so that complete recording of the dynamic behaviour of the bridge is possible. Six vertical and two transverse sensors record the response at the middle span of the bridge, whilst six sensors are installed on each of the two piers. There are also four triaxial sensors, two located at the base of each pier and two free-field that measure the acceleration time histories. The solid-state accelerometers are interconnected to provide common triggering, common sampling and common timing.

While the accelerometer network has been running continuously registering motions due to wind and traffic loading since installation, in the last few years emphasis is given only to certain high frequency events and only data caused by seismic induced motions of the bridge are being recorded. Many small and medium size earthquakes, with their epicenter being at distances in the order of 15-97km away from the bridge, have been registered by the system. Table 1 gives the most significant recent earthquake events that have triggered the accelerometers of the system.

Date	**Time**	**Location**		**Depth**	**Magnitude**	**Distance from bridge**
	GMT	$\varphi^{o}_{(N)}$	$\lambda^{o}_{(E)}$	**(km)**	**(M_W)**	**(km)**
1997 March 21	06:17	39.301	23.769	8	5.0	97
1998 May 22	16:22	38.495	23.428	19	4.3	15
1999 Sept. 07	11:57	38.059	23.571	14	5.9	43
2001 July 26	00:22	39.039	24.339	7	6.4	93
2001 July 26	00:35	39.017	24.321	4.65	5.3	90

Table 1. Recent earthquakes that triggered the accelerometer system of the Evripos bridge

Fig. 1 depicts the location of the earthquakes' epicenter (circle) while the star indicates the location of the Evripos bridge.

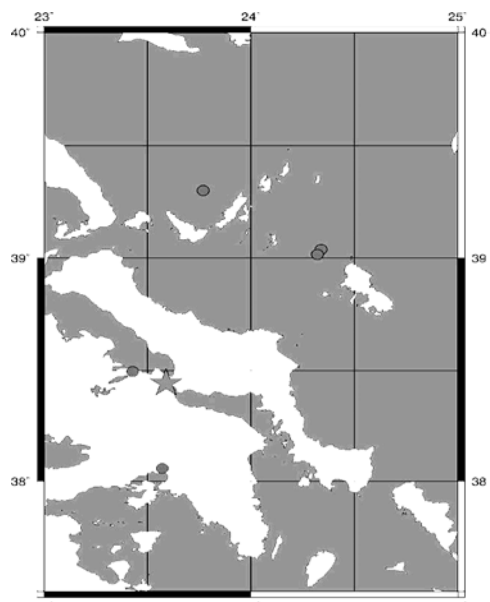
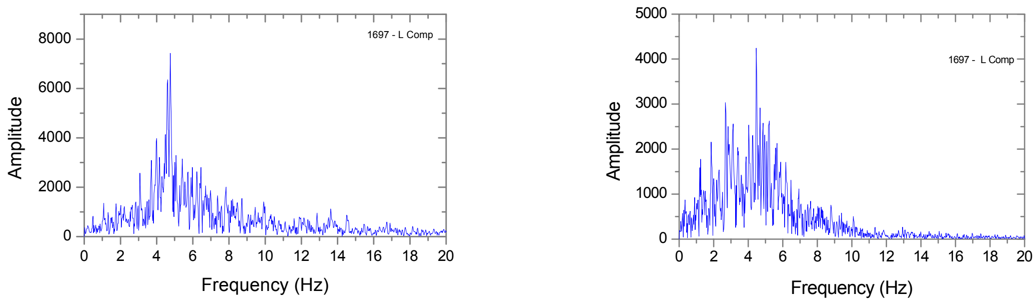


Fig. 1. Locality map of recent earthquakes' epicentre near the Evripos bridge

The most significant seismic events in Table 1, which have had an impact on the vibration response of the Evripos bridge due to their intensity, are the earthquake in Athens (7 September 1999) and the earthquakes at Skyros (26 July 2001). Fig. 2 shows an example of the power spectra derived from the accelerometer data registering from both earthquakes. The data illustrated refer to the same accelerometer, situated on a bridge pylon. It can be seen that this pylon presents a basic frequency of 0.4Hz (2.55sec). This is the same frequency observed on accelerometers located on the middle of the bridge's deck, indicating a strong interaction between these parts of the structure through the cabling design (Lekidis et al., 1999).



(a) earthquake of September 1999 (b) earthquake of July 2001

Fig. 2. Earthquake response spectra for pylon

Close inspection of Fig. 2 shows that a second modal frequency of 0.36Hz has been triggered. This value coincides with that derived from the theoretical analytical model of the bridge. Further modal frequencies at 0.9Hz and 0.33Hz have also responded due to the vibration of the structure. Such information is critical to the evaluation of the seismic performance of the bridge and to the development of analytical modeling in order to capture the overall linear and non-linear seismic response under ground motions. Determination of the modal parameters from dynamic measurements is very useful in model update, damage assessment, active control and original design evaluation.

3. Geodetic measurements

Experiments using geodetic monitoring techniques were carried out to investigate their capabilities for continuously monitoring points and determining the response of the bridge to dynamic loading effects caused by traffic, wind or seismic vibrations. Fig. 3 shows the location of the monitoring stations on the deck of Evripos bridge. Three geodetic Javad receivers (GPS/GLONASS Legacy) were used, out of which two were employed as reference receivers located on bedrock, on pillars about 300m away from the bridge. Observations at 10HZ sampling rate on both L1 and L2 frequencies were recorded in sessions of 4 hours (one session per monitoring point). Additionally, a robotic total station (Leica TCA 1800) was employed to provide independent observations of the motion of the points. The total station was collecting data at a rate of about 8Hz. Similarly, the instrument was located on a stable pillar outside the bridge's area. The two monitoring points were placed on the middle of two spans of the bridge where large displacements can be experienced. These were established on the concrete surface of the bridge's deck, each one next to an accelerometer. A special prism and antenna mount was used so that simultaneous monitoring using GPS and total station measurements could be obtained, retaining mount verticality without using a tripod. Previous work by Tsakiri et al. (2001) has shown that GPS displacement solutions exhibit high noise from the instability of the GPS receivers being setup on tripods on the bridge deck as well as centring problems. Furthermore, the use of tripod makes it difficult to distinguish between the actual motion of the monitoring points and the motion of the tripod.

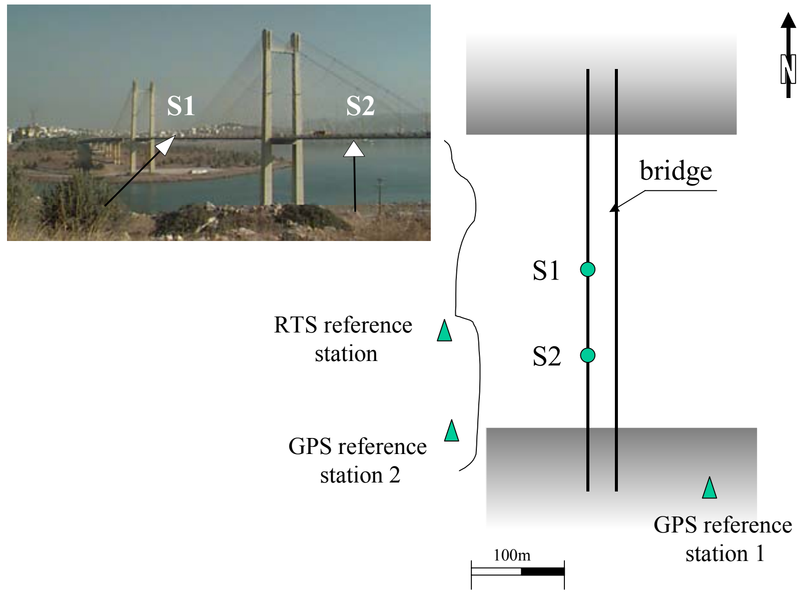


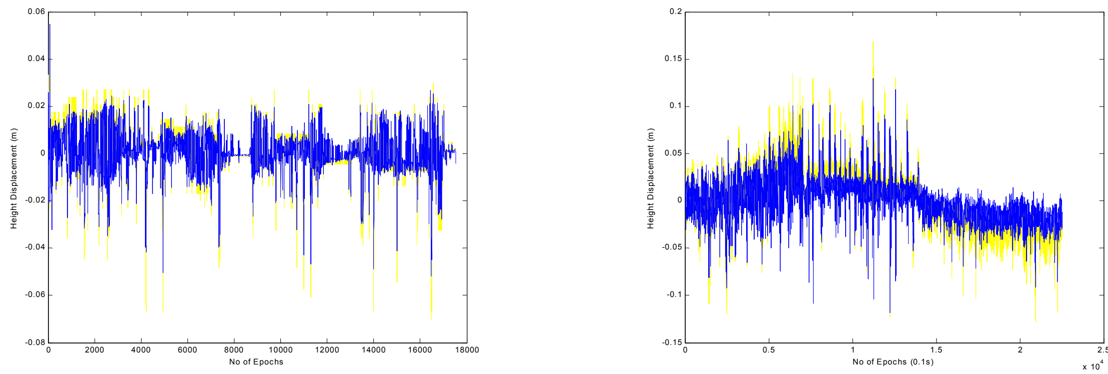
Fig. 3. Evripos cable-stayed bridge and monitoring points

The carrier phase data from both L1 and L2 frequencies were processed using in-house kinematic post-processing GPS software (Forward et al, 2001). Ambiguities are resolved each epoch by applying a tight initial constraint on the approximate coordinate of the unknown point. This coordinate has been previously estimated by a conventional static GPS solution. The epoch-by-epoch ambiguity fixed solutions become geometrically more robust by the use of data from two fixed reference stations, although baseline correlation must be taken into account. During data collection, the satellite availability varied from 4 to 11 satellites, with PDOP varying from less than 4 to greater than 14. Poor PDOPs were associated with poor sky visibility caused by the location of the GPS antennas on the deck of the bridge.

The mean formal accuracies of the estimated displacements in the three components of north, east and height were 6mm, 4mm and 11mm respectively for GPS. The robotic total station solutions yielded a precision of 5-6mm for north, east displacements and 2-3mm for absolute height displacements. The observation precision of the total station is quoted by the manufacturer as ±10mm+2ppm in range for the rapid tracking mode and 5" in vertical angles. Also in this mode, the total station has a limited range of 1km.

For brevity, this paper will focus on data from one monitoring point, S1, located at the middle span of the bridge. The response of point S1 over the observation period is shown in Fig. 4. The dominant loading effect was due to traffic on the bridge. Within the period of the experiment, other effects, such as wind or thermal effects, were insignificant. There was no seismic activity during the experiment. Fig. 4 represents the displacement in the height component only, displacements in the horizontal component being of insignificant magnitude over the course of the experiment. Such a situation automatically puts GPS at a disadvantage, with height being the most imprecisely determined component from GPS solutions. Fig. 4a refers to the robotic total station measurements and Fig. 4b to the GPS measurements. While the height variation of the total station time series is noisy but shows a periodic pattern of motion, the equivalent time series derived from GPS presents a long period drift. The range of the measured displacement is about 4cm for the total station and

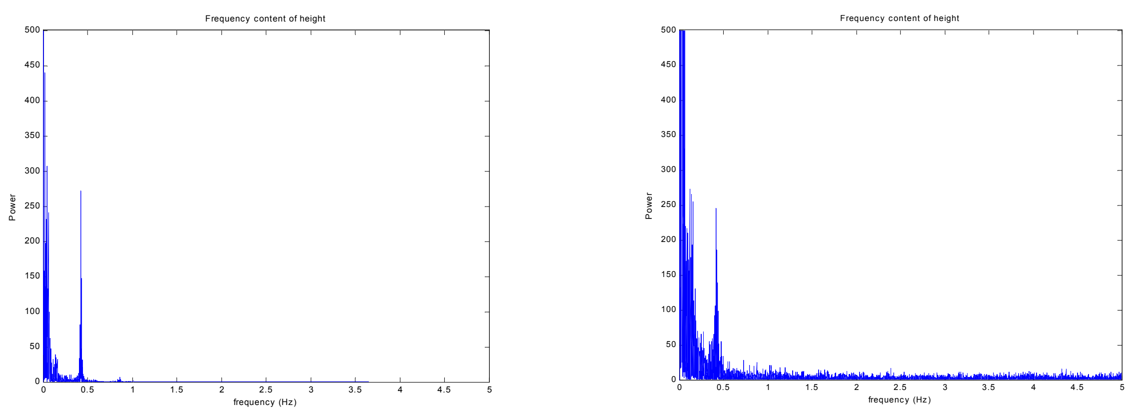
12cm for the GPS time series. Clearly there are more unmodelled residual errors in the GPS series with the most dominant being the multipath caused by the steel cables of the bridge and problems caused by weak satellite geometry. Poor signal quality is expected in this type of environment, but the results published by other authors for similar situations (eg Wieser and Brunner, 2002; Roberts et al., 2001) suggest that GPS may still be useful. The greater precision (2-3mm in the vertical component) and unbiased nature of the total station time series indicates the superiority of the total station solutions over the GPS solutions.



(a) Total station observations

(b) GPS observations

Fig. 4. Time series of height variations for point in middle of the deck bridge



(a) Total station power spectra

(b) GPS power spectra

Fig. 5. Spectral analysis of height displacement for point S1

The spectra of the height displacements derived from the total station and GPS data are given in Fig. 5. Similar spectral analyses for a suspension bridge have been reported by Xu et al. (2002). A dominant peak is seen at about 0.5Hz in both graphs. This indicates that these geodetic survey systems are capable of identifying structural motions on the bridge of frequencies up to at least 0.5Hz. It is interesting to notice the power at longer periods present in both graphs. Periods of up to 10s have been detected with the total station. The GPS spectrum indicates more power at low frequencies, caused by the long wavelength biases seen in Fig. 4b. Furthermore the peaks in the

GPS spectrum are more 'spread' than for the total station, as a direct result of the GPS solution being an order of magnitude noisier than the total station solutions.

The spectra shown in Fig. 5 correspond well to the first values of the theoretical modal frequencies of the bridge, which are given in table 2. It can be seen that the theoretical modal frequencies have very close values to each other, making them difficult to resolve individually. However, the dominant features are close to 0.5 Hz, which corroborates with the results from Fig. 5.

Mode	Period (sec)	Frequency (Hz)
1	2.579	0.388
2	2.446	0.409
3	2.131	0.469
4	1.710	0.585
5	1.452	0.689

Table 2. First five modal frequencies of Evripos bridge

This simple test highlights that the use of geodetic measurements at sampling rates of 10Hz can provide a clear measurement of displacement responses at lower frequencies and allow the extraction of the mode frequencies of the structure. This is extremely useful for on-line health monitoring. As the sensors measure different quantities (displacement and acceleration) at different frequencies (8Hz, 10Hz for the geodetic sensors and 50Hz for the accelerometers) it is impossible for the geodetic sensors to resolve the full range displacements shown in Fig. 2. However, with 100Hz GPS receivers such as the Javad JGG100 (www.javad.com) coming into the market, there is an obvious potential for GPS to provide more high frequency information than accelerometers.

4. Concluding remarks

Experiments using geodetic monitoring techniques on the Evripos cable-stayed bridge have shown that their measurements can identify the response signature of some natural or ambient excitations, such as traffic, wind, earthquake and their combination. In these experiments only response data of ambient vibrations were measurable but the actual loading conditions were unknown. While the data have succeeded in identifying key response modes only from traffic loading, these can be applied also to the modal identification of natural-excited responses, such as from earthquakes. The geodetic measurements can offer additional information to accelerometer data for the structural analysis and obtain more precise characteristics of the signal vibration. In this particular case, geodetic measurements can provide direct displacement measurements in the 0.1Hz to 2Hz frequency range, complementing the accelerometer data which best operates in the high 1Hz – 20Hz frequency range.

Whilst the robotic total station solutions yielded a precision of 2-3mm for absolute height displacements, the GPS results indicate that the bridge deck is not well suited for high precision monitoring due to shading and diffraction effects caused by the steel cables. GPS solutions revealed long period biases, probably due to multipath and weak satellite geometry. However, GPS is capable of providing higher frequency information than the total station. A possible solution would be the direct integration of the GPS and total station raw data to provide an 'optimised' geodetic displacement solution combining the high frequency GPS data with the lower frequency, but more precise total station data.

Integrated geodetic systems could be easily set up for continuous bridge monitoring, providing near real-time displacement solutions. Such systems would have advantages over accelerometer data, which require suitable processing involving double integration and requisite steps of filter choice for signal processing in order to compute displacements. Although it is not desirable to completely replace an accelerometer network with geodetic sensors, judicial placement of geodetic sensors could supply important addition information to allow for fast determination of structural modal parameters on site for on-line health monitoring.

The emergence of receivers with high logging rates (eg 100Hz) is likely to make GPS a technique that can provide data directly comparable with accelerometer data in the high frequency range. In future, the cost of a permanent monitoring network could be significantly reduced by the use of high precision GPS OEM boards as part of an augmented monitoring system, replacing accelerometers located on the top of pylons and in places of the structure with unobstructed satellite visibility.

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