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RECENT DEVELOPMENTS ON DYNAMIC MONITORING OF STRUCTURES

Mehmet Çelebi
USGS (MS977), 345 Middlefield Rd., Menlo Park, Ca. 94025
[Tel: 650-329-5623, Fax: 650-329-5143, e-mail: celebi@usgs.gov]

ABSTRACT: In this paper, a cursory summary of current seismic instrumentation objectives and methods are discussed. Such instrumentation evolved over 3-4 decades aims to obtain response data to facilitate studies to improve design and analyses procedures. However, with recent advances in electronic hardware and transmission of data, the objectives of applying dynamic monitoring of structures are shifting from its former objectives to real-time assessments of health of structures. As an example, use of Global Positioning System (GPS) to dynamically monitor long-period structures such as tall buildings and long-span bridges is now a reality. Such developments can be used to make decisions to assess the safety of structures and the public using them.

Özet: Bu tebliğde, güncel olarak kullanılan sismik aletsel ölçmenin amaç ve yöntemleri özetlenmektedir. Son 30-40 yıl içerisinde uygulamalar, genellikle, yapıların deprem esnasındaki tepkilerinin kaydedilerek davranışları hakkında incelemeleri ve dizayn ile analiz metodlarının geliştirilmesini amaçlamaktadır. Diğer yandan elektronik veri aktarımı ile donanımda kaydedilen ilerlemeler sonucu, dinamik davranışın gözlenmesindeki hedef yapıların sağlık durumlarını anında belirlemeye yönelmektedir. Buna örnek olarak Global Pozisyon Sistemlerinin (GPS) bugün için dinamik davranışın takip edilmesindeki etkinliği gösterilmektedir. Bu gelişmeler, yapıların sağlığı ve dolayısıyla yapıları kullanan halkın emniyeti ile ilgili kararlar verilmesine yardımcı olmaktadır.

Introduction

Using various tools and methods, structures have been, are being and will be monitored when it is necessary to assess their responses to changing external and internal dynamic effects in addition to its static environment. The internal and external dynamic effects may be due to random occurrences of strong shaking caused by earthquakes or strong winds. In general, in earthquake prone areas, as well as in areas where strong winds cause significant vibrations of structures, monitoring the responses of structures has been a primary method to facilitate response studies such that the analyses and design processes can be improved. To this end, different types of structures have been instrumented with arrays of accelerometers so that when accelerations exceed a pre-determined threshold, the signals from the accelerometers deployed at key locations of a structure are recorded to be processed and studied.

Recently, such monitoring has had major leaps due to vast advances in data acquisition and transmission technology as well as evolving uses of response data. Now, real-time monitoring is a reality. Thus, recent trends in dynamic monitoring is slowly shifting the objective of monitoring from acquiring data to facilitate response studies to assessing the state of health of a structure, in real-time or near real-time. These advances in technology and changes in objectives have wide implications in validation of performance of a structure.

The purpose of this paper is to introduce one of the recent developments in dynamic monitoring of structures including use of Global Positioning Systems (GPS) and wireless monitoring.

Current Methods

In general, an instrumented structure should provide enough information to (a) reconstruct the response of the structure in enough detail to compare with the response predicted by mathematical models and those observed in laboratories, the goal being to improve the models, (b) make it possible to explain the reasons for any damage to the structure, and (c) facilitate decisions for strengthening, retrofit and response modification needs. The nearby free-field and ground-level time history should be known in order to quantify the interaction of soil and structure.

Therefore, until recently, the main objective to date has been to facilitate response studies in order to improve our understanding of the behavior and potential for damage of structures under the dynamic loads of earthquakes. As a result of this understanding, design and construction practices can be modified so that future earthquake damage is minimized. Up to now, it has not been the objective of either instrumentation program to create a health monitoring environment for structures. Thus, the principal objective has been the quantitative measurement of structural response to strong and possibly damaging ground motions for purposes of improving design and construction practices.

Ultimately, keeping cost issues in mind, the types and extent of instrumentation must be tailored to how the data acquired during future earthquakes will be utilized. Although several data utilization objectives may be interwoven, it is important to consider in advance how the data is to be used. Table 1 summarizes some sample data utilization issues with sample references.

Code versus Extensive Instrumentation

The extent of instrumentation has evolved over the last 3 decades. The most widely used code in the United States, the Uniform Building Code (UBC-1997 and prior editions), recommends, for seismic zones 3 and 4, a minimum of three accelerographs be placed in every building over six stories with an aggregate floor area of 60,000 square feet or more, and in every building over ten stories regardless of the floor area. The purpose of this requirement by the UBC was to monitor rather than to analyze the complete response modes and characteristics. UBC-code type recommended instrumentation is illustrated in Figure 1a.

The de-emphasizing code-type instrumentation is as a result of strong desire by the structural engineering community to gather more data from instrumented structures to perform structural response studies. Experiences from past earthquakes show that the minimum guidelines established by UBC for 3 tri-axial accelerographs in a building are not sufficient to perform meaningful model verifications. For example, three horizontal accelerometers are required to define the (two orthogonal translational and a torsional) horizontal motion of a floor. Additional vertical sensors at the base facilitate assessment of rocking, if any. As illustrated in Figure 1b, this type of instrumentation scheme is called the ideal extensive instrumentation scheme. Whenever physically feasible,

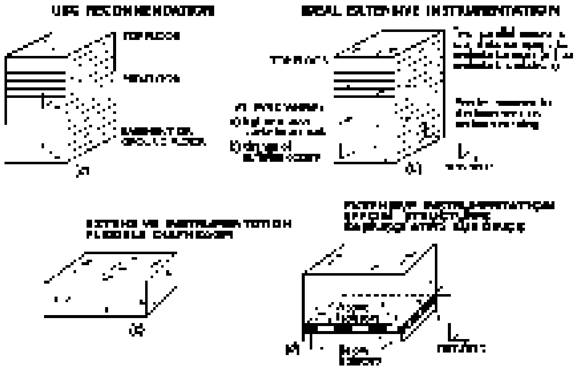

Figure 1. Typical Instrumentation Schemes

Table 1. Sample List of Data Utilization Objectives [Details of References referred to in this table can be found in Çelebi, 2001)

GENERIC UTILIZATION
Verification of mathematical models (usually routinely performed) (*e.g.*Boroschek et al, 1990)
Comparison of design criteria vs. actual response (usually routinely performed)
Verification of new guidelines and code provisions (*e.g.*Hamburger, 1997)
Identification of structural characteristics (Period, Damping, Mode Shapes)
Verification of maximum drift ratio (*e.g.* Astaneh, 1991, Çelebi, 1993)
Torsional response/Accidental torsional response (*e.g.* Chopra, 1991, DeLalera, 1995)
Identification of repair & retrofit needs & techniques (Crosby, 1994)
SPECIFIC UTILIZATION
Identification of damage and/or inelastic behavior (*e.g.* Rojahn & Mork, 1981)
Soil-Structure Interaction Including Rocking and Radiation Damping (Çelebi, 1996, 1997)
Response of Unsymmetric Structures to Directivity of Ground Motions (*e.g.* Porter, 1996)
Responses of Structures with Emerging Technologies (base-isolation, visco-elastic dampers, and combination (Kelly and Aiken, 1991, Kelly, 1993, Çelebi, 1995)
Structure specific behavior (*e.g.* diaphragm effects, Boroschek and Mahin,1991, Çelebi, 1994)
Development of new methods of instrumentation/hardware {[e.g. GPS] (Çelebi et. al., 1997, 1999, 2001, [e.g. wireless] Straser, 1997)}
Improvement of site-specific design response spectra and attenuation curves (Boore, et. al. 1997, Campbell, 1997, Sadigh *et. al.*, 1997, Abrahamson and Silva, 1997
Associated free-field records (if available) to assess site amplification, SSI and attenuation curves(Borcherdt, 1993, 1994, Borcherdt, 2001, Crouse and MacGuire, 1996)
Verification of Repair/Retrofit Methods (Crosby et al, 1994, Çelebi and Liu, 1996)
Identification of Site Frequency from Building Records (more work needed)
RECENT TRENDS TO ADVANCE UTILIZATION
Studies of response of structures to long period motions (e.g. Hall et al, 1996)
Need for new techniques to acquire/disseminate data (Straser, 1997, Çelebi, 1997, 1998)
Verification of Performance Based Design Criteria (future essential instrumentation work)
Near Fault Factor (more free-field stations associated with structures needed)
Comparison of strong vs weak response (Marshall, Phan and Çelebi, 1992)
Functionality (Needs additional specific instrumentation planning)
Health Monitoring and other Special Purpose Verification (Heo et al, 1997)

associated free-field sensors are required to interpret the motion of the foundation relative to the ground on which it rests. Furthermore, specially designed instrumentation arrays are needed to understand and resolve specific response problems.

For example, thorough measurements of in-plane diaphragm response requires sensors in the center of the diaphragm (Figures 1c) as well as at boundary locations. Performance of base-isolated systems and effectiveness of the isolators are best captured by measuring tri-axial motions at top and bottom of the isolators as well as the rest of the superstructure (Figure 1d). In case of base-isolated buildings, the main objective usually is to assess and quantify the effectiveness of isolators. If there is no budgetary constraints, additional sensors can be deployed between the levels above the isolator and roof to capture the behavior of intermediate floors.

High-precision record synchronization must be available within a structure (and with the free-field, if applicable) if the response time histories are to be used together to reconstruct the overall behavior of the structure. Such synchronization has been achieved through extensive cabling from the sensors to the recorder. Recent developments enable decreasing or minimizing and in certain cases eliminating use of extensive cabling. For example, the global positioning systems (GPS – for synchronization) is now widely used to synchronize a building instrumentation with that of a separate recorder system for the free-field; thus, eliminating cable connection between the free-field recorder and recorder within a structure. The issue here is that the choice of cable or wireless transmission for synchronization, becomes an integral part of the cost consideration for the instrumentation scheme.

Figure 2 shows instrumentation scheme for a non-typical building structure with three wings. In this cases, all wings and the core had to be instrumented to capture any effect of directionality of earthquake motions on such wing structures. The recording system in the structure consists of two 12-channel K-2's and another 6-channel K-2 to record the downhole and surface free-field motions at the south free-field site (Figure 2).

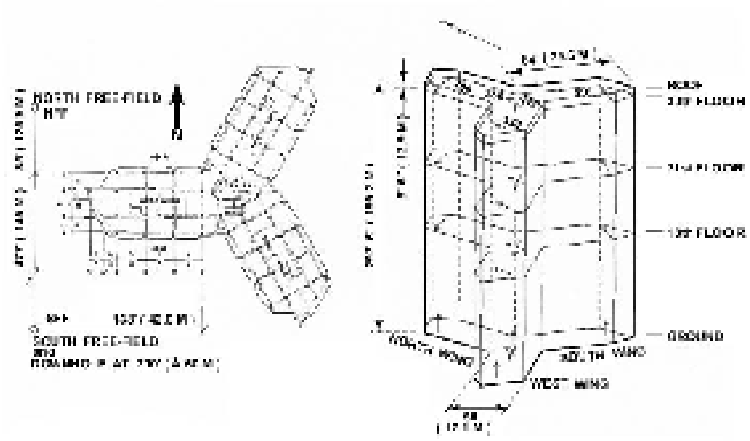

Figure 2. Instrumentation scheme of Pacific Park Plaza, Emeryville, California. The accelerometers shown are now connected to digital recorders. A tri-axial downhole accelerometer was added at the south free-field following 1989 Loma Prieta, CA earthquake.

Recent Developments in Real-Time Monitoring Using GPS

As explained above, measuring acceleration response has been and still is the most dominant method for monitoring response of structures. Once recorded, acceleration data is integrated twice to arrive at displacements. The integration process is not always readily automated because of the nature of signal processing, which requires (a) selection of filters and baseline correction (the constants of integration), and (b) use of judgment when anomalies exist in the records. Relative displacements, which are key to assessing drift and stress conditions of structures, are difficult to measure directly. However, an alternative method to measure relative displacements while monitoring structural systems can be accomplished by using real-time kinematic (RTK) GPS technology, now advanced to record at 10 sps (or better [e.g. 20 sps]) with an accuracy of ± 1 cm horizontally and ± 2cm vertically. Thus, it is possible to acquire dynamic displacements of long-period structures in real-time. Such data provides sufficient accuracy to compute the average drift ratio of a tall building or to monitor and act upon when a predetermined level of relative displacement at a particular location of a long-span bridge is exceeded. Such information can be very useful in assessing the damage to a building or long-period structure such as a long-span bridge.

To allow comparison of relative displacements measured by GPS and calculated by double integration of accelerations, GPS units were deployed in addition to accelerometers. All GPS antennas must have excellent sky visibility to communicate with a minimum of four satellites and to obtain the requisite signals to carry out the kinematic solutions within the specified horizontal and vertical errors.

We describe herein successful deployment of GPS units at the roof of a 34-story building in San Francisco (CA) - the first, permanent and pioneering deployment of GPS units (in the world) for continuous dynamic monitoring of tall buildings (Figure 3). A GPS unit (always tri-axial) and a tri-axial accelerometer each are deployed at two diagonal corners of the roof of the building to detect both translational and torsional motions. A third GPS unit is deployed as a reference at the roof of a single-story, very rigid, reinforced concrete shear wall building nearby (approx. 450m away). Our earlier tests and detailed descriptions of deployments, as well as summary of other GPS related studies for dynamic monitoring are provided elsewhere (Çelebi and others, 1999, and Çelebi and Sanli, 2002).

In Figure 3, a photo is included to show the GPS and radio modem antennas in one of the corners of the roof. Figure 4 shows samples of acceleration data from the accelerometer and displacement data from GPS, acquired during a windy day by manual triggering. Figure 5 shows a sample window of GPS and acceleration data streaming on the PC monitor. In absence of strong shaking data, the low-amplitude data will be used to demonstrate what the deployed system can more reliably record for future studies during strong shaking events. Figure 5 also shows cross-spectra of acceleration (from accelerometers) and displacement (from GPS) clearly identifying the fundamental frequency of the building at ~0.24-0.25 Hz. While manual triggering and recording any length of motions is always an option, the system is set to record at smaller thresholds to obtain data for additional studies (e.g. when 1 mm displacement or 0.5% of g acceleration is exceeded).

As the technical feasibility of recording GPS displacements with sufficient accuracy and amplitudes is being proven, the challenge is to determine how to make use of the relative displacements streaming through or being recorded. It is envisaged that measurement of roof top displacement has potential use in advancing and verifying performance-based design procedures since one of the key parameters used in the emerging performance-based design process is the roof top displacement of a building. As depicted in Figure 6, real-time structural health monitoring can be accomplished by configuring the GPS units such that they can provide data to indicate excessive displacements or significant changes in the dynamic characteristics for tall buildings

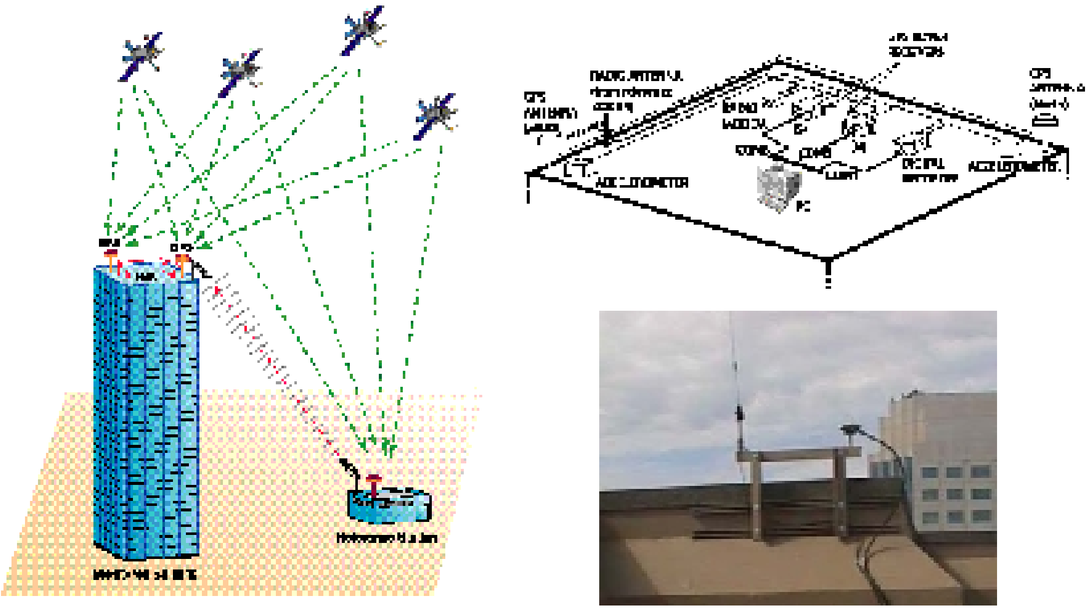

Figure 3. General schematic of the GPS deployment, layout of sensors and recorders and photo of GPS and radio modem antenna in San Francisco, CA.

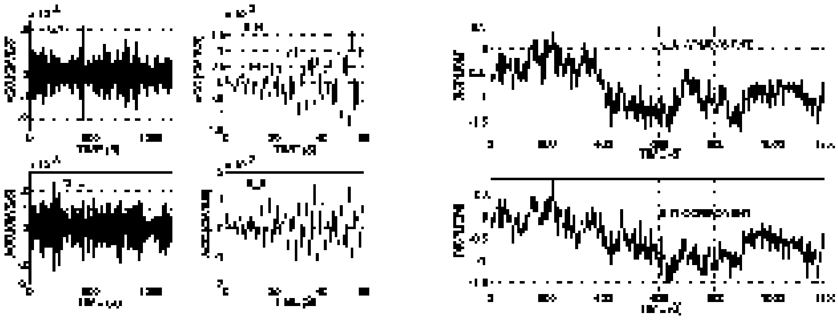

Figure 4. Remotely triggered and recorded accelerations at N (North) and S(South) locations (left) . The figure shows pairs of 1200 second long (and 60 second window from the same) record. At right, recorded displacements via GPS.

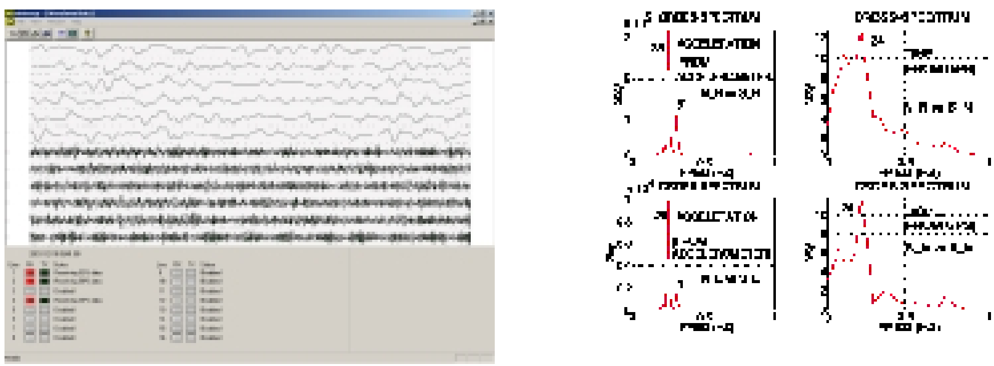

Figure 5. A window of data streaming in real-time,captured from the PC-monitor(left). Ttop 6-channels are displacements, bottom 6-channels are accelerations). At right, cross-spectra of accelerations recorded from accelerations and displacements recorded from GPS.

and long-span bridges or excessive average drift ratios of tall buildings. This information can be made available to site managers (or interested parties) in real-time or near real-time or whenever a predetermined displacement threshold is reached. The managers can assess the response of the buildings according to (a) different threshold displacements (e.g., A, B and C as shown in Figure 6), (b) drift ratios, or (c) temporally changing dynamic characteristics. If a situation is serious, the management can make decisions to evacuate the building for additional inspection and to secure the safety of the occupants and significant contents of the building. In cases of suspension or cable-stayed bridges, which usually have long fundamental periods, similar thresholds can be established to alert the management of excessive displacements and take action accordingly. In deployments of GPS units for bridges, sky visibility to see a sufficient number of satellites and appropriate reference station sites should not usually be a problem. Again, as for tall buildings, the streams of data from GPS units deployed on long-period bridges can be configured to fulfill the needs of bridge owners in providing public safety for such important lifeline structures. Such needs can be met by providing real-time alarms when and if predetermined thresholds of displacements at key locations are exceeded.

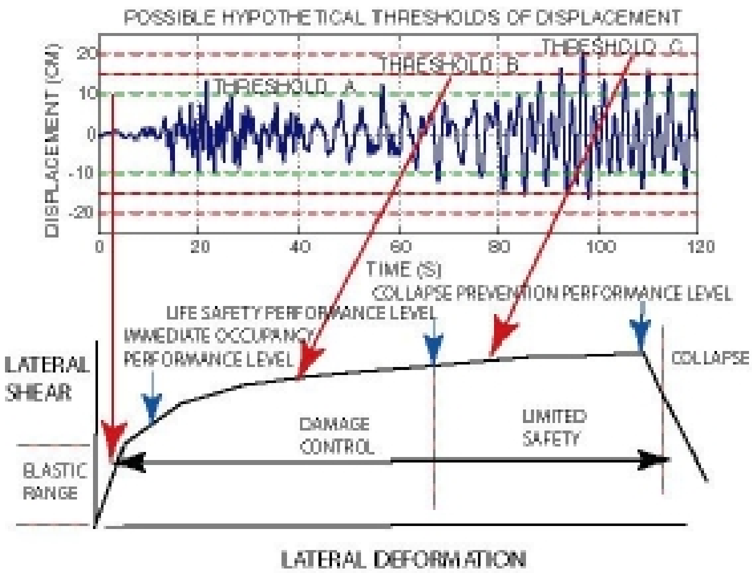

Figure 6. Hypothetical thresholds of displacements shown to demonstrate how GPS data can be configured to provide alarms at different amplitudes. Decision makers can use this information in various ways.

Conclusions

It is shown in this paper that recent advances in sampling rates of GPS technology allow real-time monitoring of long-period structures such as tall buildings and long-span bridges. The advantage over conventional monitoring using accelerometers is that relative displacements can be measured reliably in real-time and with sufficient accuracy to assess potential damage to the structures. The technical feasibility is illustrated through a set of manually recorded wind response records from a 34-story building in San Francisco, CA., now equipped with GPS units and accelerometers to provide synchronized, real-time displacement and acceleration responses. It is shown that GPS monitoring of long-period structures provide sufficiently accurate measurements of relative displacements such that dynamic characteristics of the vibrating systems can be accurately identified. This capability can be used for conventional or structural health monitoring purposes of long-period structures during earthquakes or strong winds

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