GPS in Pioneering Dynamic Monitoring of Long-Period Structures

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Global Positioning System (GPS) technology with 10–20-Hz sampling rates allows scientifically justified dynamic measurements of relative displacements of long-period structures. The displacement response of a simulated tall building in real time and permanent deployment of GPS units at the roof of a building are described. To the authors' best knowledge, this is the first permanent deployment of GPS units (in the world) for continuous dynamic monitoring of a tall building. Data recorded from the building during a windy day is analyzed to determine the structural characteristics. When recorded during extreme motions caused by earthquakes and strong winds, such measurements can be used to compute average drift ratios and changes in dynamic characteristics, and therefore can be used by engineers and building owners or managers to assess the structural integrity and performance by establishing pre-established thresholds. Such information can be used to secure public safety and/or take steps to improve the performance of the building. [DOI: 10.1193/1.1461375]

INTRODUCTION

Seismic monitoring of structural systems constitutes an integral part of National Earthquake Hazard Reduction Program of the United States. Until recently, monitoring the response of structural systems for the purpose of assessing and mitigating effects of earthquakes (and also severe winds) has relied on measuring the shaking response by deploying accelerometers throughout a particular structure of interest to the scientific and engineering communities. The reason why accelerometers are widely used is that there are no efficient or feasible methods to measure displacements directly during an earthquake or severe wind. Recordings of the acceleration responses of structures have served us well. Studies conducted on such records have been useful in assessing design/analysis procedures, improving code provisions, and correlating the response with damage.

Since the Mw=6.7 (Ms=6.8) Northridge (17 January 1994) and Mw=6.8 (Ms =6.5) Kobe (17 January 1995) earthquakes, drift studies and assessment of susceptibility to damage of tall buildings have become important issues, particularly because so many steel-framed buildings were damaged, some severely and some lightly. In the Los Angeles area, for example, following the Northridge event, several hundred steel-framed buildings had to be examined, assessed, and repaired or retrofitted. Only three of these buildings had been instrumented prior to the event. These three provided some limited acceleration response data to be used for interpretation of the widespread damage. Ad-

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ditional data, if available in real time or near-real time, could have been very useful for studies and for design of repair and retrofitting projects that followed. Therefore, there is a great need for better and more extensive monitoring of tall buildings.

Relative displacements, which are key to assessing drift and stress conditions of structures, are difficult to measure directly. Measuring acceleration response requires a double integration process to arrive at displacements. The integration process is not 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. Consequently, this process can lead to errors in the calculation of velocities and displacements. This problem is more acute for permanent displacements. It is doubtful that accelerometer measurements can be used to recover the permanent displacements at the centimeter level (Boore 1999, 2001a, 2001b); and even if they could, it is questionable if it can be done in real time. That is, the level of accuracy of displacements calculated from accelerations has not been widely verified by observations.

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 ± 2 cm vertically. This provides a great opportunity to monitor long-period structures reliably (e.g., tall buildings that are 20 to 40 stories or more). The majority of the tall buildings are flexible steel-framed structures, the fundamental periods of which can be roughly estimated with the empirical formula, T (sec) $= 0.1$ N, where N is the number of stories of the building. This roughly means that at least 20 to 40 data points will be recorded for one cycle of motion of a 20- to 40-story building vibrating at the fundamental period. This provides sufficient accuracy to compute the average drift ratio of a building or to notice 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 long-span bridge, particularly when and if this can be achieved using displacement measurements made directly in real time and with sufficient precision.

In earlier papers (Çelebi et al. 1997, Çelebi 1998, Çelebi et al. 1999), we discussed the concept and described successful preliminary tests to prove the technical feasibility of the application of GPS to monitoring structures. In this paper, we describe in detail, a successful deployment of GPS units to dynamically monitor a 34-story building. We describe the results using data acquired during a windy day by manual triggering. In the 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. Discussion of the workings of RTK-GPS units (referred to as GPS hereinafter) and kinematic solution mathematics for signals from satellites are not in the scope of this paper. To the authors' knowledge, this is the first, permanent and pioneering deployment of GPS units (in the world) for continuous dynamic monitoring of a tall building.

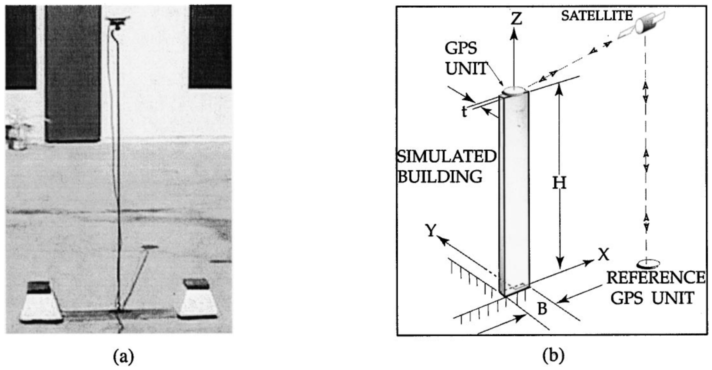

Figure 1. Photo (a) and schematic (b) of test set-up to simulate using GPS for dynamic monitoring of tall buildings.

PREVIOUS WORK

In the last few years, there have been numerous studies related to the technical feasibility of using GPS technology to measure displacements of civil structures. Aerospace atmospheric researchers have accomplished most of the initial work. Studies related to the application of GPS for static or dynamic measurements of displacements of structural systems include but not limited to those by Hyzak et al. (1997), Teague et al. (1995), Guo and Ge (1997), Kondo and Cannon (1995), Lovse et al. (1995), Hudnut and Behr (1998), Behr, Hudnut, and King (1998), and Stein et al. (1997). Very recently, since our original paper describing in detail the concept of using GPS for dynamic monitoring of long-period structures (Çelebi et al. 1999), temporary deployments to dynamically monitor excessive deflections due to wind, in the decimeter range, of the 1410-m-long Humber Bridge on the east coast of England was successfully carried out (Roberts, Dodson, and Ashkenazi 1999). In Japan, Nakamura (2000) cites semistatic displacement measurements (sampling at 1 Hz) of a suspension bridge using temporarily deployed GPS units. Although it is not directly mentioned as to whether permanent and continuous measurements are made, Toriumi, Katsuchi and Furuya (2000) depict several meter level dynamic GPS displacement measurements at the Akashi Bridge, the world's longest span suspension bridge. In the current application, the aim has been actual permanent deployment of GPS units to dynamically obtain displacements during strong-motion events in real or near-real time.

Table 1. Results of tests with GPS units

Specimen	Length [H] ft (m)	Width [B] in.(cm)	Thickness [t] in.(cm)	Measured Frequency [f](Hz)	Measured Period [T](s)	Damping [ξ] (%)
BAR A	6 (1.82)	1.5 (3.8)	1/8 (0.32)	0.245	4.08	~2.0
BAR B	6	2.0 (5.0)	1/8	0.296	3.38	~2.0

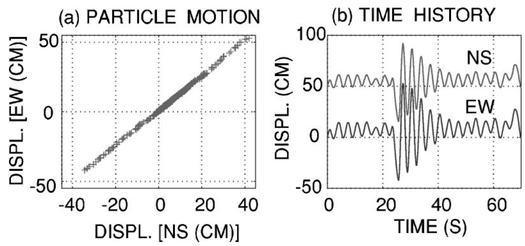

Figure 2. Particle motion and time-history of relative displacements (NS and EW components) of simulated test specimen.

To confirm technical feasibility of such an application, before investing a lot of time and fiscal resources on an actual deployment on a building, we performed tests using a model structure. Figure 1 depicts a photo and the overall set-up for a simple and inexpensive experiment designed by selecting a standard stock steel bar to simulate a 30- to 40-story flexible building. We selected the length, thickness, and width of the two bar specimens to yield a fundamental period of approximately four seconds in the weak direction. For simplicity, we purposefully selected the width and thickness of each of two bars with an extremely weaker axis in one direction. The width was varied to show the sensitivity of measurements during vibration and at 10 Hz sampling rate. Each bar was fixed at the base and the GPS unit was attached at its tip. By providing an initial displacement (simply by pulling the top of the bar and releasing), each bar was set into free vibration and its motion was recorded. Results are summarized in Table 1. Figure 2 shows the particle motion and time-history of one of the tests performed. The axes of the bar were at an angle to the NS (and EW) direction. Therefore, the NS and EW components of displacements are identical in phase and proportional in amplitude. Also, since the GPS unit is not symmetrically and concentrically mounted in the weak direction (Figure 1a), the amplitudes of positive and negative displacements measured are not the same. The detection of the effect of the eccentric mass adds to the assurance that the measurements are accurate and sensitive. These simple tests and results were and can be duplicated easily and readily.

Figure 3 is a plot of NS components of measured relative displacements and corre-

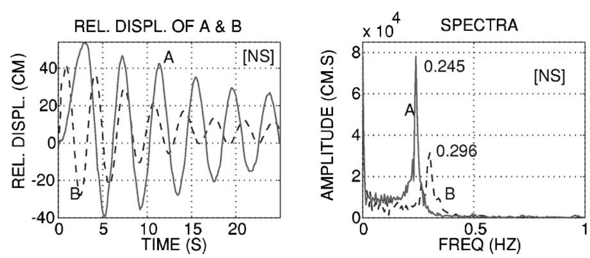

Figure 3. Relative displacements of two test specimens (NS components only) in free-vibration and corresponding amplitude spectra identifying the fundamental frequencies of the test specimens.

sponding amplitude spectra of Bars A and B. The figure shows the accuracy and sensitivity of the GPS monitoring technology at ten samples/second. The measurements differentiate between the frequency of the free-vibration response of the two bars with different dynamic characteristics. From the data, the fundamental frequency (period) of the two bars are identified to be 0.245 Hz (4.08 s) and 0.296 Hz (3.38 s), respectively. Also, a damping percentage of approximately 2% is determined. This simple test shows that sampling at 10 Hz with GPS units provides a clear and accurate displacement response history (with high signal-to-noise ratio) from which drift ratios and dynamic characteristics of the specimen can be derived (Çelebi et al. 1999).

ACTUAL DEPLOYMENT

GENERAL CONSIDERATIONS

In this initial developmental work, GPS units were deployed only on tall buildings that are also instrumented with accelerometers to allow comparison of absolute and relative displacements measured by GPS and calculated by double integration of accelerations. We wanted at least three GPS units per building: two of the units deployed on the roof to detect translational and torsional responses of the building, and the third unit to serve as a reference ground station to evaluate relative displacement. GPS antennas, both at the roof of the instrumented building and the reference station, 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.

CURRENT DEPLOYMENTS

As this paper is being written, deployment of GPS units on the roof of two buildings in Los Angeles and one in San Francisco have been completed. Figure 4 shows the actual deployment on the roof of one of the buildings in Los Angeles. As happens with field deployments, physical obstacles and owner's constraints necessitate technically sensible departure from original deployment plans. For example, in the case of the Los Angeles buildings, the window cleaning machines on the roofs of the two 44-story buildings travel on rails near the parapets and use the parapets continuously. Therefore, any deployment had to be planned away from the parapet walls. To solve this problem, in each case, a stiff auxiliary support frame (Figure 4) was erected. The figure also shows the GPS antenna and the radio antenna to communicate with the reference station so that differential displacements are obtained. This particular deployment is near final development and at the testing stage. It will be the subject matter of future data acquisition and evaluation.

DEPLOYMENT IN SAN FRANCISCO, CALIFORNIA

In this paper, we present results from now completed and operational deployment at a 34-story San Francisco building. General set-up is schematically shown in Figure 5. A GPS unit (always tri-axial) and a tri-axial accelerometer each are deployed at two diagonal corners of the roof of the building. 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. 450 m away).

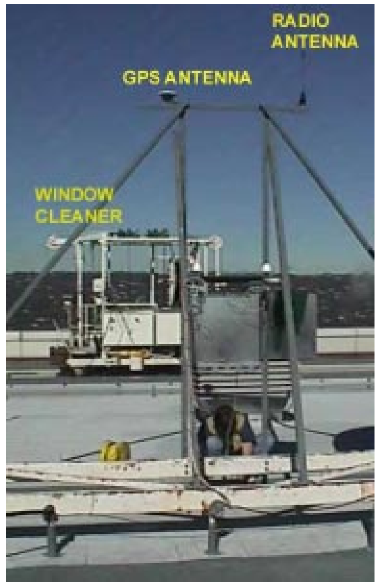

Figure 4. Deployed GPS unit and necessary frame system (Los Angeles, CA).

Figure 6 shows the overall schematic of the deployment and the various connections of the GPS units and antennas, radio modems and antennas, and accelerometers to the PC system at the roof of the building.

Figure 7 shows photographs of the GPS units deployed at two diagonal corners of the roof and data streaming into the PC. At the same location of each GPS antenna, there is a tri-axial accelerometer. Streams of GPS and accelerometer data are viewable and re-

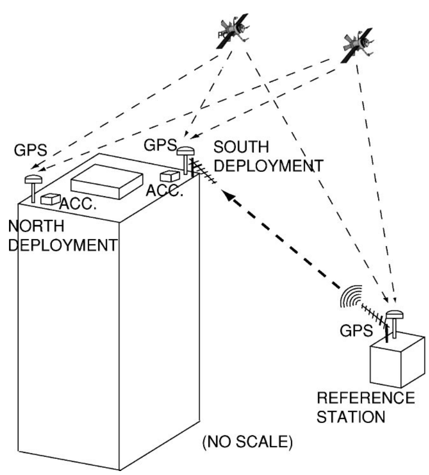

Figure 5. General schematic of the GPS deployment in San Francisco, CA.

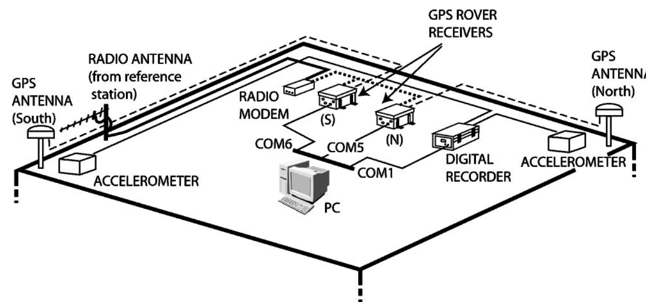

Figure 6. Details of the connections between GPS, radio modems, accelerometers, and the PC.

cordable in real time. Figure 8 shows a sample window of GPS and acceleration data streaming on the PC monitor. At any time, while manual triggering and recording any length of the streams of motions is always an option, the system is set to record at smaller thresholds to obtain data for additional studies (e.g., 1 mm displacement or exceed 0.5% of g acceleration).

SOFTWARES CURRENTLY BEING USED

The GPS units (Leica MC1000[1]) utilize a processor and software that executes the kinematic solutions of the signals from the satellites. This software is manufacturer-specific and is not in the public domain. Commercially available software utilizing similar RTK algorithms are available from a variety of sources. It is provided already installed within the units. The acceleration recorder (Kinemetrics K2[1]) is also provided with specific software that is available in the public domain.

During this developmental work of deploying the GPS units, the streams of data were handled using data management software available from Kinemetrics[1]. Data from GPS units is sent directly to the same PC on site via a serial port. Similarly, the K2 data is sent to the same PC through an RS232 cable connected to the same PC via another serial port. It should be mentioned that data management can be handled through other public-domain or specially programmed software.

During this development stage, the public-domain software, PcAnywhere[1] was used to remotely connect, control, make adjustments in configurations, and to manually trigger and retrieve data. Other software or DSL based-internet connections can facilitate the same job.

DATA ACQUISITION, ANALYSES, AND DISCUSSION

We present a 20-minute-long data set recorded by remote manual triggering in Figures 9 and 10. The figures show the time histories of accelerometer (acceleration) and GPS (displacement) data.

[1]The names of the developers and manufacturers of the hardware and software used herein. The inclusion of these names does not imply endorsement of their products by the authors or by the USGS.

Figure 7. GPS and radio modem antennas at the diagonal corners of the building and the PC receiving streams of GPS and accelerometer data in real time. Shown above the PC are the accelerograph recorder and the GPS Rover units.

The amplitudes of both acceleration and displacement data are very small and the data is noisy. The displacement data is within the margin of error specified by the manufacturer (<1 cm. horizontal). We have not attempted to filter this data set because of the high noise-to-signal ratio. However, we attempted to identify the significant frequencies

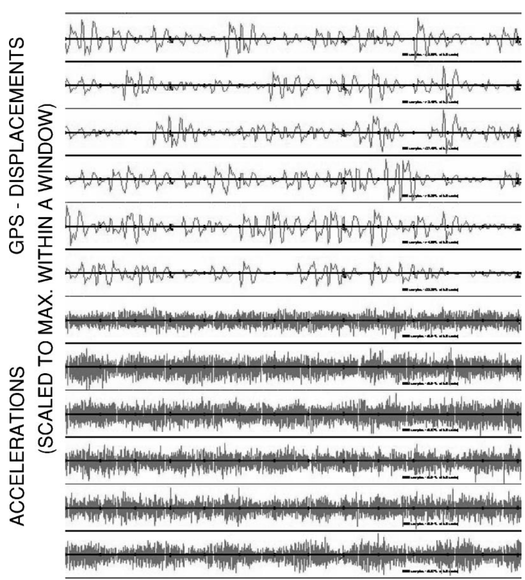

Figure 8. A window of data streaming in real time, captured from the PC monitor.

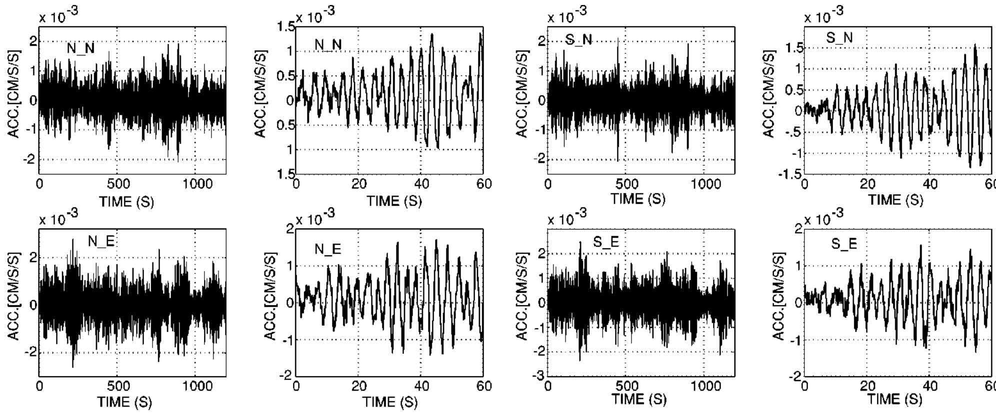

Figure 9. Remotely triggered and recorded accelerations at N (north) and S (south) locations. The figure shows pairs of 1200-second-long (and 60-second window from the same) record.

and the coherencies of the signals at those frequencies. The fact that the accelerations signals are noisy and small in amplitude inhibited clean double-integration for comparison purposes. We will revisit this issue when we can obtain larger amplitude data that is above the margin of error of the units.

In Figure 11, cross-spectra (Sxy) of pairs of parallel records (north-south component of north deployment [N_N] vs. north-south component of south deployment [S_N], and east-west component of north deployment [N_E] vs. east-west component of south deployment [S_E]) from accelerometers are calculated. The same is repeated for the differential displacement records from GPS units.

The cross-spectra (Sxy) clearly indicate a dominant frequency of 0.24–0.25 Hz from both acceleration and displacement data. This frequency is within the band of expected frequency for a 34-story building. The lower peak in frequency seen in the cross-spectra of displacement records is due to noise, which is probably microseisms. It is understood

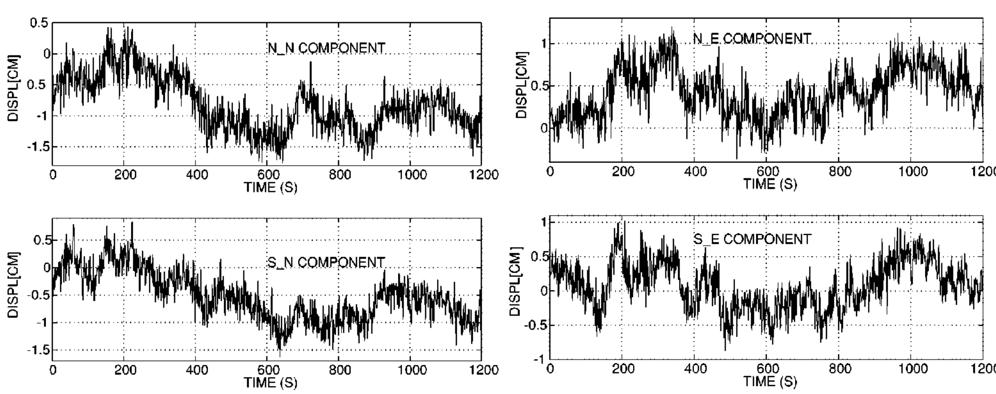

Figure 10. Remotely triggered and recorded displacements at N (north) and S (south) locations.

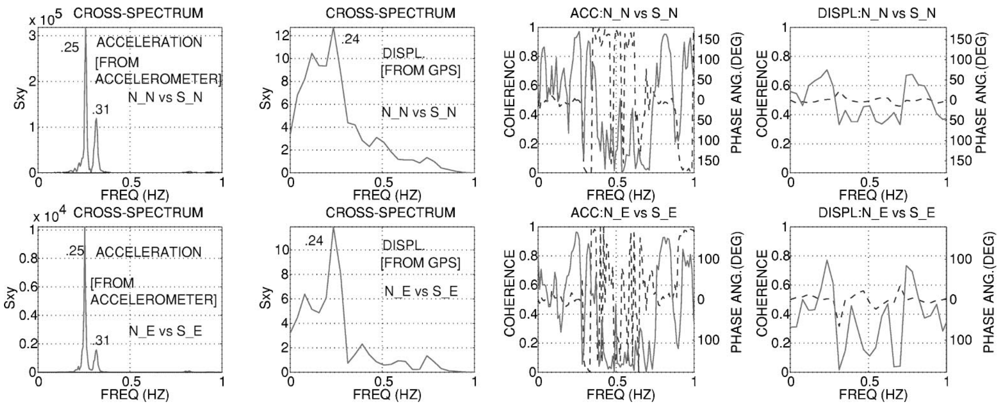

Figure 11. Cross-spectra (Sxy) and associated coherency and phase angle plots of horizontal, parallel accelerations and displacements.

that during larger amplitude motions (with higher signal-to-noise ratios, such small frequency amplitudes due to noise will not be noticeable. In the acceleration data, a second frequency at 0.31 Hz is apparent. We will accept the 0.24-0.25 Hz as the fundamental translational frequency (in both directions). This is confirmed by the fact that at this frequency, the cross-spectra of parallel acceleration records have a coherency of approximately unity (∼1) and they are in-phase (0°). On the other hand, the Sxy of parallel acceleration records at 0.31 Hz also show coherency of approximately unity but they are out of phase (180°). Therefore, this frequency corresponds to a torsional mode.

For the fundamental frequency at 0.24 Hz, the displacement data exhibits a 0° phase angle; however, the coherencies are lower (∼0.6–0.7).

The fact that the fundamental frequency (0.24 Hz) can be identified from the displacement data amplitudes of which are within the manufacturer specified error range, and that it can be confirmed by the acceleration data, is an indication of promise of better results when larger displacements can be recorded during strong shaking caused by earthquakes or strong winds.

OTHER APPLICATIONS IN PROGRESS: POSSIBILITIES AND POTENTIALS

As the technical feasibility of recording GPS displacements with sufficient accuracy and amplitudes is being proven, the challenge for each user group of such data is to determine how to make use of the relative displacements streaming through or being recorded. Beyond measurements, it can be shown that identification of variation of dynamic characteristics can be used to identify possible nonlinearities that occur during vibration (e.g., due to damage and plastic behavior of the structural members, components and/or joints, or to soil-structure interaction under larger and varying amplitudes of input motions). For example, one of the key parameters used in the emerging performance-based design process is the rooftop displacement of a building. Therefore, being able to measure the rooftop displacement has potential use in advancing and verifying performance-based design procedures.

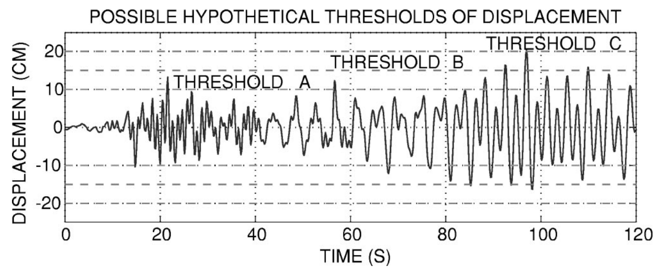

Figure 12. Hypothetical thresholds of displacements shown to demonstrate how GPS data can be configured to provide alarms at different amplitudes. Decision makers can use this information in various ways. (This particular record is for demonstration only. It is 20 times amplified from the double-integrated acceleration record of CH21 [vertical at side-span] of Vincent Thomas Bridge in Los Angeles Harbor [1996 M=6.7 Northridge earthquake]—a California Division of Mines and Geology [CDMG] record.)

One of the applications that is envisaged is for real-time structural health monitoring 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 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 12), (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.

There are plans to use GPS technology for monitoring the responses of tall buildings in the windy city of Chicago, Illinois (Kareem 2001). Tests made in Japan for wind monitoring of tall buildings showed reliable results (Tamura et al. 2001).

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.

Recognizing the potential of GPS for near-real-time monitoring of displacements, the State of California, Department of Transportation (Caltrans) recently launched a research and development project to utilize this capability in monitoring long-period bridges such as the Vincent Thomas Bridge in Los Angeles Harbor and the San Francisco Bay Bridge (Roblee and Turner 2000) following the suggestions and concepts provided by Çelebi et al. (1999). In addition, the Golden Gate Bridge Authority is deliberating the use of this technology in monitoring the landmark Golden Gate Bridge in San Francisco, CA (Bolt 2000). 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 expressed by providing real-time alarms when and if predetermined thresholds of displacements at key locations are exceeded.

REQUISITE SOFTWARE IN DEVELOPMENT

Requisite software is being developed to better record and assess the displacement responses of those structures equipped with GPS units capable of dynamic measurements during earthquakes and severe winds. A description of the software being developed was provided by Çelebi (1998).

BENEFITS AND OTHER APPLICATIONS

- The collected data on the response of the structure during strong-motion events (or strong winds) can be used to make decisions for further evaluation of the susceptibility to damage of the structure, and future repair/retrofit schemes may be developed.
- The recorded data can be used to analyze the performance of the structure and such results can be used to improve future analyses/design procedures.
- In the future, it is possible to develop the application to assess long-term displacements of critical locations of structural systems (e.g., permanent displacements, settlement of foundations). Methodologies can be developed for incorporating the findings into useful practical design procedures.

PROBLEMS ENCOUNTERED

During the deployments, we have encountered various difficulties that should be shared with the readers and future users:

1. Communication modems are subject to federal frequency permits. It is best to use those modems that do not require such permits.
2. Deployment of GPS units in downtown urban environments where most of the tall buildings are built, such as San Francisco and Los Angeles, require reference stations that may not be ideal. In our case, we had to relocate the originally selected reference station, which was only one block away. Prior to selecting the original site, we used hand-held GPS units to make sure that there were a sufficient number of satellites. However, this was not always the case when we deployed the actual unit as a reference station. At different times the number of visible satellites were reduced to two or three.
3. Thus, in selecting the alternate site as reference site, we made sure that the ground motions in the vicinity were similar to the ground motions at the base of the building instrumented with GPS and accelerometers. We were lucky that motions at the ground level of a building within 30 meters of the subject building and ground motions within 100 m of the new reference station were available for the 1989 Loma Prieta, California, earthquake to make a judgment that the new reference site could serve as a reference site in lieu of the ground level motions that can not be recorded with GPS.

4. Using different software caused logistic problems in making the connections from GPS units and accelerometers and their recorders. While this was the least expensive way, it generated a lot of debugging problems. Additional software development is necessary to meet the needs of the user of the real-time data.

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 two tests conducted on two vertically cantilevered bars that simulate tall buildings, and a set of manually recorded wind response records from a 34-story building in San Francisco, now equipped with GPS units and accelerometers to provide synchronized, real-time displacement and acceleration responses. Both approaches show 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 structural health monitoring purposes. Procedures and software are being developed to permanently deploy GPS units on tall buildings and suspension bridges by other interested parties.

There is great potential for the application of GPS technology to monitor long-period structures during earthquakes. The application can also be extended to monitoring wind-induced deformation of tall buildings, long-span suspension and cable-stayed bridges, and tall chimneys. Furthermore, with future advances in GPS technology and improvements in sampling capability (e.g., higher than 10 sps), it will be possible to monitor short-period structures as well. Additionally, direct measurements of displacements will enable us to reliably detect structural movement caused by failure of the ground under a structure (e.g., liquefaction).

We are happy that our early work on this subject in addition to those of others cited are creating interest in the engineering community to use this technology to meet their needs of real-time displacement information that can be used in different applications.

ACKNOWLEDGMENTS

As part of his duties, the senior author has frequently been asked about methods to measure relative displacements in buildings and other structures, which is difficult to do. About three years ago, Will Prescott of USGS asked whether it would be technically acceptable, that is, would displacements be small enough, to deploy GPS units on roofs (for safety reasons) of tall buildings in Los Angeles, for ground deformation studies during earthquakes. While the response to this question was negative due to expected large displacements, perhaps at decimeter levels, the senior author became inquisitive about the possibility of using GPS units for exactly the opposite purposes, that is, for dynamical monitoring and recording of the response of tall buildings. Thus the reason for beginning this developmental work. Since starting this project, encouragement and support of Will Prescott, Ross Stein, Ken Hudnut, and Jim Dieterich of the USGS are gratefully acknowledged. The particular deployment in San Francisco was made possible through a grant from the USGS-PG&E CRADA program and USGS funds. Many other people provided input and advice while we made the deployment. Jeff Behr of Orion Monitoring and the junior author of this paper were key personnel in deployment and debugging the various problems that arose. The suggestions made by Will Prescott, Chris Stephens, and Ross Stein greatly improved the manuscript.

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