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GPS Monitoring of Dynamic Behavior of Long-Period Structures

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Global Positioning System (GPS) technology with high sampling rates (~10 sps) allows scientifically justified and economically feasible dynamic measurements of relative displacements of long-period structures—otherwise difficult to measure directly by other means, such as the most commonly used accelerometers that require post-processing including double integration. We describe an experiment whereby the displacement responses of a simulated tall building are measured clearly and accurately in real-time. Such measurements can be used to assess average drift ratios and changes in dynamic characteristics and therefore can be used by engineers and building owners or managers to assess the building performance during extreme motions caused by earthquakes and strong winds, by establishing threshold displacements or drift ratios and identifying changing dynamic characteristics. Such information can then be used to secure public safety and/or take steps to improve the performance of the building.

INTRODUCTION

Seismic monitoring of structural systems constitutes an integral part of National Earthquake Hazard Reduction Program. In general, until recently, monitoring the response of structural systems for the purpose of assessment and mitigation of earthquakes (and also severe winds) has relied on measuring shaking response by deploying accelerometers throughout a particular structure of interest to the scientific and engineering community. In contrast, there are no efficient or feasible methods to measure displacements during an earthquake or severe wind. Recordings of the acceleration response of structures have served us well. Studies conducted on such records have been useful in assessing design/analyses procedures, improving code provisions and in correlating the response with damage.

Since the M_s=6.7 Northridge (17 January 1994) and M_s=6.8 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

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Northridge event, several hundred steel-framed buildings had to be examined, assessed, repaired and/or retrofitted. Only three of these buildings were instrumented prior to the event, providing some limited acceleration response data to be used for interpretation of the widespread damage. Additional data, if available in real-time or near real-time, could have been very useful for studies and design of repair and retrofitting projects that followed. Therefore there is a great need for better monitoring of tall buildings.

Relative displacements, which are key to assessing drift and stress conditions of structures, are difficult to measure directly. On the other hand, 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) often substantial 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. Accelerometer measurements cannot be used to recover the permanent displacements at the centimeter level; and even if they were, it is questionable if it can be done so in real-time. To the authors' best knowledge, such comparisons have not been made. That is, the level of accuracy of displacements calculated from accelerations has not been widely verified by observations (e.g., some shake table tests performed to compare the performances of accelerometers and accelerographs have not been directed to check displacements).

As an alternative method of measuring relative displacements while monitoring structural systems, we introduce GPS technology. In general, GPS monitoring systems are used for other purposes because of the sampling rates used (e.g., one sample per hour, day, etc.). A few such applications including those for structural systems are summarized in Appendix A. However, the technology has advanced to such a stage that it is now possible to record at 10 sps. This provides a great opportunity to monitor long-period structures reliably (e.g., tall buildings that are 20–40 stories or more). The majority of the tall buildings are flexible steel-framed structures. The fundamental period of such a flexible-framed building can be estimated with the empirical formula[1]: $T = 0.1\ N$, where N is the number of stories of the building. This means that at least 20–40 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 assess the average drift ratio of a building. Such information can be very useful in assessing the damage to a building. In addition, the main value in using GPS technology to assess the condition of a building is that the displacement measurements can be made directly in real-time and with sufficient precision. As discussed later, we have made preliminary tests to prove the technical feasibility of the application of GPS to monitoring structures.

There is great potential for the development of 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

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[1] For most flexible buildings, the fundamental period (T) is approximated by 0.1N, where N is the number of floors of a building (even though the fundamental period can vary between [0.05-0.15]N depending on the flexibility of the building). Therefore, to simulate a 40-story building, we set the period (frequency) equal to 4 s (0.25 Hz) and proportioned the length, width and thickness of the cantilever.

improvements in sampling capability (e.g., higher than 10 sps), it will be possible to monitor short-period structures as well. The current technologies do not readily lend themselves to automated, real-time applications. Additionally, direct measurements of displacements will enable us to reliably detect structural movement caused by failure of the ground under the structure (e.g., liquefaction).

TECHNICAL JUSTIFICATION

In the last few years, there have been numerous studies related to technical feasibility of using GPS units to measure displacements of civil structures. Most of the initial work has been accomplished by aerospace atmospheric researchers. The number of studies related to application of GPS for static or dynamic measurements of displacements of structural systems include but not limited to those by Hyzak and others (1997), Teague and others (1995), Guo and Ge (1997), Kando and Cannon (1995), and Lovse and others (1995). In our study, we direct the efforts to actual permanent deployment of GPS units alongside with accelerometers and also to use the displacement measurements with GPS as a health monitoring tool.

MODEL TESTS SIMULATING A TALL BUILDING

To investigate the feasibility of using GPS technology to monitor tall buildings (and other long-period structures), we conducted two experiments. 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. To make things simple, 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

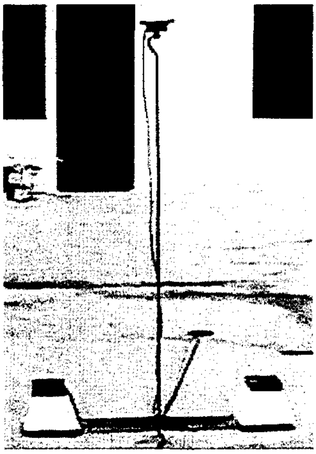

Figure 1a. Photo of test set-up for using GPS for dynamic monitoring tall buildings.

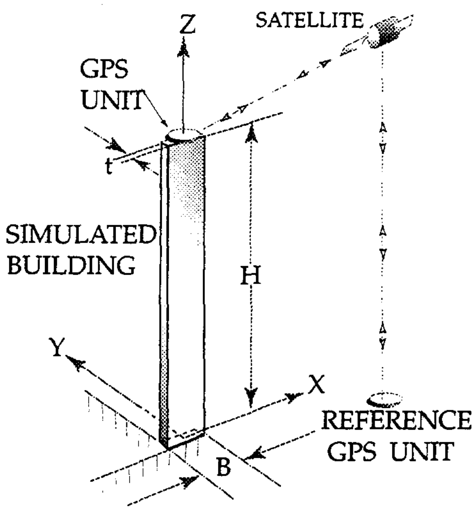

Figure 1b. Schematic of test set-up for using GPS for dynamic monitoring of tall buildings.

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 (photo in Figure 1), 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.

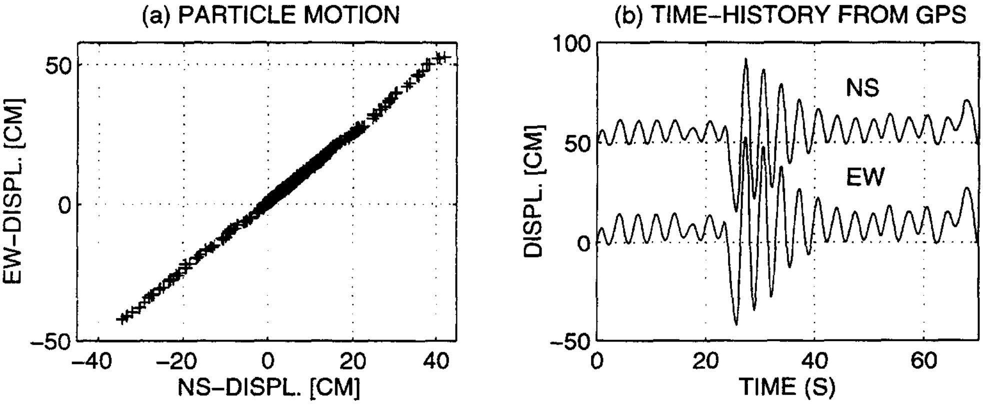

Figure 2. Particle motion and time-history of relative displacements (NS and EW components) of simulated test specimen.

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 3 is a plot of NS components of measured relative displacements and corresponding 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 extracted. This simple test shows that sampling at 10 Hz with GPS units provides a clear and accurate displacement response history from which drift ratios and dynamic characteristics of the specimen can be derived (Çelebi et al., 1997a). The implications of this go beyond just the measurements. It can be shown that identification of variation of dynamic characteristics can be used to identify not only different structural systems, but also the possible nonlinearities that occurs during vibration (e.g., due to damage and plastic behavior of the structural members, components and/or joints or soil-structure interaction under varying amplitudes of input motions).

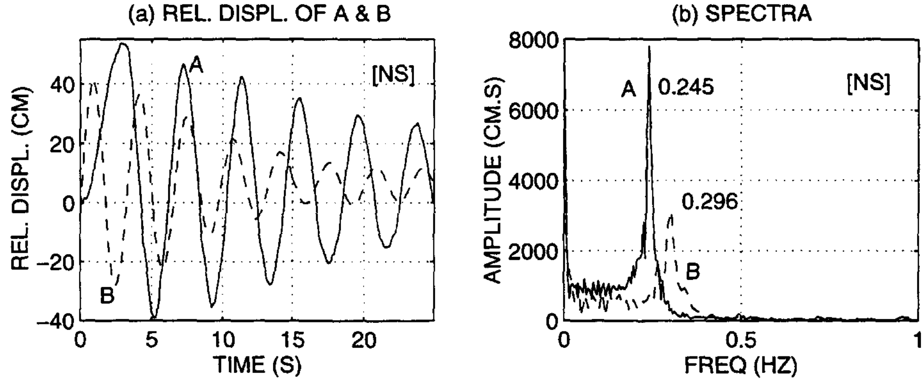

Figure 3. Relative displacements of two test specimens (NS components only) in free-vibration and corresponding amplitude spectra identifying the fundamental frequencies of the test specimens.

GPS AMBIENT TEST OF A 44-STORY BUILDING AND STRONG-MOTION ACCELERATION RECORDS

In a second test, we measured ambient vibration (due to winds and traffic noise) of a 44-story building with a GPS unit temporarily deployed on its roof. A reference GPS unit was located within 500 m of the building. The signals were very noisy and amplitudes very small; therefore, most common methods to identify structural characteristics did not work. Only the cross-spectrum of the two orthogonal, horizontal, low-amplitude ambient displacement recordings (when the signals are coherent and approximately 180° out of phase) was used to identify the fundamental frequency of the building at 0.23 Hz (Figure 4), with another frequency at ~ 0.3 Hz. Despite the very small signal, these frequencies appear to be reliable when compared with the 0.23 Hz frequency calculated from accelerations recorded with a triaxial accelerograph on the 38th floor (accepted here as the roof response) during a small earthquake (Figure 5). A comparison of these frequencies is provided in Figure 6.

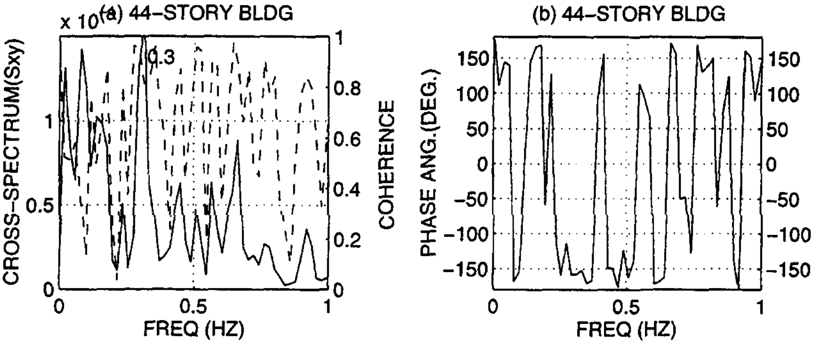

Figure 4. Ambient test of a 44-story building with GPS technology: Cross-spectrum (left-solid), coherence (left-dashed) and phase-angle (right) of two orthogonal horizontal motions.

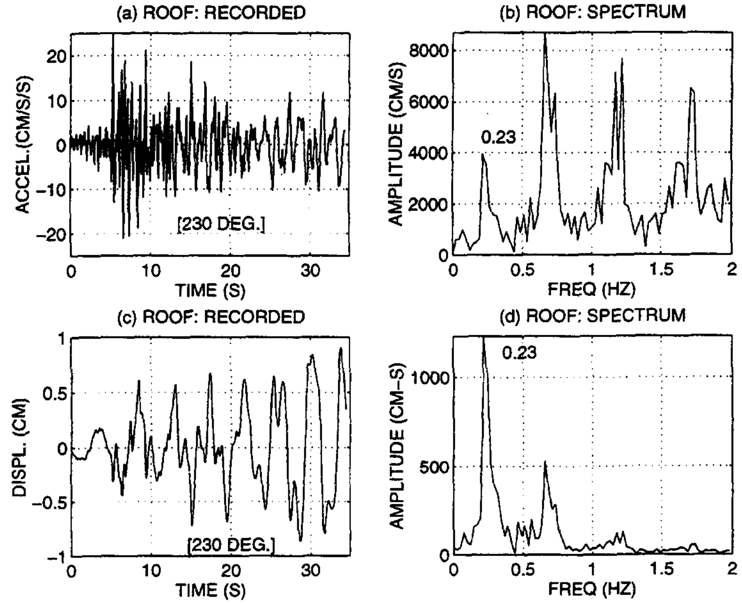

Figure 5. Recorded roof (38th floor accepted in lieu of roof) accelerations of a 44-story building and displacements (derived by double integration) and amplitude spectrum.

Despite the small displacements (<1 cm) and large noise to signal ratio of this experiment, the fact that dynamic frequencies could be identified indicates that during larger displacements, better identification of the dynamic characteristics as well as drift ratios can be made with higher confidence.

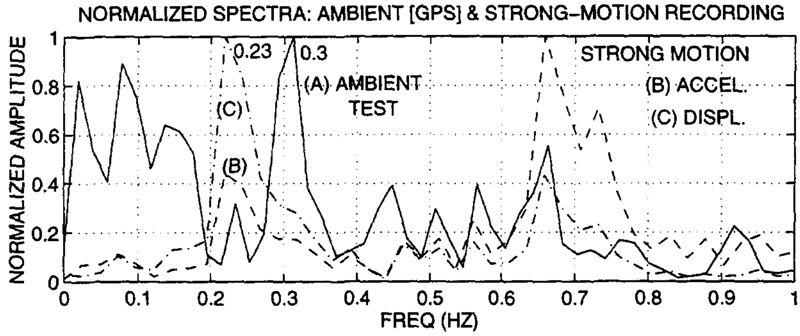

Figure 6. Comparison of normalized frequencies for ambient GPS recording (from cross-spectrum) and strong-motion recording (from amplitude spectrum).

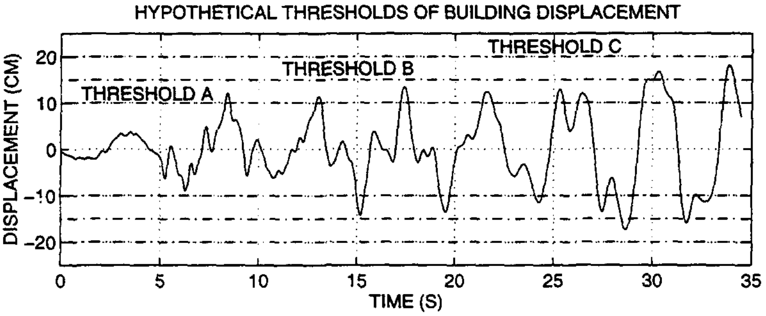

Figure 7. Hypothetical thresholds of displacements. The time-history of displacements shown is actually integrated from accelerations recorded at the 38th floor (accepted in lieu of roof) of a 44-story building. The actual record (in Figure 5) is amplified by 20 times for illustration purposes.

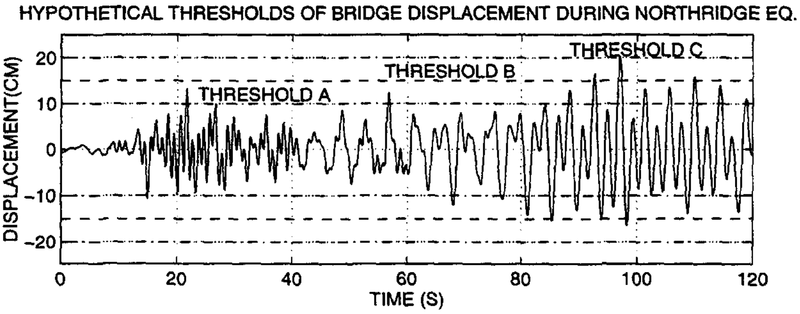

Figure 8. Hypothetical thresholds for displacement (from double-integration of recorded acceleration) of channel 21 (vertical at mid side-span) of Vincent Thomas Bridge (1994 [M=6.7] Northridge earthquake).

LOOKING TO THE FUTURE: REAL-TIME MONITORING

We are developing a real-time structural monitoring technique using GPS. Our approach in developing this application is as follows:

- We are planning to deploy GPS units on one or more tall buildings that are already instrumented with accelerometers. This will facilitate comparison of absolute and relative displacements. The GPS units will be configured to provide data to indicate the real-time average drift ratio and changes in the dynamic characteristics of the tall building. This information can be made available to building managers (or interested parties) in real-time or whenever a predetermined displacement threshold is reached. The building managers can assess the response of the buildings according to (a) different threshold displacements (e.g., A, B, and C as shown in Figure 7), (b) drift ratios, or (c) changing dynamic characteristics. If a situation is serious, the management can make decisions to evacuate the building for additional inspection. Therefore, one by-product of the effort would be to secure the safety of the occupants and significant contents of the building. Thus, a real-time structural health-monitoring environment will be created. At least three GPS units per building are required to monitor a tall building. Two of the units should be deployed on the roof to detect translational and torsional response of the building. The third unit will serve as a reference ground station to evaluate relative displacement. This also needs a site with excellent sky visibility.

- Similar deployments are being planned for other types of long-period structures. One project in development at this time is for deploying GPS units on one of the long-period suspension bridges such as the Golden Gate Bridge and Bay Bridge (San Francisco) or Vincent-Thomas Bridge (Los Angeles). As in the case of tall buildings, changes in dynamic characteristics after the displacements at critical locations of a bridge have exceeded predetermined thresholds can be calculated in near real-time (Figure 8). When warranted, the management can make decisions to inspect the bridge (e.g., decisions can be made to stop the traffic, thus securing the bridge safety, which is one of the objectives of lifeline earthquake engineering). With the GPS technology, we can furnish time-dependent displacements for the relative movements of critical locations of structures. For example, for the bridges, GPS units placed at pre-selected locations of bridge elements can indicate, in real-time, the amplitude of the displacements of the decks and towers, as well as movements of key bridge elements relative to local bedrock reference points. Thus, movements of the piers relative to the abutments, the top of a tower with respect to its base, or the span with respect to the ground, can be made at a centimeter-level of precision, in real-time. We will recover both the dynamic motions that accompany the earthquake, as well as the static or permanent displacements experienced by the bridge once the shaking has stopped. Such permanent displacements affect the state of stress of a bridge, and provide evidence for distortion or failure of bridge elements or subsidence of piers due to ground compaction induced by earthquake shaking.

- Requisite software is being developed to assess and mitigate the two natural hazards (earthquake and severe wind) affecting the structures by using the displacements measured by the GPS units.

- The collected information 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.
- The data collected will also be used to assess long-term displacements of critical locations of structural systems (e.g., permanent displacements, settlement of foundations, long-term deformations due to change of temperature and the plate tectonic deformation spanning the San Francisco Bay and parts of the Los Angeles Basin) and to develop methodologies on how the findings can be incorporated into useful practical design procedures.

CONCLUSIONS

It is shown in this paper that recent advances in sampling rates of GPS technology allows real-time monitoring of long-period structures such as tall buildings and long-span bridges. The advantage is that relative displacements can be measured in real-time and with sufficient accuracy. The technical feasibility is illustrated through two tests conducted on two vertically cantilevered bars that simulated tall buildings and ambient test of a 44-story building. Both approaches show that GPS monitoring of long-period structures provide sufficiently accurate measurements of relative displacements and 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.

APPENDIX : OTHER APPLICATIONS

POST-EARTHQUAKE GPS SURVEYS ON BRIDGES

The Federal Emergency Management Agency funded two USGS studies, in concert with the National Geodetic Survey and Caltrans, in which the permanent (or static) displacements of bridges and other engineered structures were measured following large earthquakes. These studies revealed that large permanent displacements of bridge abutments are easily measured from GPS and leveling surveys. After the M=7.0 Cape Mendocino, California, earthquake, displacement of geodetic monuments on bridge abutments relative to the ground revealed damage to a major bridge crossing the Eel River, as well as road and rail embankment failures caused by landslides and liquefaction. One abutment settled 70 mm, and the abutment on the opposite bank settled 130 mm (Stein et al. 1993). After the 1994 M=6.7 Northridge earthquake, the USGS resurveyed the 1045 leveling and GPS monuments, and added 128 new GPS monuments spaced 5 km apart along the I-405 Freeway for rapid damage assessment after future earthquakes. The Northridge analysis revealed four monuments in bridge abutments with subsidence of up to 116 mm, and uplift of up to 58 mm (Hodgkinson et al. 1996, Hudnut et al. 1996). Because few bridge or other highway structures were assessed for earthquake effects except by visual inspection, subtle or hidden damage suggested by the settlement or uplift of the structures merits re-inspection. This study is accessible via <www-socal.wr.usgs.gov/fema>.

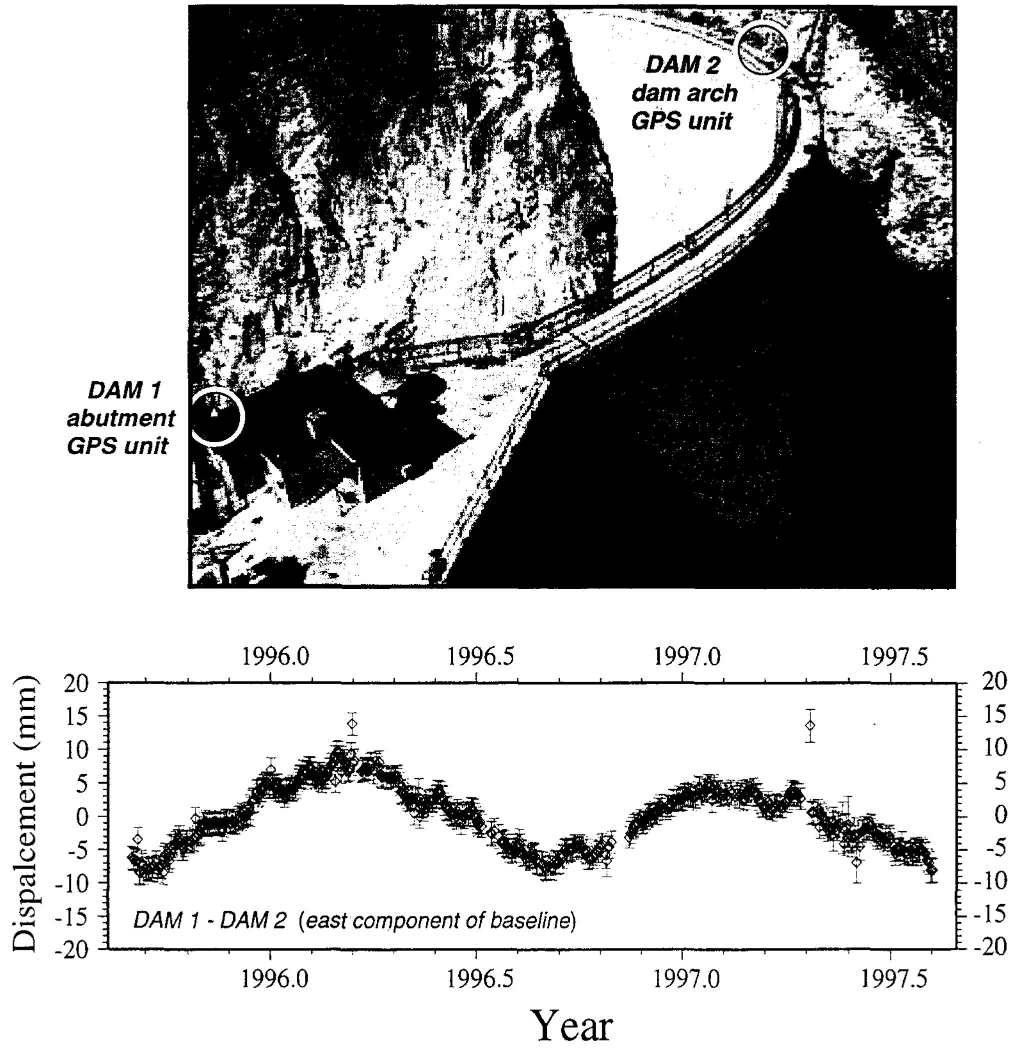

Figure 9. Structural displacement history of Pacoima Dam, Los Angeles, from continuous GPS measurements of a remotely operated, telemetered three-station network run by Kenneth Hudnut (USGS) since 1995. Pacoima Dam was damaged by ~1g accelerations during both the 1971 San Fernando and 1994 Northridge earthquakes. Two GPS stations are visible in the photograph; a third station is located several km away on bedrock. Thermal contraction of the 120 m high double-arch structure is evident, as well as an apparent long-term expansion of the arch of several millimeters per year. Note that horizontal precision is ±2 mm. The experiment demonstrates field reliability of telemetered, autonomous GPS installations on large engineered structures; the results reveal previously unmeasured thermal processes (adopted from Hudnut and Behr, 1998).

PACOIMA DAM PILOT PROJECT

An experimental pilot project with Los Angeles County to monitor Pacoima Dam (Figure 9) has demonstrated the feasibility of a precise telemetered GPS monitoring system. The USGS began monitoring the double-arch dam wall in 1995, and initiated near real-time production of results in January 1996 (Hudnut 1996, Stein, et al. 1997). Daily plots are posted on the Internet (www-socal.wr.usgs.gov/hudnut/dam.html). Horizontal repeatability of the data between daily estimates is <4 mm, and vertical repeatability is <12 mm. The experiment demonstrates the field reliability of continuous GPS units on an engineered structure, and the results (Figure 9) reveal heretofore-unmeasured thermal expansion and contraction of 20 mm seasonally (Hudnut and Behr 1998).

Bay Area Regional Deformation (BARD) and Southern California Integrated GPS Network (SCIGN)

Continuous GPS nets in Southern and Northern California, SCIGN (50 stations growing to 250 within two years) and BARD (20 stations within the San Francisco Bay Area), provide continuously updated information about the regional strain pattern to which the bridges are subjected. The bridge and building monitoring stations discussed herein will be located within a few kilometers of existing BARD or SCIGN sites. Long-term deformation associated with plate tectonics for the SCIGN and BARD sites is well established, thus, there will be a good background against which to examine both the static and dynamic deformation indicated by the bridge units.

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