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RECORDING GROUND MOTIONS WHERE PEOPLE LIVE

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Public Seismic Network and Sedimentary Basins: Recording Ground Motions Where the People Live)

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Introduction

The 1989 Loma Prieta, California Earthquake caused spectacular damage to structures 100 km away in the San Francisco Bay sedimentary basin—the Cypress Street viaduct overpass, the Bay Bridge and buildings in the San Francisco Marina district. Although the few mainshock ground motions recorded in the northern San Francisco Bay area were "significantly larger . . . than would be expected from the pre-existing dataset," none were recorded at the sites of these damaged structures (Hanks and Krawinkler, 1991). Loma Prieta aftershocks produced order-of-magnitude variations of ground motions related to sedimentary basin response over distances of 1-2 km and less (Cranswick *et al.*, 1990). In densely populated neighborhoods, these distances can encompass the residences of thousands of people, but it is very unlikely that these neighborhoods are monitored by even one seismograph. In the last decade, the complexity of computer models used to simulate high-frequency ground motions has increased by several orders of magnitude (*e.g.*, Frankel and Vidale, 1992), but the number of seismograph stations—hence, the spatial density of the sampling of ground motion data—has remained relatively unchanged. Seismologists must therefore infer the nature of the ground motions in the great unknown regions between observation points.

The strong response of sedimentary basins to seismic waves was largely responsible for the damage produced by two devastating earthquakes in the last decade: the 1985 Michoacan Earthquake which severely damaged parts of Mexico City, and the 1988 Spitak Earthquake which destroyed most of Leninakan, Armenia. Much of this response can be explained by the conversion of seismic body-waves to surface waves at the sediment/rock contacts of sedimentary basins (Bard *et al.*, 1988). The effectiveness of waveform conversion is a function of the angle of incidence of the body waves and the geometry of the basin, and thus, the ground motions are sensitive to the depth and direction of the source in a fashion not predicted by one-dimensional, plane-layer models of velocity structure (Papageorgio and Kim, 1991).

Seismographs are usually installed at good sites for observing seismic sources, on rock characterized by low seismic noise. For site-response research and to assess earthquake hazard, we need to deploy dense seismograph arrays within the densely inhabited metropolitan areas built on sedimentary basins. Such arrays would be prohibitively expensive if implemented using traditional methods, but would be economical with new approaches to the three requirements of data acquisition: 1) sites; 2) instrumentation; 3) data management. The continuous operation of such arrays would generate a database to constrain ground motion models and begin to define the "site/source response."

A Modest Proposal

Cranswick and Banfill (1990) proposed the Public Seismic Network (PSN) as a model for dense urban arrays. The PSN consists of event-triggered digital seismographs owned and operated by private citizens. The waveform timeseries recorded by each unit are automatically uploaded over the owner's telephone to a data management center which monitors and archives the data. The owner can also upload the timeseries to his/her personal computer.

Permitting, installation and maintenance of seismographs represent major costs of operating a network; utilizing station owner/operators eliminates these costs. The owner/operator is also best able to deal with problems of local cultural seismic noise and of vandalism, major difficulties of operating seismographs in urban areas. There is no substitute for a human being who regularly monitors the operation of a piece of equipment, and there are many amateur seismologists and interested citizens interested in and capable of doing so.

The network needs an inexpensive, reliable, standardized and mass-produced seismograph: the digital seismological equivalent of a Sony Walkman. It must be able to record three components of ground acceleration with a dynamic range of 10^{-5}-1.0 g in the frequency band 0.1-20.0 Hz and maintain absolute time to a precision of 5 ms. Typical records would be sampled at 50 sps/component and have a duration of 30-300 s. The unit must be constructed ruggedly enough and supplied with sufficient data storage and a self-contained power source to function as a strong motion recorder for several weeks of unattended operation. The unit would make trivial the cost of data telemetry—a very large expense for most seismic networks—by employing a 1200-baud modem to transmit the compressed digital records over local telephone lines to the data center. Using "state of the market" technology, we estimate that 1,000 such units can profitably be manufactured and sold for $500-1,000 apiece (see Nolet, 1993).

The data management center would be similar to the voicemail service offered by phone companies: a telemetry, storage/retrieval system for digitized waveforms. Most scientific databases do not dynamically interact with the sources of the data, but the realtime credit verification of a typical credit card system provides a model of how the data center could maintain the integrity of a PSN network. Amplitude/time calibrations, trigger/false-trigger counts, and ground motion statistics of each seismograph could be automatically scrutinized as regularly and rigorously as a credit card balance. Every time the seismograph was triggered and called the data center to upload waveform timeseries, a clock correction, corrected for telephone transmission delay, would also be recorded. The seismograph would call the data center at least once each day to be clock corrected and to transmit its state of health, including a response calibration. Near-realtime comparison of the records of adjacent seismographs would also monitor instrument reliability. Based on its current and comprehensive history of all seismographs, the data center could upload instructions to seismographs that exhibited anomalous behavior to increase their frequency of clock corrections, change their trigger parameters, perform more exhaustive response calibration procedures, *etc.*

Both the credit card verification systems and telephone voice mail systems now employed throughout the United States and many other countries are able to dynamically maintain databases which are similtaneously accessed in realtime over conventional telephone lines by thousands of transmit/receive stations at rates of ~10^5 phone calls per day. Background seismicity would generate ~10^3 one-minute phone calls per day from a PSN system of a thousand stations. The aftershock sequences of large local earthquakes could exceed the ability of the data center to process all potential phone calls in realtime, but the seismographs could store a hundred waveforms internally and be programmed to prioritize waveform storage/transmission according to some measure of event size. The data center would also function as an electronic bulletin board system (BBS) for seismograph owner/operators.

The PSN at Present

A prototype of the envisioned PSN network is already operated by amateur seismologists in California who perform all the basic functions of a PSN. They record seismograms from event-triggered digital seismographs deployed in their own homes and upload the waveform timeseries *via* modem to a PC-based BBS where the data is available to PSN members and the public. On 28 June 1992, within a few hours of the Landers, California Earthquake, we uploaded a waveform timeseries of that event recorded by a PSN station in the Santa Clara Valley, California to computers at the USGS in Golden, Colorado and gave a hardcopy of the seismogram to the National Earthquake Information Center (see Figure 1a). There are 50-100 PSN members and about 10 PSN stations at present. The PSN currently operates BBSs in San Jose [(408) 226-0675], Pasadena [(818) 797-0536], and at the USGS in Menlo Park [(415) 327-1517], California, and one in Memphis, Tennessee [(901) 360-0302]. The PSN also has a program to install seismographs and PSN BBS links in the California public schools.

USGS Calnet stations in the hills surrounding the Santa Clara Valley provide extensive source monitoring of local earthquakes (Eaton, 1991), but only PSN seismographs regularly record ground motions on the valley floor. Figure 1b displays the displacement seismogram of a local microearthquake recorded by a PSN station at the Los Altos High School. The undispersed character of the surface waves is similar to those recorded by a temporary array deployed 10 km away to study the surface waves converted from the body waves of Loma Prieta aftershocks (Frankel *et al.*, 1991). The large amplitudes and long durations of the surface waves emphasize the important contribution of surface waves to strong ground motions in sedimentary basins.

Site/Source Response

Site response is a measure of the amplification of ground motions produced by local site conditions, *e.g.*, sites underlain by soils exhibit ground motions several times larger than those at sites underlain by rock (Borcherdt, 1970). It is customarily assumed that the site response is independent of source location, but the interference of surface waves in sedimentary basins makes the ground motions at a specific site a non-linear function of source location.

Consider the S-wave from a source below the center of a symmetric 2-D sedimentary basin which generates two surface-wave pulses of equal amplitude at opposite sides of the basin. The pulses propagate towards each other across the basin and meet at the center, where their amplitudes momentarily reinforce one another. The peak ground motion will be twice as large at the center as at sites immediately adjacent to it. If the source were shifted a small distance from the center, the meeting point would be slightly shifted in the opposite direction. Therefore, a small change in source location could lead to a factor-of-two variation in peak amplitude at a specific site for two otherwise identical sources.

Their sensitivity to site/source parameters suggest that the ground motions of sedimentary basins may be chaotic phenomena. Lacking precise information about the basin geometry and the temporal and spatial sequence of fault slip, it may be as difficult to predict the ground motion at a specific site as to predict the weather on 21 May next year. Climate characterizes the chaotic phenomenon of the weather in terms of its longterm behavior, *i.e.*, many observations. The extreme values of the temperature on 21 May and the probability that it will be within a given range can be obtained from the historical record. The PSN would provide a spatially dense array of stations, where ground motion information is needed, which record the temporally complete catalog of earthquakes distributed throughout the region. These data would characterize the variation of the basin-wide pattern of site response as a function of source and elucidate the mechanisms responsible for this.

Conclusions

The disparity between the goal of comprehensive site-response assessment of the increasingly populated seismically hazardous regions of the Earth and the lack of ground motion data needed to do this calls for a fundamental change in the means of high-frequency earthquake data acquisition. Recent analysis of teleseismic waveforms recorded by regional short-period networks (Vidale and Benz, 1992) emphasizes that many low-quality stations can provide information not available from a few high-quality stations. The technology to manufacture the required seismographs and sensors and to maintain a telecommunications database already exists; it is only a matter of employing it. The envisioned seismograph would be able to record microearthquakes in the magnitude range 1-2 at distances of 10-30 km within the urban area and so compile an extensive record of ground motions associated with different source/site combinations. It would also be able to record local catastophic, macroseismic events on-scale, and so be used to determine the near-field details of the rupture process.

Many private citizens, particularly in seismically hazardous regions, want to participate in a PSN. A PSN would directly connect scientific observations—instrumental recordings of ground motions—to their human consequences—damage to buildings and other structures, *i.e.*, Modified Mercalli Intensity. The complex "vascular system" of lifelines (transportation, telephone, electricity, gas, water, sewage) requires a "nervous system" of a dense seismic array to monitor the earthquake hazards which threaten it. The data recorded by such dense arrays would provide a solid empirical basis for our understanding of the response of sedimentary basins.

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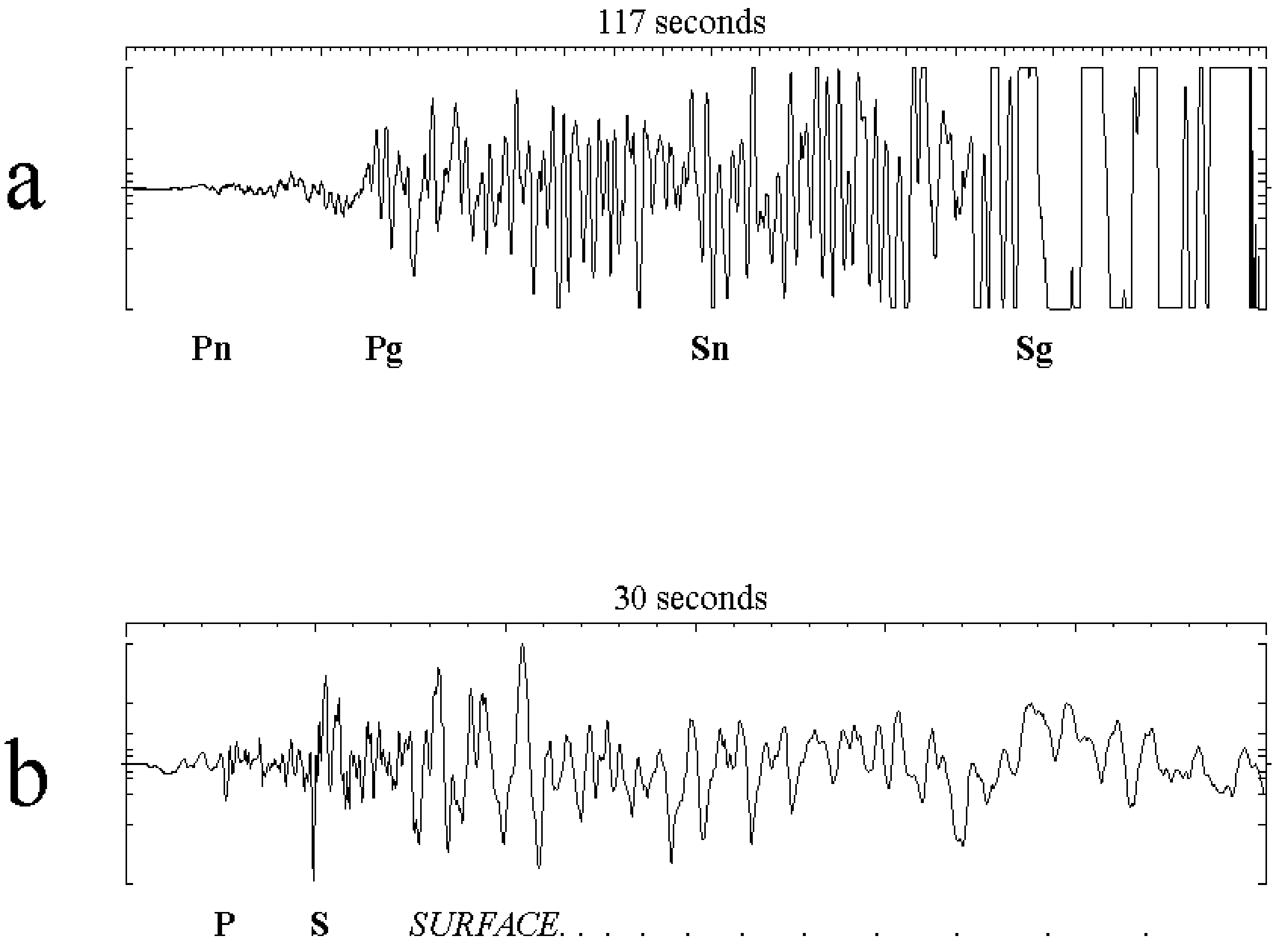

Figure 1. PSN recordings from the Santa Clara Valley, California. a) 1992 Landers, California Earthquake (magnitude 7.5, range 600 km) recorded by an E-W horizontal seismometer with a natural period of 10 seconds. The record is severely clipped after the onset of the **Sg** phase. b) Local microearthquake (1992 Sep 5 01:33 UTC, magnitude 2.0, range 20 km) recorded by a N-S horizontal seismometer with a natural period of 2 seconds. The original velocity timeseries has been integrated to displacement. Note the extended duration of the *SURFACE* waves.