THE DEVELOPMENT OF GROUND AND STRUCTURAL RESPONSE STRONG-MOTION INSTRUMENTATION ARRAYS IN THE UNITED STATES

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SUMMARY

Recent strong ground motion arrays developed by the U.S. Geological Survey include: 1) multi-channel digital recording surface arrays 305 to 610 m long with a distribution of up to 7 triaxial accelerometers along these short baselines, 2) an array of paired accelerographs installed on opposite sides of a 125 km segment of the Hayward fault and 3) liquefaction studies designed to simultaneously monitor transient changes in pore pressure and ground acceleration. Structural arrays described are: 1) three-dimensional arrays at earthfill dams combining surface and downhole accelerometers, and 2) a 39 channel system used to record ground and building response data on and near a 7 story steel frame building, and 3) instrumentation installed on a 122 m bridge span.

INTRODUCTION

The measurement of earthquake induced strong motions provide fundamental data required for the study of damaging shaking in surface deposits and for the development of satisfactory criteria for the aseismic design of structures. The need for this information has been extensively noted in the proceedings of numerous meetings dealing with the problems of earthquake hazards including those sponsored by the National Academy of Sciences (Refs. 1, 2, and 3,) and the National Science Foundation (Refs. 4, 5, and 6).

The development of a network to record required strong-motion data has been a function for more than 50 years of the U.S. Geological Survey (USGS) and several predecessor organizations. This effort includes coordination of similar projects, chiefly among government organizations concerned with the seismic safety of their own structures.

During the past 15 years there has been a rapid increase in the sophistication and reliability of accelerographic instrumentation resulting in the establishment of elaborate strong-motion monitoring systems in ground and structural arrays in the western United States. Several newer arrays operated by the USGS are described in this report.

GROUND MOTION ARRAYS

When surface waves are propagated horizontally through shallow layers, the wavelengths may approach the dimensions of a large structure

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resulting in differential motions that can apply significant stresses across the foundations of large buildings, dams, bridges, pipelines, and tunnels. To study these motions, a short baseline array of instruments is needed in a relatively high seismic region where there is a large velocity contrast between underlying and surface layers.

Such a differential motion array has been jointly developed by the USGS and the Federal Highway Administration on a broad alluvial plain near El Centro, California, 5 km from the Imperial fault (Ref. 7). This 18 channel array has six triaxial accelerometers installed in a straight line at 0, 18, 55, 128, 213, and 305 m spacings. Since n accelerometers provide n(n-1)/2 pairs of points, there are 15 inter-sensor dimensions for earthquake analysis. The sensors are Terra Technology borehole force balance accelerometers mounted in stainless steel cylinders suitable for direct burial. Each unit was placed 1.3 m deep in a small borehole, tamped in position with coarse (2 to 3 mm) quartz sand, and then backfilled with natural soil. Analog data are transmitted to a nearby recorder housing where it is digitized at 100 samples per second and stored on magnetic tape. The system is triggered by vertical motions exceeding .01 g in the range of 1 to 10 Hz and has a 1.5 second pre-event memory thus allowing the recording of pre-triggering onset motions. All data channels are synchronized for a common time base and are accompanied by a recorded WWVB (UTC) radio signal. An additonal self-contained analog triaxial accelerograph is located in the recorder housing.

A second 24 channel two-dimensional differential array has recently been installed near Hollister, California, 11 km from the San Andreas fault (Ref. 8). This array has two legs at a 33° separation with accelerometers placed at 0, 61, 457, and 610 m on one leg and 244 m and 305 m on the second leg (Fig. 1). The sensors are Kinemetrics triaxial force balance accelerometers mounted at the center of a 2.1 m diameter concrete pad, well coupled to the soil. The system has a 2.5 second pre-event memory and similar timing and triggering systems as those at the El Centro array. The data is digitized at a rate of 200 samples per second with a total recording time of 20 minutes. Two triaxial accelerographs are mounted on an isolated pier in the recorder house.

An array of cross fault paired accelerographs has been partially installed along a 125 km section of the Hayward fault 25 km east of San Francisco. This fault is recognized as a potential source of a magnitude 7 earthquake that would endanger many structures located on or near the fault zone including hospitals, high occupancy public buildings, and numerous industrial and lifeline structures. The instrumentation sites have been selected to investigate cross fault displacements and source mechanisms during moderate to large earthquakes when surface rupturing may occur. Each pair of sites is being located approximately .5 km from opposite sides of the faultline with pair spacings of about 10 km. The present instrumentation consists of radio equipped three component analog accelerographs installed in small fiberglass buildings.

Several combined acceleration and pore pressure measurement projects have been established in areas with a potential for liquefaction.

Instrumentation consists of a 12 channel analog recorder receiving acceleration data from two triaxial sensors, one downhole and one at the surface, and from a shallow array of six pore pressure sensors. These arrays are designed to begin recording at the onset of an earthquake and monitor the transient changes in both ground motion and pore pressures through the stage of liquefaction. Instrumented sites are located near El Centro where repetitive liquefaction has occurred, Mammoth Lakes, California, and at two sites on the debris slide created below Mount Saint Helens during the eruption of May 18, 1980.

STRUCTURAL ARRAYS

Dams

General objectives of strong-motion instrumentation programs for dams are to obtain ground and structural response data for the analysis and design of future dams, to evaluate earthquake hazards of existing dams, and to determine the safety of dams subjected to strong-motion (Ref. 9). Early programs concentrated on locating one to several accelerographs at surface locations including the abutment, crest, toe, and downstream. With improvement in instrumentation and recording techniques, it became feasible in the 1970's to place surface sensors at selected locations and transmit the data by cable to a central recorder. The further development of direct burial accelerometers led to the feasibility of locating sensors within the embankment thus creating a three-dimensional array to analyze the complex motion of earthfill dams during earthquakes.

Four U.S. Bureau of Reclamation earthfill dams have been instrumented with three-dimensional arrays combining triaxial sensors located in drill holes with surface accelerographs. One of these is Casitas Dam located in southern California. The structure, completed in 1959, has a crest length of 610 m and a maximum height of 87 m. Holes were drilled through center crest for emplacement of accelerometers in basement rock at 105 m, and in the embankment at 30 m and 9 m depths (Fig. 2). A fourth sensor is located 9 m deep in a mid-section of the downstream embankment. The accelerometers were placed at the bottom of each hole with orientation poles, cemented in position, and the hole was then backfilled with quartz sand. This 12-channel system is complemented by accelerographs on the crest and toe of the dam. The latter instruments include WWVB radio receivers and vertical starters for triggering the system.

Other Bureau of Reclamation dams instrumented with similar downhole configurations are Boca and Sugar Pine Dams, California and Hyrum Dam near the Wasatch fault in Utah. Downhole sensors at two of these dams are held in position by coarse sand and thus are retrievable by dislodging the sand with a high pressure hose and lifting out the accelerometers with a cable attached to the containment case. This method was selected because of concern for failures at depth using irretrievable accelerometers.

Buildings

In 1965 Los Angeles amended the building code requiring three accelerographs in most new buildings over six stories, one in the basement, one at midheight, and one near the top. Similar provisions were soon added to the Uniform Building Code. By the time of the San Fernando earthquake in 1971, more than 70 Los Angeles area buildings had accelerographs installed under provisions of the two codes. Analysis of records from this earthquake indicated that this method of locating instrumentation in buildings did not provide sufficient data for a rigorous analysis of dynamic structural response during strong earthquake motion. Subsequently, with the development of remote-transducer recording systems, more adequate techniques for instrumented buildings were proposed that would provide essential data for improving aseismic design of representative types of structures (Ref. 10). This new scheme called for the siting of accelerometers throughout the structure to record three mode sets in buildings with rigid floor systems: two sets primarily horizontal translational motion and the third set primarily torsional motion. When flexible floor systems are considered, the sensors are located to detect in-plane bending.

A seven story building located near Los Angeles has been instrumented in this manner, a joint venture supported by the USGS and the building owner. The structure is rectangular 41 m by 141 m, 35 m tall and has a steel ductile moment resisting frame resting on a foundation consisting of drilled-in-place caissons. The building has steel pan concrete floors and an exterior facing of pre-cast concrete panels.

Twenty-seven accelerometers were installed throughout the structure near the ceiling at the center and ends of floors 7, 4, 1, and basement, on the basement concrete slab, and near the bottom of a center column caisson 8 m deep (Fig. 3). Upper level sensors were attached to steel mounting plates welded to the frame at appropriate locations near column beam connections. Basement accelerometers are bolted to the floor at the east and west ends and to the pier cap in the center of the building. The downhole accelerometers were installed during construction by strapping the module to the bottom of a steel cage which was then lowered into the drill hole and correctly oriented before the caisson concrete was poured. To our knowledge this is the first time strong-motion sensors have been installed near the base of a pile foundation.

Four ground level (free-field) accelerographs have been installed around the building in small fiberglass shelters. These instruments are located nominally 30 to 90 m from the building and form the ground response network not only for that structure but also for an adjacent seven-story building instrumented with three triaxial accelerographs. The entire complex of eight accelerographs plus 24 channels of remote transducer data are synchronized for simultaneous time by either common starting and timing signals or by WWVB radio time.

Bridges

Failure of highway grade separation bridges during the 1971 San Fernando, California earthquake, pointed out the need for dynamic recordings from typical type structures during strong earthquake motion (Ref. 11). Prior to the San Fernando earthquake, bridge instrumentation was rare indeed and consisted only of triaxial accelerographs incapable of being located in critical structural locations. When remote transducer equipment was developed in the early 1970's, it was appropriate to establish extensive bridge monitoring systems in seismically active areas.

The USGS and the Washington Department of Transportation have instrumented three freeway overcrossings in the Seattle and Bellingham areas of Washington. The Bellingham bridge is a four-span pre-stressed concrete curved box girder structure 122 m long supported by three mid-piers approximately 5.4 m tall and two end piers at the embankments. The mid-piers rest on pile caps supported by multiple timber piles.

Nine accelerometers are located in the boxes at the tops of all five piers and at two places on the underdecking (Fig. 4). A triaxial downhole accelerometer is installed two feet below ground level on the top of one pier cap. The 12 channels of structural data are transmitted by buried cable to an analog recorder in a small instrument shelter 9 m north of the bridge. A triaxial accelerograph located in the recorder housing provides a trigger and timing for the combined system.

Other similarly instrumented bridges operated by the USGS include: two Washington freeway overcrossings near Seattle, three Federal Highway Administration structures in New York, Missouri and Alaska, and a California Department of Transportation bridge in San Jose.

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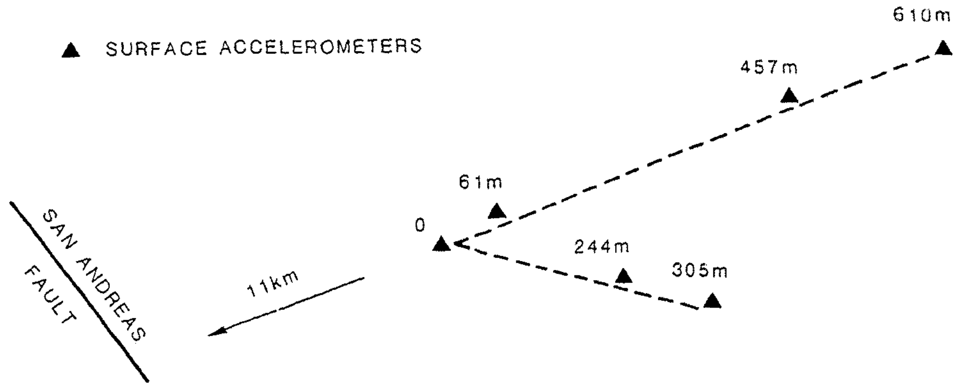

Figure 1.- The Hollister, California Differential Array.

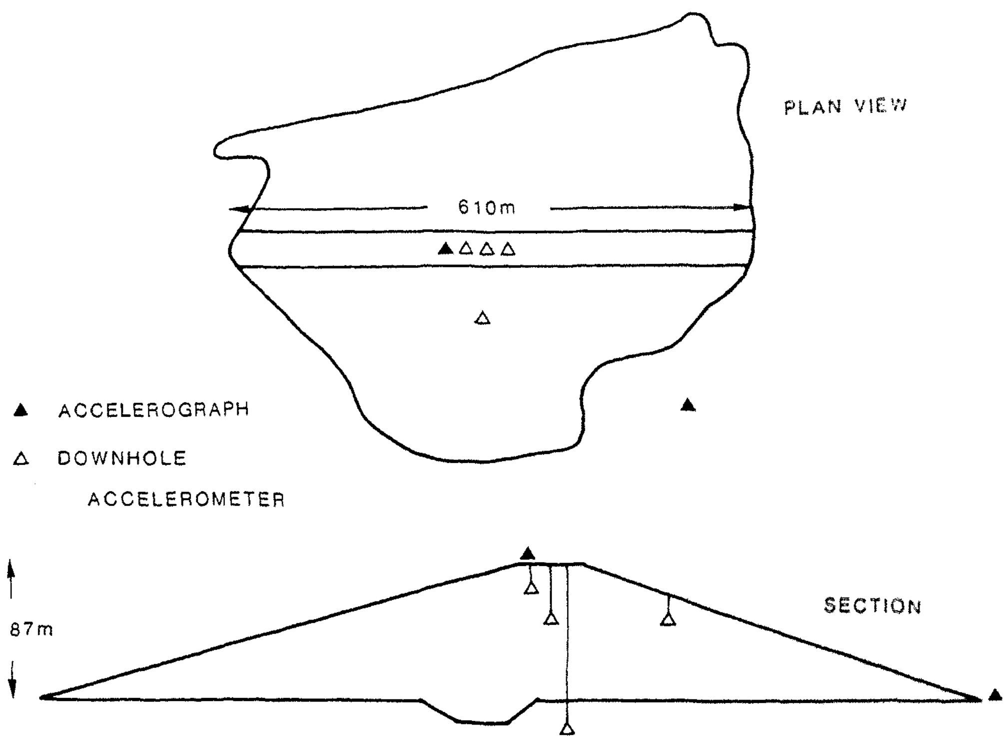

Figure 2.- Instrumentation at Casitas Dam, California.

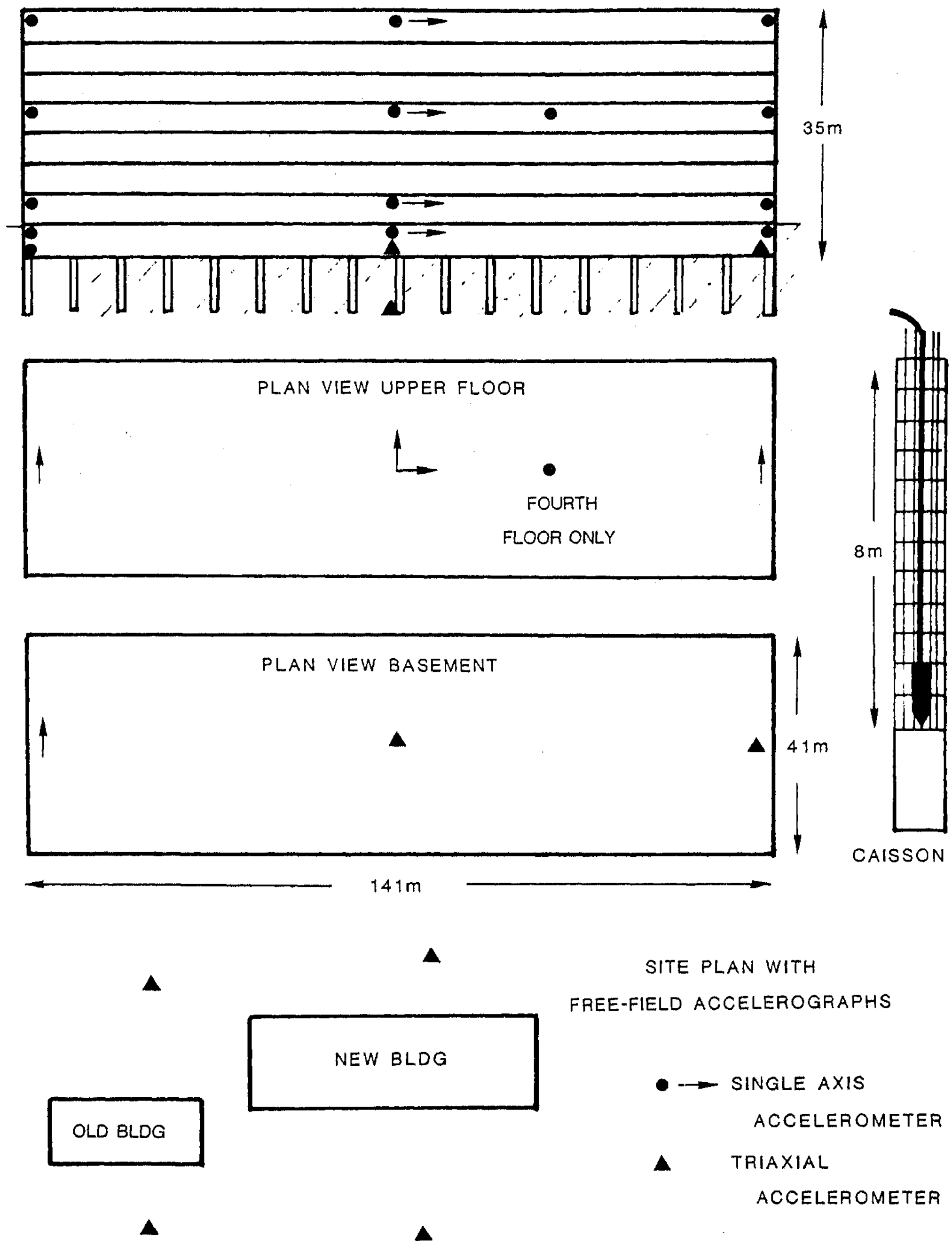

Figure 3.- Strong-motion system, 7 story building near Los Angeles.

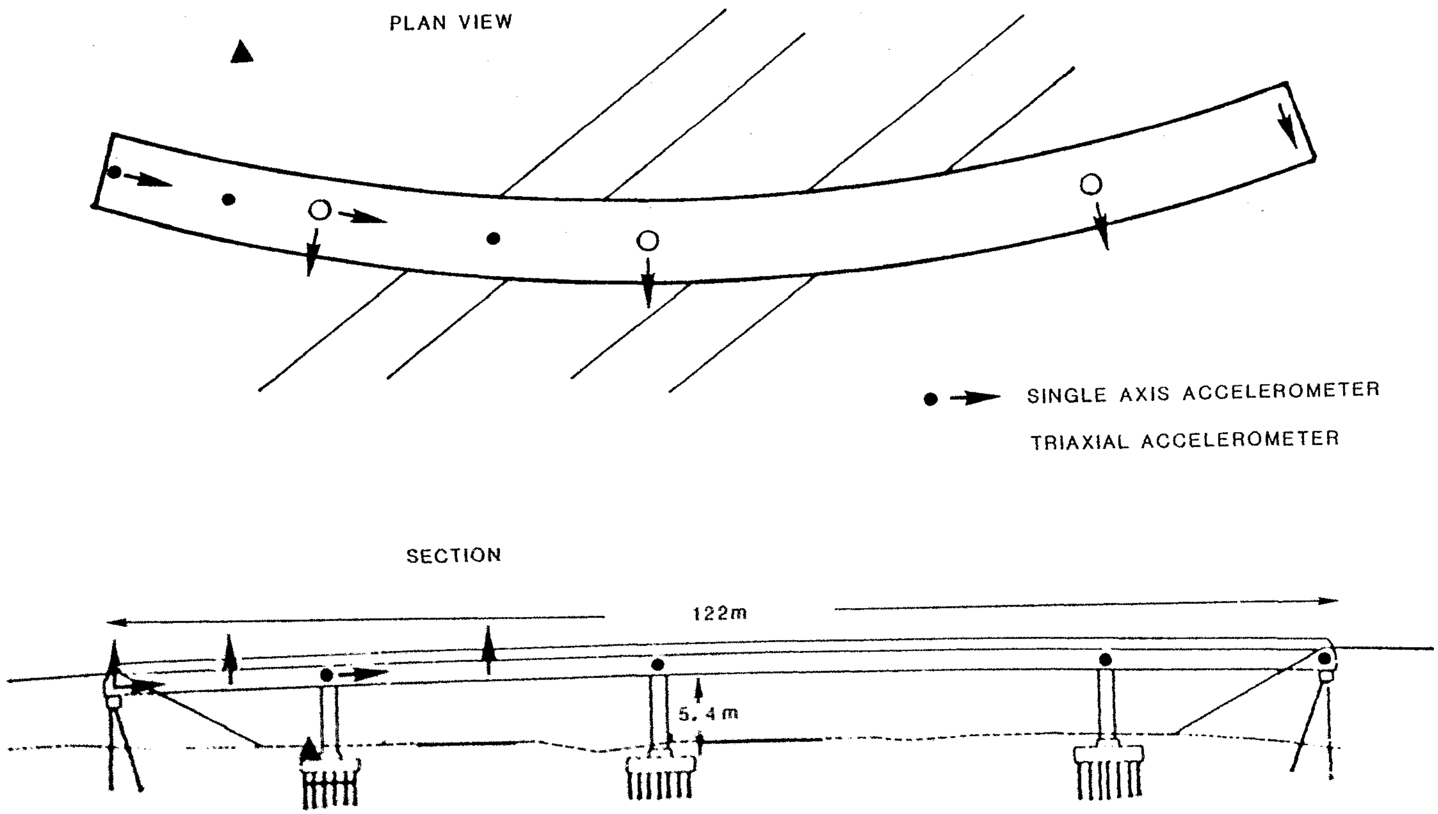

Figure 4.- Instrumentation on the Bellingham, Washington overcrossing.