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Measurement of Structural Response Characteristics of Full-Scale Buildings: Selection of Structures

U.S. Department of Commerce
National Institute of Standards and Technology
Building and Fire Research Laboratory
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R. D. Marshall
Long T. Phan
M. Celebi*

*Branch of Engineering Seismology and Geology
U.S. Geological Survey
Menlo Park, CA

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John W. Lyons, *Director*
Building and Fire Research Laboratory
Gaithersburg, MD 20899

ABSTRACT

This report describes the selection of existing building structures for subsequent field measurements of low-level ambient vibrations. By comparing measurement results with previously recorded high-level responses, it is anticipated that guidance can be developed for improved measurement practice. The buildings selected for this effort represent a cross-section of contemporary structural systems and materials, foundation types, and a range of building heights and aspect ratios. Each building was subjected to strong shaking during the Loma Prieta Earthquake of October 17, 1989.

Keywords: buildings, earthquake, instrumentation, dynamic response, field measurements, structural dynamics

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INTRODUCTION

This report presents a summary description of building structures in the San Francisco Bay area that have been selected for use in a study of dynamic characteristics. Specifically, the validity of small-amplitude testing methods for the assessment of dynamic characteristics will be studied. Each of the buildings described herein was instrumented with strong-motion accelerometers prior to the Loma Prieta Earthquake of October 17, 1989 ($M_s = 7.1$) and yielded excellent sets of response records during the earthquake. The buildings have been selected to cover a range of structural systems, construction materials, aspect ratios, and foundation types.

BACKGROUND

Reliable estimates of modal frequencies, stiffness and damping of structural systems are essential for predicting the dynamic response under loading conditions associated with serviceability or structural safety. Although response characteristics of isolated structural components usually can be predicted with acceptable accuracy using simple models, this is not the case for complete structures where primary and secondary systems can interact in complex ways. Examples of such interaction include the participation of cladding in overall system stiffness and damping, the participation of infill walls and non-structural partition walls, and the interaction of floor systems with columns and bearing walls.

Analytical models for calculating building response usually involve substantial simplification of the real structure and, for various reasons, detailed physical scale models for controlled testing in the laboratory often prove impractical. Consequently, each of these approaches must depend on reliable full-scale field measurements for validation and/or improvement of the modeling technique. Changes in the dynamic properties of structures subjected to strong seismic excitation are related to the intensity and extent of damage and, therefore, reliable full-scale response measurements are of potential use in the assessment of structural damage.

Numerous studies of structural response have been carried out on tall buildings, long-span bridges, and large dams. The most widely used technique has been to rely on ambient vibrations for excitation or, in certain cases, to use one or more mechanical shakers to excite specific modes of vibration in the structure. In rare cases response measurements have been obtained during extreme events such as earthquakes or wind storms. Generally, these measurements suggest a strong dependence of response parameters on displacement amplitude, thus raising questions about the validity and proper interpretation of response measurements obtained under low levels of excitation. It is not unknown for seemingly identical structures to exhibit basic characteristics such as stiffness that differ by as much as 50 percent (Ellis and Littler, 1987). In the case of structural damping, determinations may differ by a factor of two or more. How much of this disparity can be attributed to actual physical differences and how much can be attributed to measurement errors and incorrect interpretation of test results is unknown.

TEST PROGRAM

The Loma Prieta Earthquake of October 17, 1989, provided a unique opportunity to carry out a program of field measurements and analytical modeling of a select number of existing structures to better understand the significance of factors such as displacement amplitude in full-scale response measurements. In particular, it should be possible to interpret characteristics measured under low-level response in the light of known (recorded) high-level response. The approach will be to select a number of undamaged buildings that were subjected to strong ground shaking during the Loam Prieta Earthquake and for which valid response records are available. It should be possible from these records to obtain estimates of overall damping, the first two or three modal frequencies and the peak accelerations and displacements.

Existing analytical models can be used to estimate transverse and torsional modes of vibration and to predict response to low-level excitation. These predicted responses can then be used as a basis for selecting and installing suitable instrumentation with which to conduct low-level response measurements. To the extent possible, instrumentation systems installed in the buildings at the time of the Loma Prieta Earthquake will be utilized in the field measurement program.

CANDIDATE STRUCTURES

Buildings that are considered to be good candidates for additional study are listed in Table 1 and are located on the local area map of Figure 1. This map also indicates the major ground failures caused by the Loma Prieta Earthquake. The instrumentation systems in these candidate structures were installed and are maintained by the United States Geological Survey (USGS) and by the California Division of Mines and Geology (CDMG). The structural systems include steel frames, reinforced concrete moment frames and combinations of the two. No attempt has been made to include shear-wall systems in the selection although some of the structural systems include shear wall or core walls in the lower stories of the structure. The data included in Table 1 were extracted from post-earthquake reports by Maley et al., 1989, and by Shakal et al., 1989. Photographs of the buildings are included in Figures 2-6.

TABLE 1. DESCRIPTION OF BUILDINGS SELECTED FOR LOW-LEVEL RESPONSE MEASUREMENTS

BUILDING/STRUCTURAL SYSTEM	BUILDING HEIGHT (ft)	BASE DIMENSION (ft)	TYPICAL FLOOR PLAN (ft)	FLOORS ABOVE/BELOW GROUND	FOUNDATION TYPE	YEAR DESIGNED	YEAR CONSTR.	INSTRUMENTED BY
No. 1 ADMINISTRATION BUILDING California St. Univ. at Hayward Hayward, California Steel moment frame core and exterior reinforced concrete moment frame. Concrete shear walls around elevator shaft to second floor.	201	122 x 125	113 x 113	13/0	Bearing piles with RC caps and 18-in RC slab on grade.	1969	1969-71	CDMG
No. 2 SANTA CLARA COUNTY OFFICE BUILDING 70 West Hedding Street San Jose, California Moment resisting steel frame	187	167 x 173	167 x 167	12/1	Concrete mat	1972	1975-76	CDMG
No. 3 COMMERCIAL OFFICE BUILDING 900 Cherry Avenue San Bruno California Reinforced concrete moment frame	78	90 x 200	90 x 200	6/0	Individual spread footings.	1977	1978	CDMG
No. 4 TRANSAMERICA BUILDING 600 Montgomery Street San Francisco, California Steel frame	844	174 x 174	Varies	60/3	9-ft thick concrete mat, no piles.	-	1972-73	USGS
No. 5 PACIFIC PARK PLAZA 6363 Christie Avenue Emeryville, California Reinforced concrete moment-resisting frame. Each of three wings forms 120 degree included angle at central core.	312	56 x 111	56 x 111	30/1	5-ft thick concrete mat on friction piles.	-	1983	USGS

Note: 1 ft = 0.3048 m

CDMG = California Division of Mines and Geology
USGS = United States Geological Survey

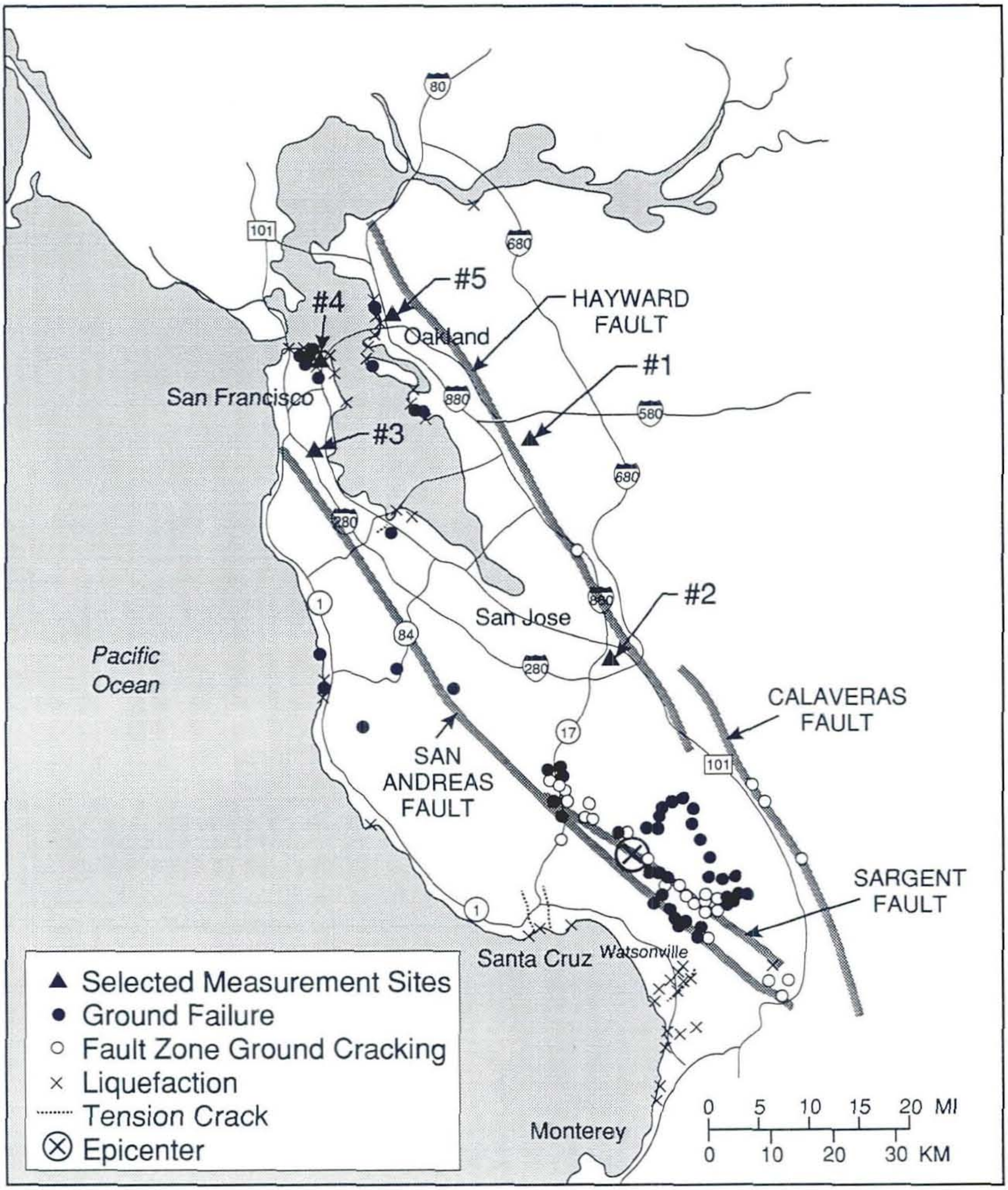

Figure 1: Locations of Selected Measurement Sites and Major Faults.

Figure 2: Administration Building, CSUH, Hayward.
View to northwest.

Figure 3: Santa Clara County Office Building, San Jose.
View to southeast.

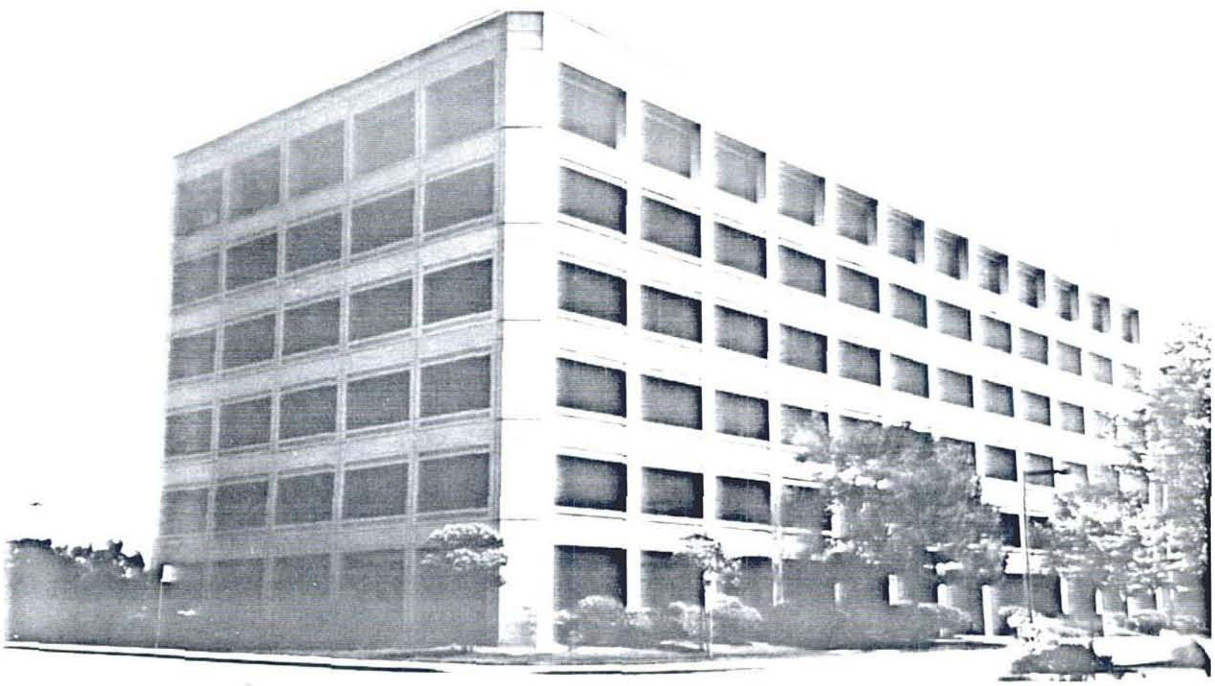

Figure 4: Commercial Office Building, San Bruno. View to southeast

Figure 5: Transamerica Building, San Francisco. View to southeast.

Figure 6: Pacific Park Plaza, Emeryville. View to west.

GROUND RESPONSE RECORDS

Table 2 contains a summary of peak ground accelerations at basement level in each of the five selected buildings and at strong-motion sites in the vicinity of the selected buildings. In most cases the sites represent free-field conditions, not being affected significantly by nearby buildings or other structures. In some cases the instrumentation is either in or adjacent to a single-story building such as a fire house. For the Transamerica Building in San Francisco, the strong-motion sites at Diamond Heights, Pacific Heights and Telegraph Hill are located within two-story buildings.

TABLE 2. SUMMARY OF LOMA PRIETA GROUND RESPONSE RECORDS AT OR NEAR BUILDINGS SELECTED FOR ADDITIONAL STUDY

STATION NAME	EPICENTRAL DISTANCE (km)	ACCELERATION COMPONENTS (g)
<u>ADMINISTRATION BUILDING - CSUH</u> N. Lat. = 37.655 W. Long. = 122.056 Site Geology: Franciscan metavolcanic rock	70	050 = 0.09 Up = 0.05 320 = 0.08
Fremont - Mission San Jose N. Lat. = 37.530 W. Long. = 121.919 Site Geology: Alluvium	55	090 = 0.11 Up = 0.09 360 = 0.13
Hayward - CSUH Stadium Grounds N. Lat. = 37.657 W. Long. = 122.061 Site Geology: Franciscan greenstone	71	090 = 0.08 Up = 0.05 360 = 0.08
Hayward - Muir School N. Lat. = 37.657 W. Long. = 122.082 Site Geology: Alluvium	71	090 = 0.14 Up = 0.10 360 = 0.18
Hayward - BART Station Parking Lot N. Lat. = 37.670 W. Long. = 122.086 Site Geology: Alluvium	73	310 = 0.16 Up = 0.08 220 = 0.16
<u>SANTA CLARA COUNTY OFFICE BUILDING</u> N. Lat. = 37.353 W. Long. = 121.903 Site Geology: Alluvium	35	067 = 0.10 Up = 0.10 337 = 0.11
San Jose - Santa Teresa Hills N. Lat. = 37.210 W. Long. = 121.803 Site Geology: Alluvium over serpentine	21	225 = 0.28 Up = 0.22 315 = 0.27
Saratoga - Aloha Avenue N. Lat. = 37.255 W. Long. = 122.031 Site Geology: Alluvium	27	090 = 0.34 Up = 0.41 360 = 0.53

(Table 2 continued)

STATION NAME	EPICENTRAL DISTANCE (km)	ACCELERATION COMPONENTS (g)
San Jose Interchange - 101/280/680 N. Lat. = 37.340 W. Long. = 121.851 Site Geology: Not available	34	232 = 0.13 Up = 0.08 322 = 0.18
Halls Valley - Grant Park N. Lat. = 37.338 W. Long. = 121.714 Site Geology: Alluvium	37	090 = 0.11 Up = 0.06 360 = 0.13
Agnew - Agnew State Hospital N. Lat. = 37.239 W. Long. = 121.952 Site Geology: Alluvium	40	090 = 0.16 Up = 0.10 360 = 0.17
Sunnyvale - Colton Avenue N. Lat. = 37.402 W. Long. = 122.024 Site Geology: Not available	43	270 = 0.19 Up = 0.10 360 = 0.22
<u>OFFICE BUILDING - SAN BRUNO</u> N. Lat. = 37.628 W. Long. = 122.424 Site Geology: Alluvium	81	245 = 0.12 Up = 0.12 335 = 0.14
Upper Crystal Springs Reservoir (Skyline Blvd.) N. Lat. = 37.465 W. Long. = 122.343 Site Geology: Sandstone	63	090 = 0.09 Up = 0.04 360 = 0.10
Upper Crystal Springs Reservoir (Pulgas Water Temple) N. Lat. = 37.49 W. Long. = 122.31 Site Geology: Sandstone	63	090 = 0.09 Up = 0.06 360 = 0.16
Foster City - Redwood Shores N. Lat. = 37.55 W. Long. = 122.23 Site Geology: Alluvium to 210 m, serpentine	63	090 = 0.29 Up = 0.11 360 = 0.26

(Table 2 continued)

STATION NAME	EPICENTRAL DISTANCE (km)	ACCELERATION COMPONENTS (g)
San Francisco International Airport N. Lat. = 37.622 W. Long. = 122.398 Site Geology: Deep alluvium	79	090 = 0.33 Up = 0.05 360 = 0.24
South San Francisco - Sierra Point N. Lat. = 37.674 W. Long. = 122.388 Site Geology: Not available	84	115 = 0.06 Up = 0.05 205 = 0.06
<u>TRANSAMERICA BUILDING</u> N. Lat. = 37.80 W. Long. = 122.40 Site Geology: Not available	97	083 = 0.12 Up = 0.07 351 = 0.11
San Francisco - Golden Gate Bridge N. Lat. = 37.806 W. Long. = 122.472 Site Geology: Not available	100	270 = 0.24 Up = 0.06 360 = 0.12
San Francisco - Presidio N. Lat. = 37.792 W. Long. = 122.457 Site Geology: Serpentine	98	090 = 0.21 Up = 0.06 360 = 0.10
San Francisco - Diamond Hts. N. Lat. = 37.74 W. Long. = 122.43 Site Geology: Franciscan chert	92	090 = 0.12 Up = 0.05 360 = 0.10
San Francisco - Pacific Hts. N. Lat. = 37.79 W. Long. = 122.43 Site Geology: Franciscan sandstone, shale	97	270 = 0.06 Up = 0.03 360 = 0.05
San Francisco - Telegraph Hill N. Lat. = 37.80 W. Long. = 122.41 Site Geology: Franciscan shale, sandstone	97	090 = 0.08 Up = 0.03 360 = 0.06

(Table 2 continued)

STATION NAME	EPICENTRAL DISTANCE (km)	ACCELERATION COMPONENTS (g)
San Francisco - Rincon Hill N. Lat. = 37.79 W. Long. = 122.39 Site Geology: Franciscan sandstone, shale	95	090 = 0.09 Up = 0.03 360 = 0.08
Yerba Buena Island N. Lat. = 37.81 W. Long. = 122.36 Site Geology: Franciscan sandstone	95	090 = 0.06 Up = 0.03 360 = 0.03
Treasure Island N. Lat. = 37.825 W. Long. = 122.373 Site Geology: Fill	98	090 = 0.16 Up = 0.02 360 = 0.11
<u>PACIFIC PARK PLAZA - EMERYVILLE</u> N. Lat. = 37.844 W. Long. = 122.295 Site Geology: Silty fine sand fill and Bay mud on hard silty clay	97	080 = 0.21 Up = 0.06 350 = 0.17
Pacific Park Plaza Free Field - South	97	090 = 0.26 Up = 0.06 360 = 0.22
Pacific Park Plaza Free Field - North	97	090 = 0.22 Up = 0.09 360 = 0.20
Piedmont - Piedmont Jr. High Grounds N. Lat. = 37.823 W. Long. = 122.233 Site Geology: Weathered serpentinite	93	045 = 0.08 Up = 0.03 315 = 0.07
Berkeley - UCB Memorial Stadium Grnds. N. Lat. = 37.87 W. Long. = 122.25 Site Geology: Not available	98	135 = 0.13 Up = 0.03 225 = 0.07
Berkeley, U.C. - Strawberry Canyon N. Lat. = 37.87 W. Long. = 122.24 Site Geology: Not available	98	135 = 0.04 Up = 0.02 045 = 0.08

(Table 2 continued)

STATION NAME	EPICENTRAL DISTANCE (km)	ACCELERATION COMPONENTS (g)
Berkeley - Lawrence Berkeley Lab N. Lat. = 37.876 W. Long. = 122.249 Site Geology: Thin alluvium on shale, siltstone	99	090 = 0.12 Up = 0.04 360 = 0.05
Richmond - 2501 Rydin Road N. Lat. = 37.884 W. Long. = 122.302 Site Geology: Not available	101	057 = 0.08 Up = 0.04 327 = 0.11
Richmond - City Hall Parking Lot N. Lat. = 37.935 W. Long. = 122.342 Site Geology: Alluvium	108	280 = 0.11 Up = 0.04 190 = 0.13

STRUCTURAL RESPONSE DATA

Representative structural response data obtained during the Loma Prieta Earthquake are listed in Table 3. A considerable amount of response data from these and other structures has not yet been processed or analyzed. Also included in Table 3 are selected results of forced vibration studies carried out prior to Loma Prieta and measurements of ambient vibrations carried out by USGS and NIST personnel on May 10-11, 1990.

FIELD MEASUREMENTS

To the extent possible, use will be made of the permanently installed instrumentation in the candidate structures. The advantages of this approach are that it allows a direct comparison of low-level measurements with high-level measurements and considerably reduces the amount of time and effort required to carry out the field measurements. The major disadvantage is that the sensitivities of the permanently installed sensors may in certain cases be too low to obtain reliable acceleration measurements. In most cases the permanently installed sensors are force-balance accelerometers (FBA's) with a nominal sensitivity of 2.5 volts/g and a resolution of approximately 1 micro-g. If necessary, additional point measurements can be obtained using portable accelerometers provided by USGS.

The NIST data acquisition system to be used in the field measurement program has an input range of ± 10 volts and employs

TABLE 3. SUMMARY OF RESPONSE DATA FOR CANDIDATE STRUCTURES

BUILDING	DISTANCE FROM EPICENTER (km)	NUMBER OF DATA CHANNELS	LOMA PRIETA EARTHQUAKE RESPONSE DATA: PEAK ACCELERATION (g) GROUND	ROOF	NATURAL FREQ. (Hz)	NATURAL FREQ. AMBIENT SURVEY (This Study)* (Hz)
ADMINISTRATION BUILDING - CSUH Hayward, California Job North = 320 Deg.	70	16	0.07 (N-S) 0.09 (E-W) 0.05 (Vert)	0.15 (N-S) 0.24 (E-W)	0.80 (N-S) - (E-W)	1.10 (N-S)* 0.85 (E-W)*
SANTA CLARA COUNTY OFFICE BUILDING San Jose, California Job North = 337 Deg.	35	22	0.11 (N-S) 0.10 (E-W) 0.10 (Vert)	0.35 (N-S) 0.36 (E-W)	0.44 (N-S) 0.45 (E-W)	0.55 (N-S)* 0.75 (E-W)*
COMMERCIAL OFFICE BUILDING San Bruno, California Job North = 335 Deg.	81	13	0.14 (N-S) 0.12 (E-W) 0.12 (Vert)	0.25 (N-S) 0.32 (E-W)	1.28 (N-S) 1.04 (E-W)	1.75 (N-S)* 1.40 (E-W)*
TRANSAMERICA BUILDING San Francisco, California Job North = 351 Deg.	97	22	0.11 (N-S) 0.12 (E-W) 0.07 (Vert)	49th Floor 0.29 (N-S) 0.31 (E-W)	0.28 (N-S) 0.28 (E-W)	1st Mode 0.337 (N-S) 0.330 (E-W) 0.345 (N-S)** 0.345 (E-W)** 5th Mode 1.52 (N-S) 1.50 (E-W) 1.62 (N-S)** 1.53 (E-W)**
PACIFIC PARK PLAZA Emeryville, California Job North = 350 Deg.	97	21	0.17 (N-S) 0.21 (E-W) 0.06 (Vert)	0.24 (N-S) 0.38 (E-W)	- (N-S) - (E-W)	1st Mode 0.59 (N-S) 0.59 (E-W) 0.59 (N-S)** 0.59 (E-W)** 4th Mode 4.52 (N-S) 4.44 (E-W) 4.36 (N-S)** 4.39 (E-W)**

NOTE: ** Forced Vibration

a 12-bit A/D converter capable of performing up to 250,000 conversions per second. A total of 16 data channels can be multiplexed at the 250,000/sec rate. Each data channel is provided with a differential input amplifier, a 3-pole active filter, and a sample-and-hold amplifier. Thus the samples obtained in each scan of the data channels have zero time skew. The differential amplifiers have nine jumper-selectible gains covering the range x1 to x500. If desired, DC components in the amplified signal can be nulled with a programmable offset voltage of up to 40 percent of the dynamic range. The effective dynamic range of the data acquisition system is extended by a programmable-gain amplifier in the A/D section with a gain selection of 1, 2, 4, or 8. The filter type and cutoff frequency can be changed by changing resistor and capacitor networks on the signal conditioning cards. The configuration to be used in this measurement program is a Butterworth low-pass filter with a cutoff frequency of 10 Hz. The sample rate will be 50 samples per second per channel. The minimum record length will be 2,048 samples or approximately 40 seconds. It is anticipated that several minutes of recordings will be collected at each field site.

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The authors wish to acknowledge the assistance of Dr. M. J. Huang, Office of Strong Motion Studies, California Division of Mines and Geology, who provided valuable information on structural systems and Loma Prieta response data for the field sites. Mr. Marion Salsman, Branch of Engineering Seismology and Geology, U.S. Geological Survey, provided valuable assistance in conducting the field measurements.

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