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Building Strong-Motion Earthquake Instrumentation

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ABSTRACT

Based on the recommendations of a special ad-hoc committee, twenty-one geographic areas will be instrumented under the building instrumentation phase of the California Strong-Motion Instrumentation Program, a statewide program established by law in 1971 and funded through an assessment of estimated construction costs collected statewide from building permits. The areas were selected on the basis of population density, locations of buildings already instrumented, and the probability for potentially damaging earthquakes. Buildings to be instrumented will be of typical construction, simple in framing and design, and of various heights with the instrumentation of low-rise buildings emphasized. Remote recording instrumentation, consisting of single or multiaxial accelerometers connected via data cable to a central recorder, will be installed in each building. The accelerometers will be placed on the lowest level, at the roof level, and, in many cases, at one or more intermediate levels. The instrumentation will be situated so as to separately record both translational and torsional response.

On the basis of current projected revenues, and instrument procurement, installation and maintenance expenses, it is estimated that as many as 400 buildings may be instrumented under the State program.

INTRODUCTION

In 1971 the State of California established a Strong-Motion Instrumentation Program to assure the development of a scientifically sound distribution of strong-motion instruments throughout the State. The California Division of Mines and Geology (CDMG) operates the program with the advice of an Advisory Board. Funding is provided by a .007 percent (7¢ per $1000) assessment of estimated construction costs collected statewide from building permits.

During the first two years the program was in effect (1972-73), the instrumentation of ground or "freefield" sites was emphasized and all available funding was used to purchase and install strong- motion accelerographs for that purpose. In 1974, with the "freefield" instrumentation phase of the program well established, a large segment of the available funding was channeled for use in instrumenting buildings, the second priority of the program. At the request of the CDMG and its Advisory Board, a set of detailed guidelines for selecting and instrumenting buildings was developed by a special ad-hoc committee. Those guidelines, their background and subsequent implementation, are the subject of this paper. Similar guidelines, not discussed herein, have also been developed for a third phase of the program in which dams throughout the State are being instrumented.

The basic objectives for the building instrumentation phase of the State program were adopted by the Advisory Board's Site Selection Committee in mid-1973 as follows: to place a high priority on instrumenting buildings in Zone III of the Preliminary Map of the Maximum Expectable Earthquake Intensity in California, figure 1 (Alfors, Burnett, and Gay, 1973), and a lower priority on instrumenting buildings in Zone II; to place the highest priority on instrumenting buildings located within five miles of the major faults along which there is significant activity; to seek the assistance of the Structural Engineers Association of California in selecting buildings to be instrumented under the program; to select representative types and heights of buildings; to instrument many buildings moderately rather than a few buildings extensively; and to use remote recording accelerograph systems with accelerometers located so as best to record both translational and torsional response of each building. With these objectives and at the request of the Site Selection Committee, the specially appointed ad-hoc committee (the Subcommittee on Instrumentation for Structures) developed a series of guidelines defining where, which types, and how buildings should be instrumented under the program. Those guidelines, discussed in detail below, are now being implemented.

GEOGRAPHIC DISTRIBUTION OF INSTRUMENTED BUILDINGS

In adopting its objectives for the building instrumentation program, the Site Selection Committee stipulated that areas within Zone III (zone of maximum expected intensity) of the Preliminary Map of Maximum Expectable Earthquake Intensity in California, and especially areas within five miles of the major active fault zones, should be given highest priority for the instrumentation of buildings. In light of these stipulations and considering population densities, locations of buildings in which strong-motion instrumentation had already been installed, and a best-educated-guess on the probability for potentially damaging earthquakes in various areas throughout the State, the Subcommittee on Instrumentation for Structures established a list of 21 areas recommended for instrumentation and suggested how many buildings should be instrumented in each area (expressed as a percentage of the total number of buildings to be instrumented). With the exception of the highly populated San Diego area, all selected areas were either in or immediately adjacent to Zone III. The area along the Hayward fault between Milpitas and Geyserville was selected for the largest number of buildings because of the high concentration of buildings adjacent to the fault, high probability for potentially damaging earthquake activity, and lack of existing instrumented buildings. The area along the San Andreas fault between Los Gatos and Fort Bragg was chosen for similar reasons. In Los Angeles, where a large number of mid- and high- rise buildings have already been instrumented under the terms of the city ordinance, the concentration of buildings and probability for potentially damaging earthquake activity were also considered to be high and the need to instrument low-rise buildings was considered to be great. A slightly lower number of buildings were recommended along the Calaveras fault system as it extends from San Jose to Napa, along the San Jacinto fault from Cajon Pass to Hemet and from Hemet to El Centro, and along the San Andreas fault from Cajon Pass to Calipatria. These areas were considered to have a high probability for potentially damaging earthquake activity, moderately dense populations, and few instrumented buildings. In the remaining selected areas, a relatively small number of buildings were recommended because of lower population densities and postulated lower potential for seismic activity.

Because of the manner in which seismic waves propogate and attenuate in the California region (high frequencies tend to attenuate more quickly with distance than lower frequencies, which tend to be more pronounced away from the source of energy release) and the fact that the natural periods of vibration of buildings are approximately proportional to the number of stories (the higher the building, the longer the fundamental period), recommendations were made on the distribution of the height of instrumented buildings relative to the distance from potentially active faults. Those recommendations, shown in table 1, suggest that instrumented low-rise buildings (one to six stories) should be within 10 miles (16 km) of the fault of interest, that most of the instrumented mid-rise buildings (seven to fifteen stories) should be within a 25-mile (40-km) range, and that most of the instrumented high-rise buildings (greater than fifteen stories) should be in the 5- to 25-mile (8- to 40-km) range.

SELECTION OF TYPES AND HEIGHTS OF BUILDINGS

In its interpretation of the legislation creating the State program, the Advisory Board indicated that one of the primary objectives should be to provide data on which to base improvements in engineering design practice. In light of this objective and the general stipulation that representative buildings throughout the State should be instrumented, it was recommended that: all major building types, construction techniques, and materials should be equitably represented; each instrumented building should be relatively simple in framing and design so that the response can be readily interpreted; and the instrumentation of low-rise buildings should be emphasized.

In regard to building type, an attempt was made to ascertain an equitable distribution of the types of buildings shown in table 2. No recommendations were made with regard to date of design or construction although it was believed that the instrumentation of buildings designed since the Long Beach earthquake of 1933 should be emphasized.

With respect to the percentage distribution of instrumented building heights, it was suggested that 28% of the instrumented buildings should be in the one to two-story range, 32% in the three to six-story range, 26% in the seven to fifteen-story range, and 14% greater than fifteen stories (table 1). This distribution reflects the attitude that low-rise buildings (one to six stories) should make up 60% of the total number of buildings instrumented under the State program. The emphasis on low-rise buildings stems from the fact that they are vastly more numerous throughout the State than their high-rise counterparts, and that they have historically been more hazardous when subjected to strong ground shaking (all known deaths in the 1971 San Fernando earthquake, for example, occurred in low-rise buildings). Furthermore, relatively few low-rise buildings had been instrumented prior to the development of the State program.

SELECTION AND PLACEMENT OF INSTRUMENTS IN BUILDINGS

In general, it was recommended that all buildings instrumented under the State program should be instrumented using remote recording instrumentation, consisting of single or multiaxial accelerometers connected via data cable to a central recorder(s), and that the accelerometers should be installed at locations prescribed by the guidelines for instrumenting buildings developed by the author and R. B. Matthiesen (Rojahn and Matthiesen, 1975).

Remote recording systems were recommended rather than triaxial optical-mechanical self-contained accelerographs (triaxial accelerographs are presently required by the city of Los Angeles and other municipalities that adopted similar ordinances) because remote recording systems give greater flexibility for accelerometer placement, space requirements are minimized, and the recorder can be centrally located for easy maintenance and record retrieval. Furthermore, triaxial systems like those presently required by the city of Los Angeles do not provide enough data to isolate translational and torsional response, a capability that forced-vibration tests (Goebler, 1969; Hart, DiJulio and Lew, 1974; Jennings, Matthiesen and Hoerner, 1972) as well as analyses of records from the 1971 San Fernando earthquake (Blume and Associates, 1973; Gates, 1973) indicate is vital even in highly symmetrical buildings.

As a minimum, accelerometers should be placed on the lowest level and at the main roof level. On the lowest level, it is recommended (as a minimum) that three orthogonal accelerometers (two horizontal and one vertical) be attached firmly to the foundation or floor near the center of plan with the horizontal accelerometers oriented parallel to the transverse and longitudinal axes of the building. If the foundation conditions are such that differential horizontal motion may occur (Yamahara, 1970), one or more additional horizontal accelerometers are recommended. In a building that is large and relatively square in plan, two additional accelerometers should be positioned along and parallel to two adjacent outside walls, whereas in a building that is very long in comparison with its width, one additional accelerometer positioned and parallel to one of the outside end walls may be sufficient (figure 2a). If the building has a rigid mat foundation and rocking motion is expected, two additional vertical accelerometers are recommended. These should be positioned so that rocking motion can be recorded along any azimuth, i.e., one vertical accelerometer should be positioned in each of three corners of the building (figure 2b). In a building that is quite large in plan with significantly varying foundation conditions, it is recommended that additional triaxial packages be installed on the different foundation materials.

Instrumentation at the main roof level, as well as at all instrumented intermediate floors, should consist of an array of remote horizontal accelerometers arranged so as separately to record both translational and torsional motion. If the roof or instrumented floor is very stiff and is expected to be rigid in the horizontal plane, only three horizontal accelerometers are required. A biaxial pair should be located at the predicted or known center of rigidity so as to record pure translational motion along the transverse and longitudinal axes of the building. The third accelerometer should be positioned along and parallel to the most distant outside end wall so as to record torsional motion (figure 3a). If the roof is not expected to be rigid in the horizontal plane, one or more additional horizontal accelerometers is recommended. The location of each of these will be dependent upon the expected response of the roof (floor). For example, in the case of a rectangular-plan exterior shear-wall building with the roof (floor) diaphragm flexible in the transverse direction and not in the longitudinal direction, one additional accelerometer is recommended. It should be positioned so as to facilitate the interpretation of relative motion in the transverse direction between the end walls and the center of the roof (floor) diaphragm (figure 3b). Because the most significant motions in building response to strong ground shaking are normally in the horizontal direction, vertical accelerometers are not felt to be as crucial above ground level as horizontal accelerometers. If vertical response is of interest, however, vertical accelerometers sufficient in number to determine all significant relative motions should be installed. In masonry-wall buildings, for example, where ultimate strength is a function of bearing stress (Mayes and Clough, 1975), the vertical accelerometers should be aligned vertically on the wall(s) of interest at various heights throughout the building, including the lowest level. Likewise, if the vertical response of a floor slab or beam is of interest (in any type of building), multiple vertical accelerometers should be installed at the slab edges, or beam ends, and the mid-span.

The number of intermediate levels at which instrumentation should be installed is a functon of the structural framing system, number of stories, architectural configuration and known dynamic characteristics of the building. Unless mode shapes have been predetermined by forced-vibration or in-depth ambient vibration tests and intermediate level instrumentation is not considered to be necessary, instrumentation should be placed at as many intermediate floors as is economically feasible because the accuracy with which a building's response to earthquake motion can be determined is largely proportional to the number of levels instrumented. As a minimum, it is recommended that at least two intermediate levels be instrumented in buildings having more than six stories above ground and at least one be instrumented in buildings having three to six stories. The level(s) should not coincide, if at all possible, with a nodal point of any of the modes of predominant response (usually some or all of the first four modes). Close examination of the mode shapes in figure 4 indicates the most optimal "anti-node" areas for buildings uniform in plan with height are located at about 25%, 40% and 70% of the above ground building height. If no other information is available, it is recommended that one or two of these levels be instrumented. If, however, mode shapes based on a computerized model of the building are available, such mode shapes should be used to determine the optimal locations. Stiffness discontinuities must also be considered in the process and should be instrumented whenever their effect on mode shapes is unknown. Instrumentation at such locations could either serve as or complement the intermediate level instrumentation recommended as minimal. In some buildings, such as one having a slender tower on a wide base, the discontinuity is obvious, whereas in others, stiffness discontinuities may be revealed only through a thorough investigation of the structural framing system.

Other recommendations designed to enhance and facilitate the analysis of records obtained from instrumented buildings are as follows: "free-field" accelerographs should be located near each instrumented building in order to obtain data on site-structure resonance effects and soil-structure interaction; the CDMG should collect and archive plans, specifications, calculations, and pertinent construction and inspection records for each instrumented building as well as site soil and geology descriptions.

IMPLEMENTATION OF THE PROGRAM

The above guidelines were submitted to the Advisory Board in mid-1974 and approved shortly thereafter with the stipulation that they be regularly updated (perhaps annually) as more geologic, seismological, engineering analysis and other pertinent information becomes available. After approval, the CDMG solicited and received from the Structural Engineers Association of California (SEAOC) a list of 54 buildings to be instrumented under the first phase of the program. The size and location distribution of this first set of buildings (figure 5) are not in exact adherence to the criteria established by the above guidelines, though the basic intent of the guidelines certainly has been met. Significant deviations from the recommended distributions will be rectified in subsequent phases of the program.

On the basis of current projected revenues, and instrument procurement, installation and maintenance expenses, it is estimated that as many as 400 buildings may be instrumented under the State program (California Division of Mines & Geology, unpublished report to the California Legislature). The installation phase of the program is expected to be completed in the year 2035, the time at which program revenues are expected to be sufficient only for covering instrument maintenance (a major cost), personnel (minimal staff), and data analysis expenses.

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Table 1 - Proposed Distribution of Instrumented Buildings as a Function of Distance from Fault of Interest, in percent

Distance from fault in miles (km) \ Number of stories	1-2	3-6	7-15	>15
0-5 (0-8)	16	16	4	0+
5-10 (9-16)	12	16	12	4
10-25 (16-40)	0+	0+	8	8
>25 (>40)	0+	0+	2	2

Table 2 - Recommended Types of Buildings to be Instrumented

I. One and two-story buildings.
   A. Open frame type - gymnasiums, auditoriums.
   B. Continuous frame - school classrooms, offices.
   C. Box structures - commercial masonry or concrete wall structures with flexible diaphragms.

II. Three to six-story buildings.
   A. Frame.
   B. Shearwall.
   C. Combination.
   D. Precast structural elements.

III. Buildings over six stories.
   A. Frame.
   B. Shearwall.
   C. Combination.

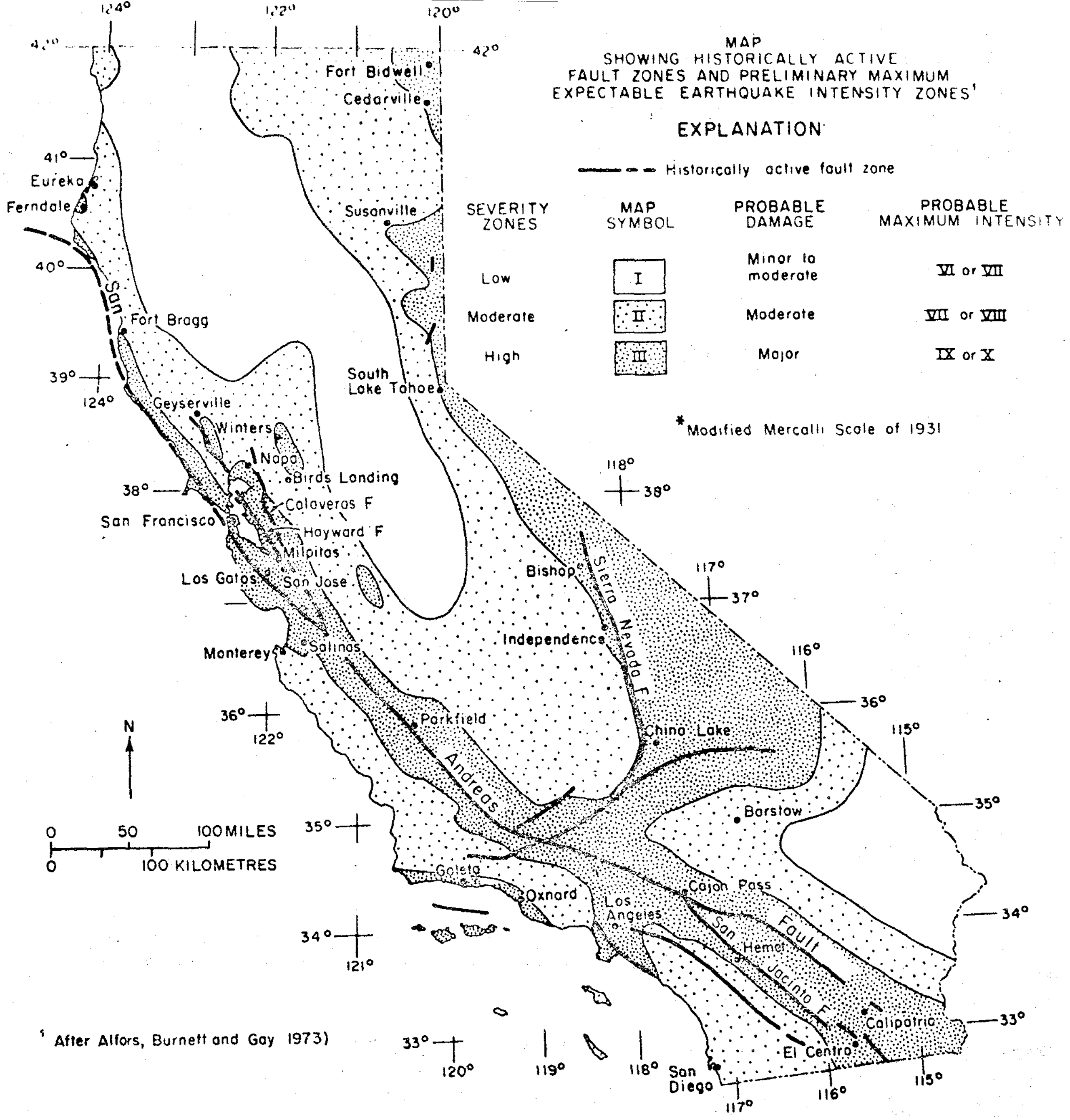
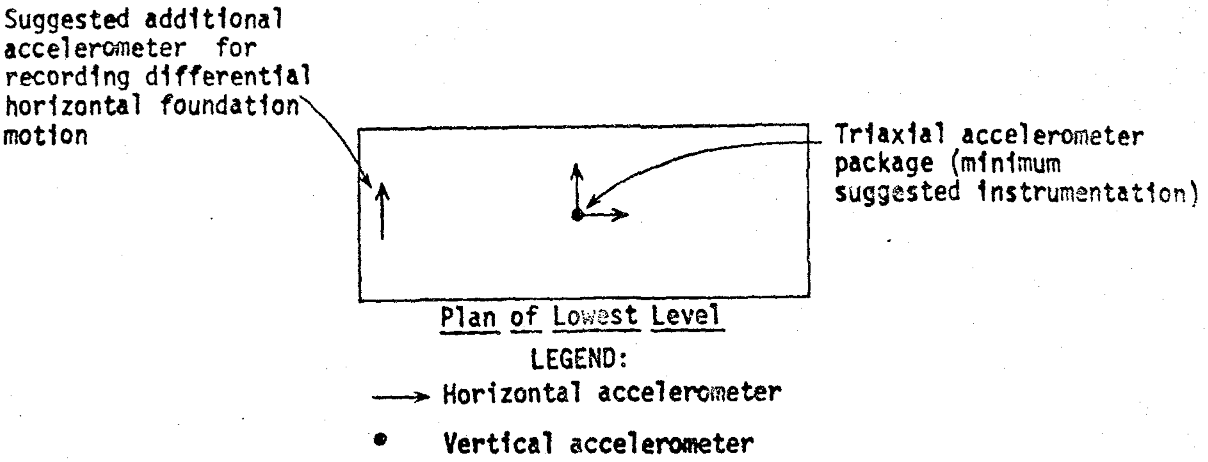


Figure 1.- Map showing historically active fault zones and preliminary maximum expectable earthquake intensity zones (Alfors, Burnett, and Gay, 1973).


Suggested additional accelerometer for recording differential horizontal foundation motion

Triaxial accelerometer package (minimum suggested instrumentation)

Plan of Lowest Level

Figure 2a.- Suggested strong-motion instrumentation scheme for recording differential horizontal foundation motion in a building whose length is very large in comparison with its width.

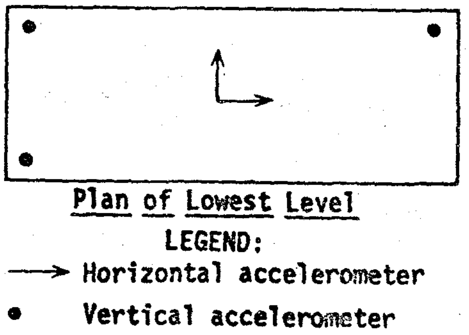

Plan of Lowest Level

Figure 2b.- Suggested strong-motion instrumentation scheme for recording rocking motion at lowest level.

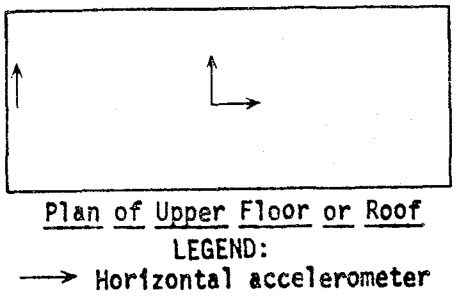


Figure 3a.- Suggested strong-motion instrumentation scheme for roof (or floor) expected to be rigid in the horizontal plane.

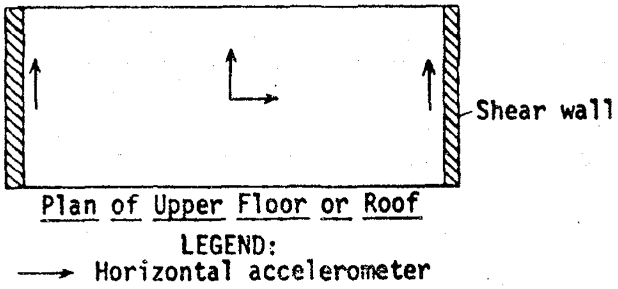
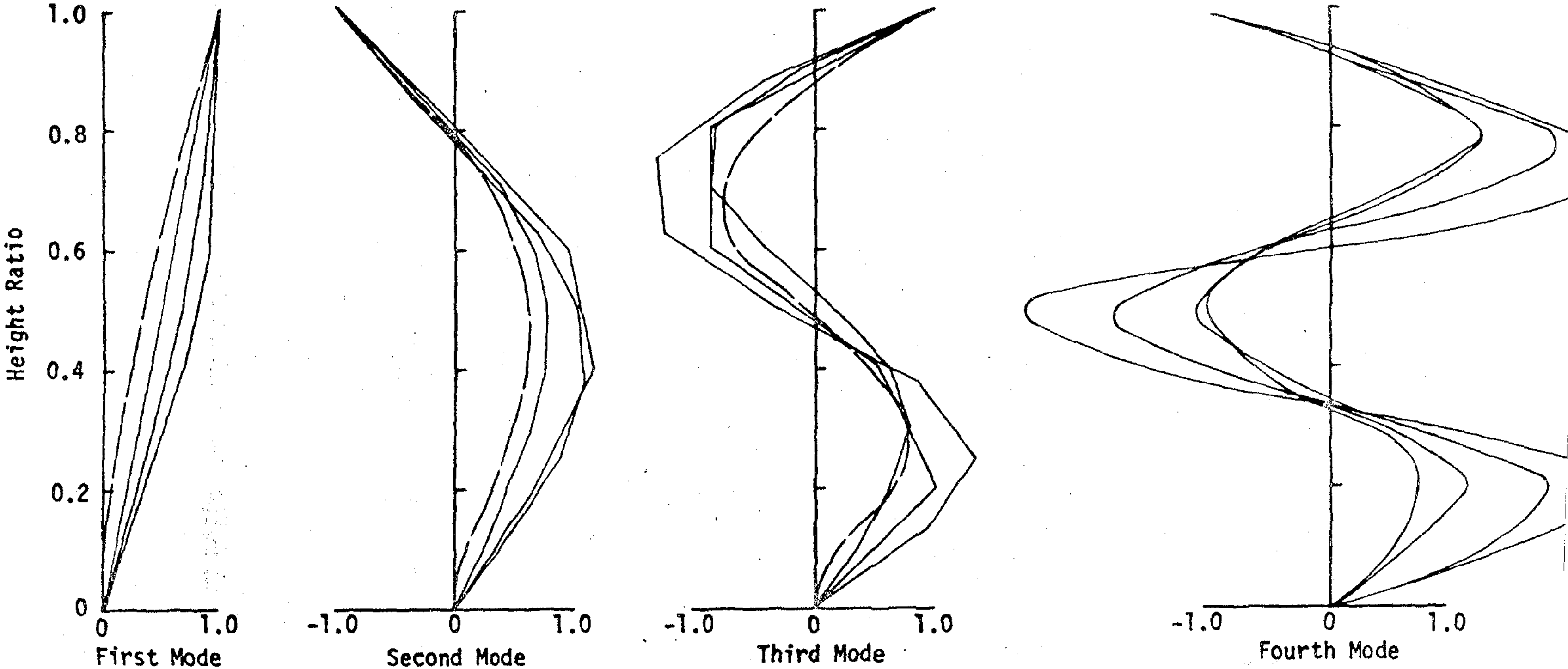


Figure 3b.- Suggested strong-motion instrumentation scheme for roof (or floor) where relative diaphragm motion is expected in the transverse direction.



(After Jennings, 1969)

Figure 4.- Experimental and analytical mode shapes for buildings.

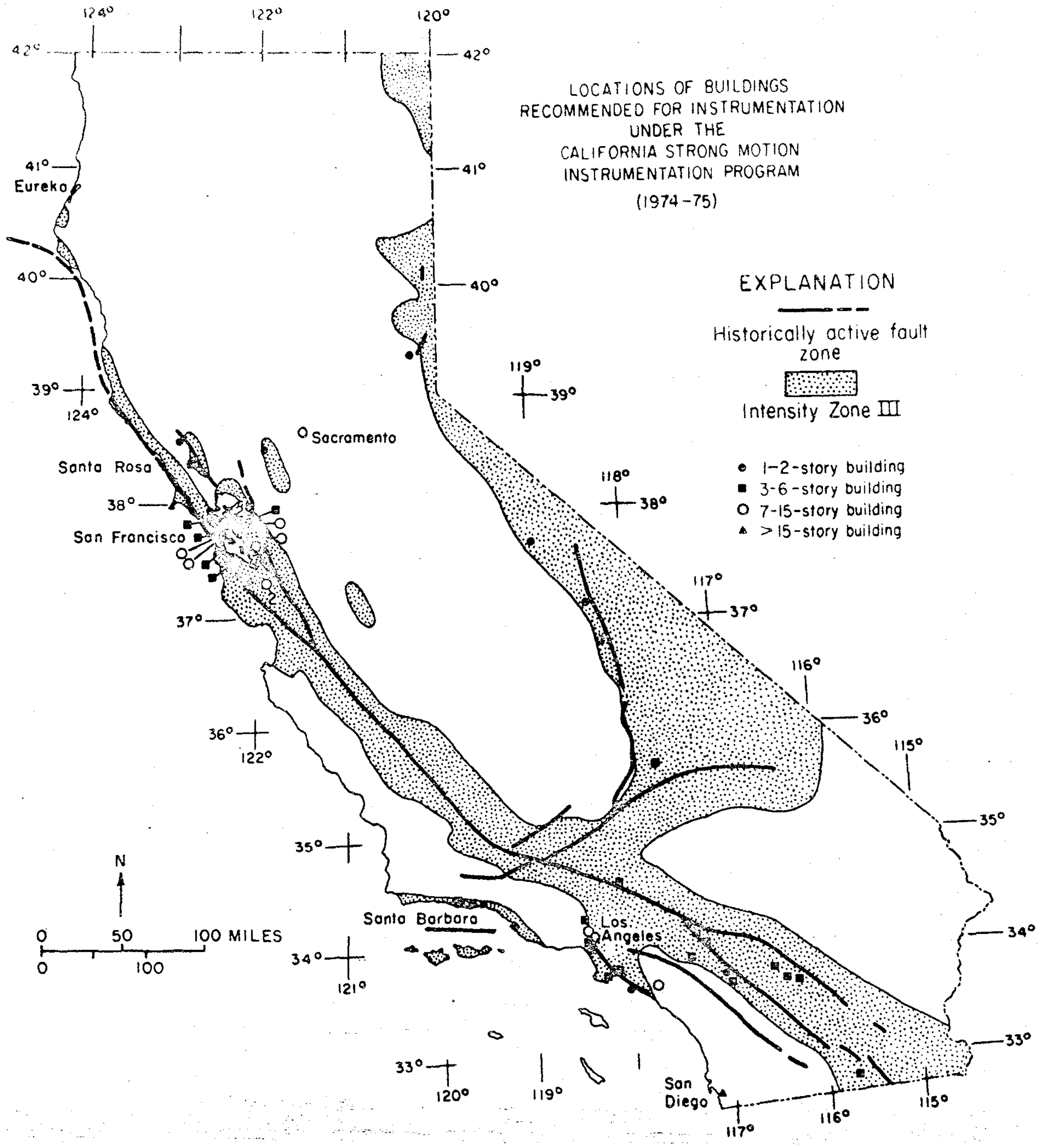


Figure 5.- Locations of buildings recommended for instrumentation under the California Strong-Motion Instrumentation Program (1974-1975).

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16. Abstract (Limit: 200 words)

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17. Document Analysis a. Descriptors

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Torsion

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California Strong-Motion Instrumentation Program

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