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# STRONG-MOTION RECORDS FROM BUILDINGS

Moh-jiann Huang, Carlos E. Ventura and Anthony F. Shakal

California Strong Motion Instrumentation Program
Division of Mines and Geology
California Department of Conservation

## ABSTRACT

Since the establishment of the California Strong Motion Instrumentation Program in 1972, over 90 buildings have been instrumented extensively to measure their response during earthquakes. Significant strong-motion records have been obtained from many of these buildings. Many aspects of structural response can be investigated through visual examination of the records and through detailed computer structural modelling.

## INTRODUCTION

During the last 15 years the California Strong Motion Instrumentation Program (CSMIP) has instrumented over 90 buildings, typically installing 12 to 15 sensors in each building. The primary goals of the CSMIP building instrumentation effort are to obtain data to improve engineering design practice and assess the response of existing buildings. Strong-motion records have been recorded in buildings representing many building types, construction techniques, and materials. This paper describes CSMIP building instrumentation objectives and some results of analyses of records obtained during earthquakes.

## INSTRUMENTATION OBJECTIVES

CSMIP instrumentation of buildings always includes installation of a 3-component set of sensors to measure the motion of the base of the building in the vertical and two horizontal directions. If surroundings permit, a 3-component accelerograph is also installed on the ground at some distance from the building in order to obtain an estimate of the input motion. At upper levels of the building, the objectives are to measure the lateral motion, or drift, and torsional motion. The upper levels instrumented include the roof and as many other levels as are economical and appropriate for a particular building. Other objectives sometimes included are the measurement of overturning motion at the building base and measurement of diaphragm motion at the roof or other levels. The measurement and analyses of lateral motion, torsional motion, and motion at the base of the building are considered in the following sections. To illustrate the locations of sensors to achieve various objectives in the instrumentation of a building, Figure 1 shows a schematic of a building with sensors.

## LATERAL BUILDING MOTION

Lateral building motions are measured at the roof and at intermediate levels of a building by single-component sets of instruments such as sensors 1, 3, 6 and 8 (transverse motion) and 10, 11, 12 and 13 (longitudinal motion) in Figure 1. The number of intermediate levels instrumented depends on the building height and configuration: a) For buildings up to three stories in height, each level is usually instrumented in order to measure interstory motions (drift) at each story.

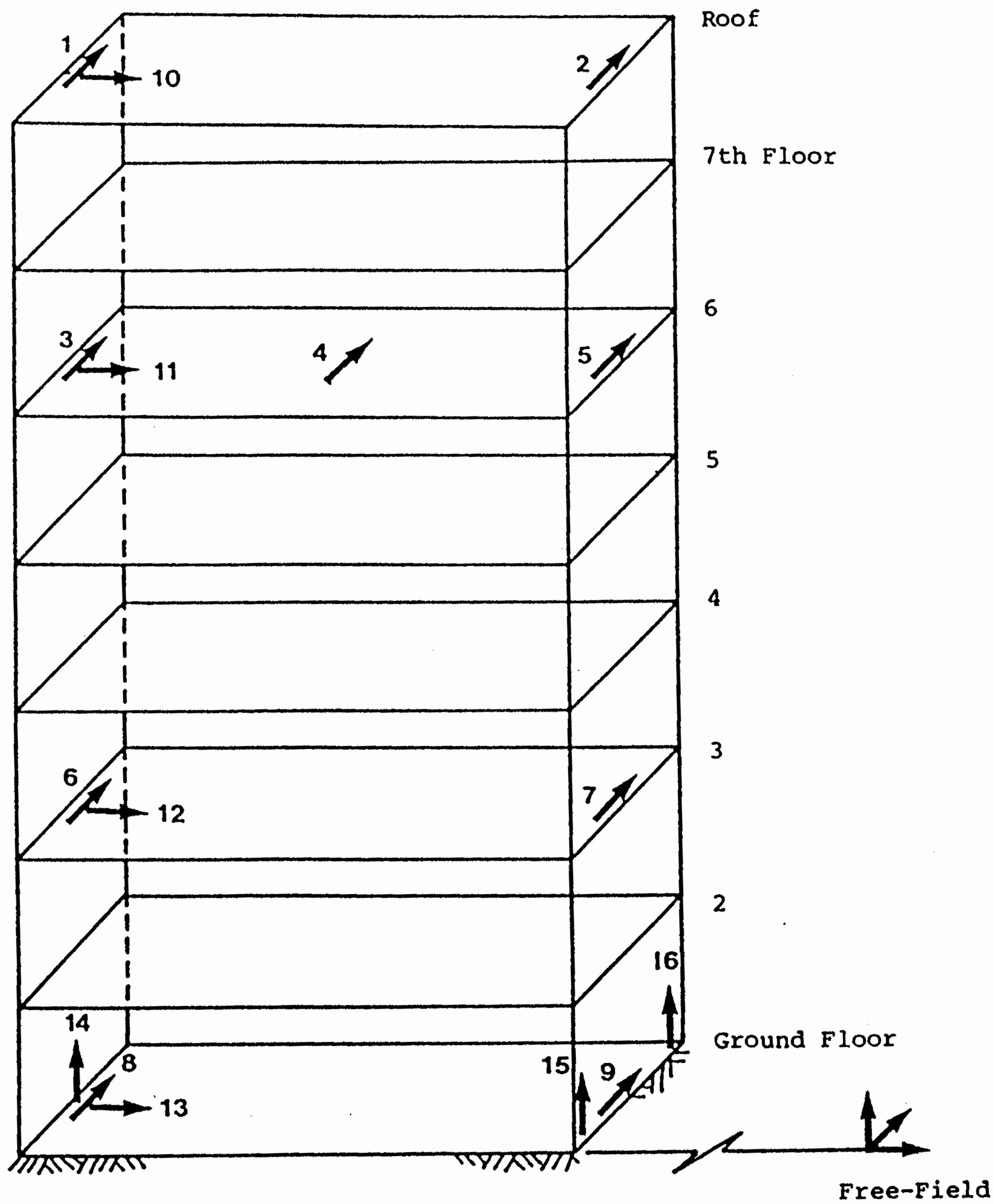


Fig. 1. Typical sensor locations for instrumentation of a building. (Arrows indicate the location and sensing direction of each sensor.)

b) For mid-rise buildings, from four to seven stories in height, two intermediate levels are usually instrumented. c) For high-rise buildings, eight stories or more in height, at least two intermediate levels are instrumented, and additional instruments may be added at levels where there is a discontinuity in stiffness. This provides the opportunity to obtain detailed information about interstory displacement in short buildings where it is more economical to do so, while more general information about response mode shapes is obtained from tall buildings.

The motion at any level in a building is a sum of the ground motion and the relative motion of that level with respect to the ground. It thus depends on the characteristics of the building and the frequency content of the input ground motion. For example, the fundamental mode of a building with period of 3 seconds will not be excited by ground motion with little energy near 3 seconds, and the higher mode motions will be dominant in the recorded response. Many ground motion records contain high frequency motion for the first several seconds followed by lower frequency motion. In most CSMIP building records, the first part shows the building responding in its second mode, while the later part of the record is usually dominated by the fundamental modal response. Therefore, the period of the fundamental and second modes of the building can often be estimated from the acceleration records (e.g., Gates, 1973; Housner and Jennings, 1982).

As an example, Figure 2 shows the records from a 10-story concrete office building in San Jose. Built in 1967, this building was one of the first reinforced concrete structures designed for ductility, and was reported as Building 3 in the ATC-2 report (1974). The lateral force resisting system consists of two end shear walls and six interior frames in the transverse direction, and two exterior and two interior frames in the longitudinal direction. The acceleration records in Figure 2 were obtained during the 1984 Morgan Hill earthquake. The records are arranged in roof-to-basement order for motion in the transverse (EW) and longitudinal (NS) direction, respectively. Visual examination of the records and some simple calculations give information such as period of building vibration, lateral force distribution, and deflection. As seen in this record, the higher modes of the structure were excited by the ground shaking between 0 to 15 seconds while the building motions after 18 seconds are in the fundamental mode. The records indicate that the fundamental period of the building in the later part of motion is about 0.64 second in the transverse direction and 0.92 second in the longitudinal direction. An analysis of the building using the computer program TABS, described in the ATC-2 report, yielded somewhat lower fundamental periods of 0.44 second in the transverse direction and 0.74 second in the longitudinal direction. The corresponding periods computed from the 1964 UBC formula, in use at the time of construction, are 0.69 second transverse and 0.45 second longitudinal. For comparison, the periods computed according to the current 1988 UBC formula (Method A) are 0.44 second transverse and 1.11 second longitudinal. These estimates are summarized below.

| | Building Period (seconds) | |
|---|---|---|
| | Transverse | Longitudinal |
| Estimated from 1984 Record | 0.64 | 0.92 |
| Calculated in ATC-2 | 0.44 | 0.74 |
| Calculated from 1964 UBC Formula | 0.69 | 0.45 |
| Calculated from 1988 UBC Formula | 0.44 | 1.11 |

Maximum instantaneous accelerations during the period that the first mode dominated the response in each direction can be obtained from the record in Figure 2, and the

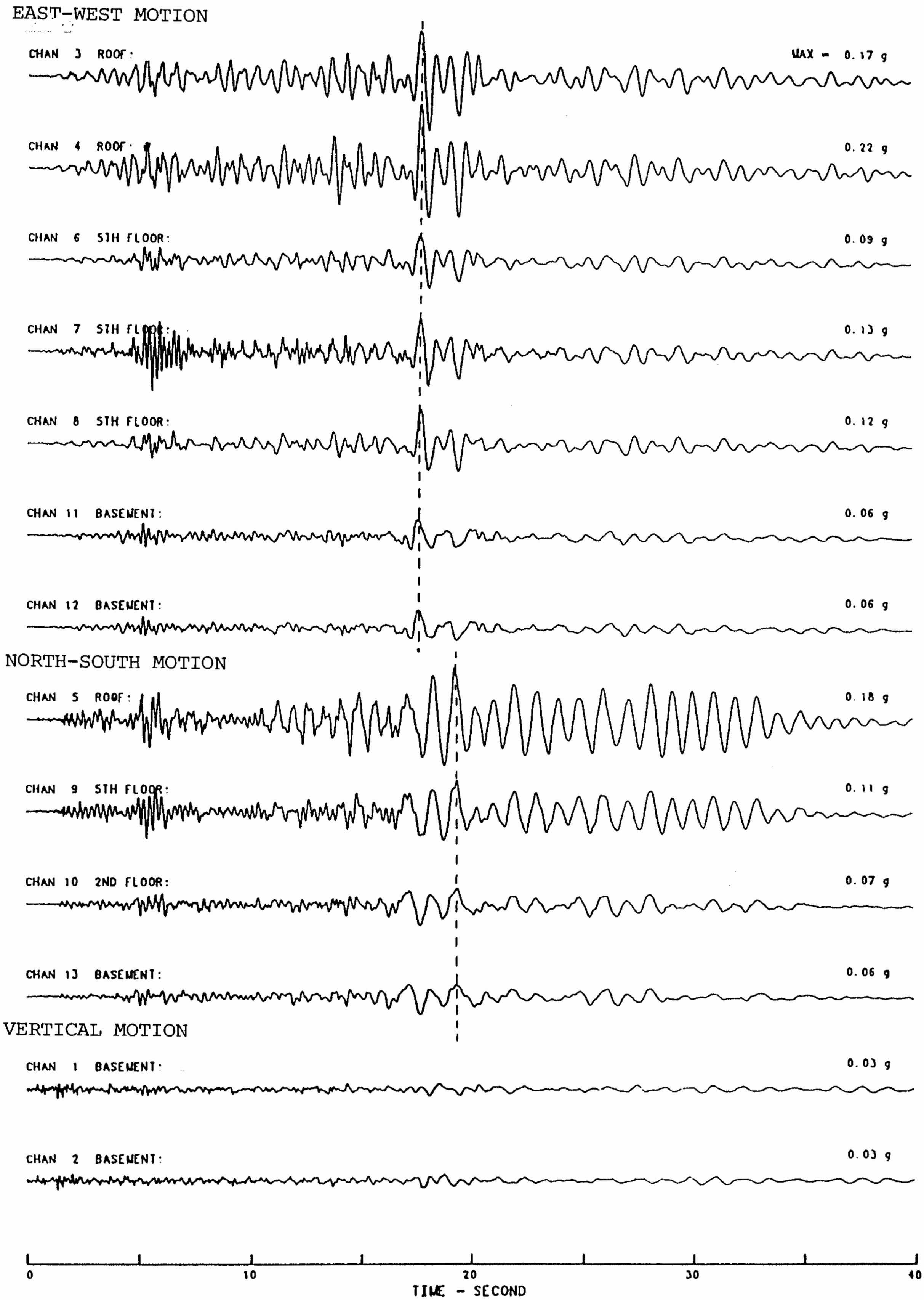


Fig. 2. Acceleration records from a 10-story concrete building in San Jose for the 1984 Morgan Hill earthquake. The dashed lines indicate the times for which the earthquake forces listed in Table 1 are computed.

values are listed in Table 1. The lateral force at each floor level may be calculated by multiplying the estimated weight of each floor by the acceleration in g's, i.e., $F = W(a/g)$. The lateral forces calculated are also listed in Table 1. For comparison, the original design forces reported in the ATC-2 report and the total base shear in each direction are also shown in Table 1. The values in Table 1 indicate that the lateral forces were between 1.2 and 3.3 times the design forces. The base shear is about 1.5 times the design shear in the longitudinal direction and 2 times the design value in the transverse direction.

From the integrated records, the maximum displacements or drift at the roof relative to the basement are about 2.8 cm and 1.8 cm in the longitudinal and transverse directions, respectively. The maximum allowable drifts at the roof calculated according to the 1988 UBC for this building are 9.4 cm and 11.4 cm in the longitudinal and transverse directions, respectively. The earthquake record indicates that the drifts were much smaller than the code maximum values.

## BUILDING BASE MOTION AND INPUT GROUND MOTION

The motion at the base of buildings instrumented by CSMIP is measured by a triaxial set of accelerometers such as sensors 8, 13 and 14 shown in Figure 1. These sensors record the base motions in two horizontal directions and the vertical direction, and provide data on the input motion and the building's response during an earthquake. For buildings where there is sufficient open area at some distance from the instrumented building and other structures, a triaxial accelerograph, as shown in Figure 1, is placed on the ground surface away from the building.

The motion at the base of the building may differ considerably from the input motion because of the soil-structure interaction. The records obtained at the Imperial County Services Building during the 1979 Imperial Valley earthquake are a good example of this difference. The accelerations recorded at the reference, or free-field, site and on the ground floor of the building are compared in Figure 3. The two motions differ significantly. The vertical motion at the free-field site is generally larger than that at the ground floor, while for horizontal motion the opposite is true. The horizontal acceleration recorded at the ground floor contains relatively high amplitude motion at 0.25 to 0.3 second period that is not present in the free-field motion.

## TORSIONAL BUILDING MOTION

Torsional motions of a rigid floor can be measured by placing pairs of sensors at opposite ends of the floor, such as sensors 1 and 2, 3 and 5, and 6 and 7 in Figure 1. An estimate of the torsional motion may be obtained by differencing the motions from the pair of sensors on each floor. Figure 4 shows the accelerations obtained from a pair of horizontal sensors on the roof, 12th, 7th, 2nd and ground floors in a 13-story steel-frame office building in San Jose during the 1984 Morgan Hill earthquake. Differencing the motions from the parallel sensors on the same floor allows estimation of the torsional motion at that floor. Figure 5 shows the result of this estimation for each level. The torsional input motion at the ground level is very small while noticeable torsional motions can be seen on the upper floors. It is clearly seen from this figure that the building experienced torsional vibrations during the earthquake. A more detailed discussion of this response is given in Shakal and Huang (1986).

Table 1. - Maximum lateral forces estimated for a 10-story concrete building in San Jose during the 1984 Morgan Hill earthquake.

| Floor Level | Weight (kips) | Longitudinal(NS) Direction (at t=19.36 sec. in the record) Acceleration (g) | Earthquake Force (kips) | Design Force (kips) | Transverse(EW) Direction (at t=17.82 sec.) Acceleration (g) | Earthquake Force (kips) | Design Force (kips) |
|---|---|---|---|---|---|---|---|
| Roof | 2700 | 0.18 * | 486 | 384 | 0.20 * | 540 | 332 |
| 10 | 2400 | 0.17 | 408 | 311 | 0.19 | 456 | 269 |
| 9 | 2400 | 0.16 | 384 | 282 | 0.18 | 432 | 244 |
| 8 | 2400 | 0.15 | 360 | 253 | 0.17 | 408 | 219 |
| 7 | 2400 | 0.13 | 312 | 224 | 0.16 | 384 | 194 |
| 6 | 2400 | 0.12 | 288 | 195 | 0.14 | 336 | 169 |
| 5 | 2400 | 0.11 * | 264 | 166 | 0.13 * | 312 | 144 |
| 4 | 2400 | 0.10 | 240 | 137 | 0.12 | 288 | 119 |
| 3 | 2400 | 0.09 | 216 | 109 | 0.10 | 240 | 94 |
| 2 | 2400 | 0.07 * | 168 | 85 | 0.08 | 240 | 73 |
| Total Base Shear | | | 3126 | 2146 | | 3588 | 1857 |
| Percent of Total Weight | | | 13% | 9% | | 15% | 8% |

Footnotes: Design forces are from ATC-2 report (1974).
* -- Maximum acceleration values from the record; the maximum accelerations for other levels are estimated by linear interpolation between the values at the levels recorded.

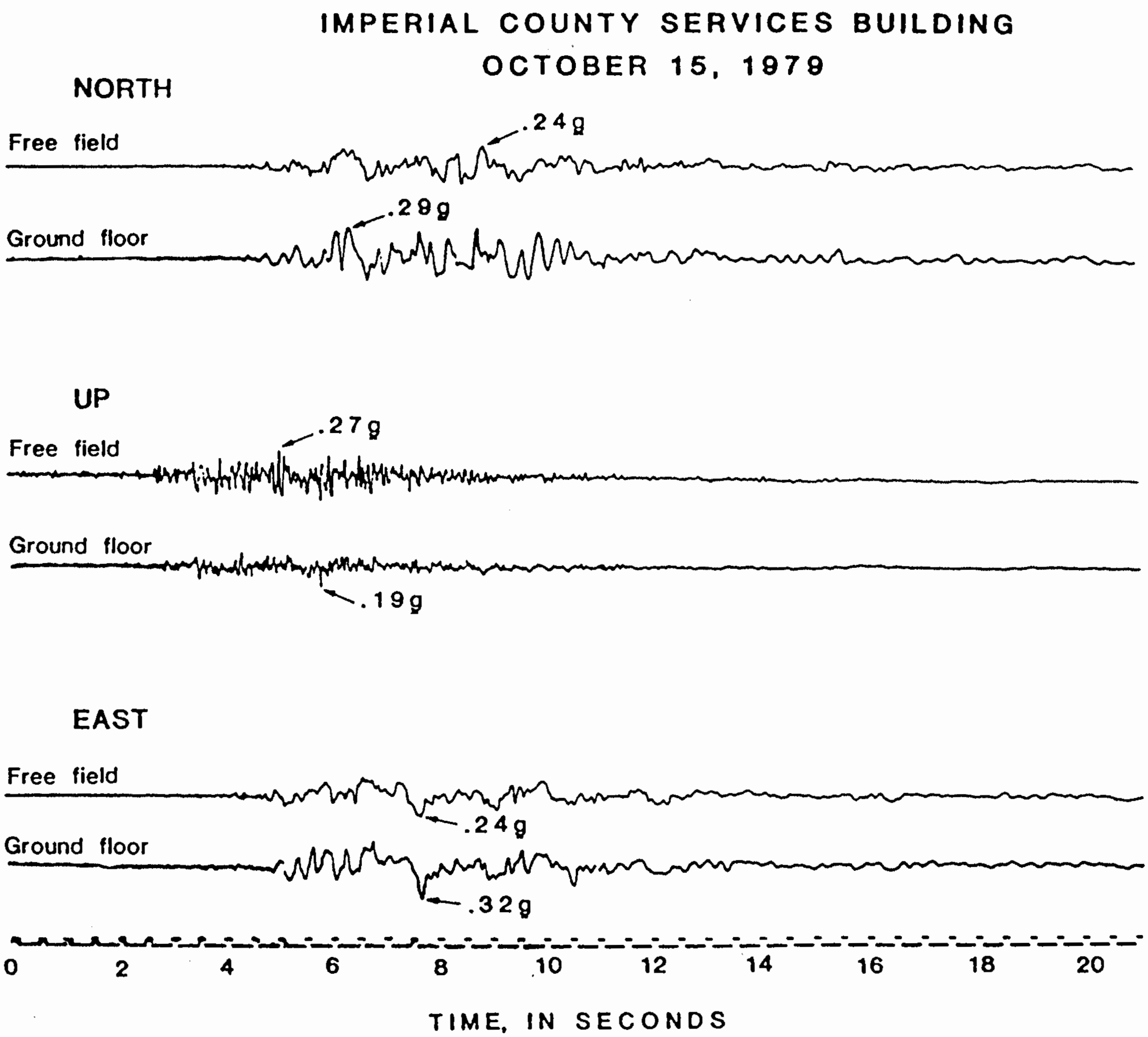


Fig. 3. Acceleration time histories recorded at the ground level of the Imperial County Services Building and adjacent free-field site during the Imperial Valley earthquake of October 15, 1979 (from Rojahn and Mork, 1981). The free-field accelerograph was located 340 feet from the building.

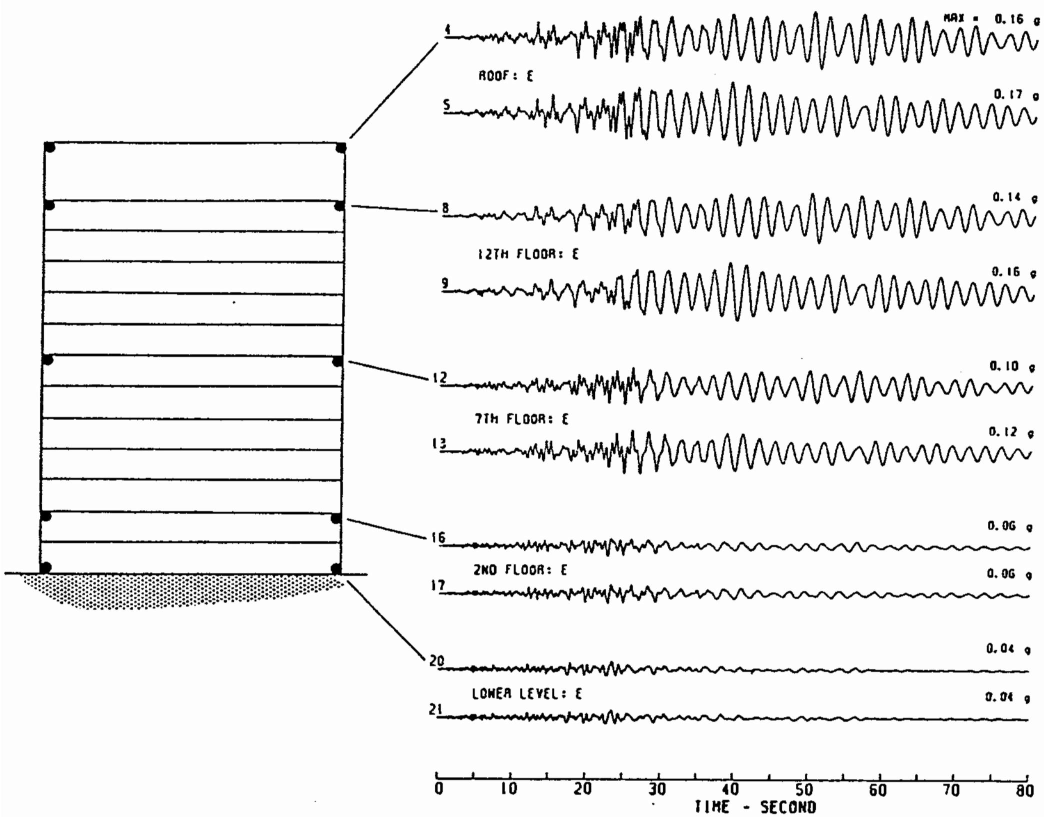


Fig. 4. Acceleration records from pairs of horizontal sensors at the roof, 12th, 7th, 2nd floors and ground level of a 13-story steel frame building in San Jose during the 1984 Morgan Hill earthquake.

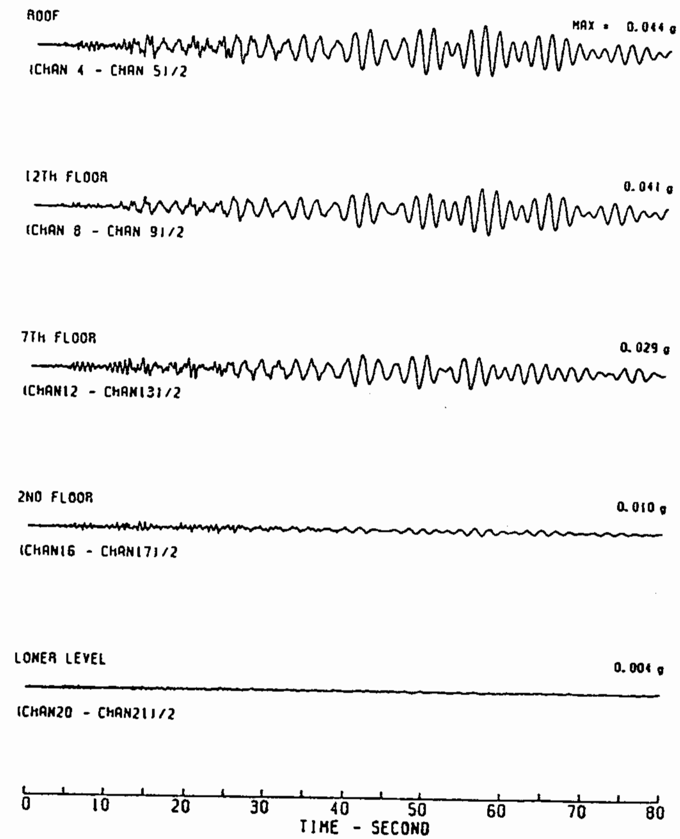


Fig. 5. Torsional accelerations at the roof, 12th, 7th, 2nd floors and ground level of a 13-story steel frame building in San Jose during the 1984 Morgan Hill earthquake. The torsion is computed from the records in Figure 4.

In addition to the lateral and vertical motions at the base of the building, there may be torsional motion input at the base of the building. In order to measure this torsional motion, an additional sensor may be placed on the other side of the building as illustrated by sensor 9 in Figure 1. Although the CSMIP has collected a number of records from buildings instrumented in this manner, significant torsional input motions have not yet been observed.

## SUMMARY

The objectives of instrumenting buildings and some examples of records obtained by CSMIP have been presented. Numerous other building records have been obtained and most have been digitized and processed. Table 2 lists the most important building records obtained to date and the maximum accelerations recorded at the ground level and on the structure. Among them, the record from the Imperial County Services Building in the 1979 Imperial Valley earthquake is very important since it is the first record obtained in a building undergoing damage during earthquake shaking. In addition, the records obtained at the base-isolated San Bernardino County Law & Justice Center during the 1985 Redlands, 1986 Palm Springs, and 1987 Whittier earthquakes are particularly important although the recorded motions are of low amplitude. The most recent set of important strong-motion records are from the Whittier earthquake of October 1, 1987 for which records were obtained from 100 CSMIP sites, including 27 buildings (Shakal and others, 1987). As indicated in Table 2, a total of 26 building records with roof-level accelerations over 0.15g have been recorded, of which 16 have accelerations over 0.25g. The analyses in this paper have only dealt with two of these sets of records.

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Table 2. - Selected building records obtained by the California Strong Motion Instrumentation Program.

| Building* | Type of Structure | No. Stories above/below Ground | No. of Sensors | Maximum Horizontal Acceleration (g) Ground | Structure | Earthquake | Epicentral Distance (km) |
|---|---|---|---|---|---|---|---|
| Goleta - SN 213 | RC Shear Walls | 3/0 | 9 | 0.40 | 0.99 | 1978 Santa Barbara(5.1ML) | 14 |
| Santa Barbara -SN 302 | RC Shear Walls | 4/1 | 9 | 0.23 | 0.65 | 1978 Santa Barbara | 6 |
| El Centro - SN 260 | RC Shear Walls & Frame | 6/0 | 16 | 0.34 | 0.58 | 1979 Imperial Valley(6.6ML) | 28 |
| Mammoth Lakes - SN 301 | RC Shear Walls | 1/0 | 10 | 0.31 | 0.95 | 1980 Mammoth Lakes(6.1ML) | 11 |
| San Ramon - SN 187 | Tilt-up Concrete Walls | 1/0 | 6 | 0.28 | 0.47 | 1/26/80 Livermore(5.5ML) | 21 |
| Walnut Creek - SN 364 | RC Shear Walls&Frame | 10/0 | 16 | 0.06 | 0.21 | 1/26/80 Livermore | 36 |
| San Jose - SN 357 | Steel Frame | 12/1 | 22 | 0.04 | 0.32 | 1986 Mt. Lewis(5.8ML) | 23 |
| San Jose - SN 356 | RC Shear Walls | 10/0 | 13 | 0.06 | 0.21 | 1984 Morgan Hill(6.2ML) | 19 |
| San Jose - SN 355 | RC Shear Walls&Frame | 10/1 | 13 | 0.06 | 0.22 | 1984 Morgan Hill | 19 |
| Saratoga - SN 235 | RC Columns&Shear Walls | 1/0 | 11 | 0.10 | 0.41 | 1984 Morgan Hill | 30 |
| Watsonville - SN 459 | RC Shear Walls | 4/0 | 13 | 0.11 | 0.33 | 1984 Morgan Hill | 45 |
| Hollister - SN 391 | Tilt-up Concrete Walls | 1/0 | 13 | 0.14 | 0.35 | 1986 Hollister(5.5ML) | 11 |
| So. San Francisco-SN261 | Steel Frame | 4/0 | 11 | 0.03 | 0.26 | 1986 Morgan Hill | 78 |
| Palm Springs - SN 299 | Steel Frame | 4/1 | 13 | 0.19 | 0.62 | 1986 Palm Springs(5.9ML) | 19 |
| Palm Desert - SN 284 | RC Shear Walls | 4/0 | 9 | 0.12 | 0.20 | 1986 Palm Springs | 35 |
| Redlands - SN 495 | Tilt-up Concrete Walls | 1/0 | 12 | 0.05 | 0.25 | 1986 Palm Springs | 57 |
| Los Angeles - SN 468 | RC Shear Walls | 8/1 | 16 | 0.39 | 0.48 | 1987 Whittier(5.9ML) | 9 |
| Los Angeles - SN 463 | Concrete Frame | 5/0 | 13 | 0.18 | 0.24 | 1987 Whittier | 14 |
| Los Angeles - SN 236 | Concrete Frame | 14/0 | 12 | 0.12 | 0.21 | 1987 Whittier | 25 |
| Burbank - SN 370 | Steel Frame | 6/0 | 13 | 0.22 | 0.30 | 1987 Whittier | 26 |
| Burbank - SN 385 | RC Shear Walls | 10/0 | 16 | 0.26 | 0.54 | 1987 Whittier | 26 |
| N. Hollywood - SN 464 | Concrete Frame | 20/1 | 16 | 0.11 | 0.21 | 1987 Whittier | 28 |
| Long Beach - SN 311 | RC Shear Walls | 5/0 | 9 | 0.10 | 0.36 | 1987 Whittier | 31 |
| Sherman Oaks - SN 322 | Concrete Frame | 13/1 | 15 | 0.15 | 0.17 | 1987 Whittier | 38 |
| Van Nuys - SN 386 | Concrete Frame | 7/0 | 16 | 0.17 | 0.20 | 1987 Whittier | 41 |
| Sylmar - SN 514 | Steel & RC Shear Walls | 6/0 | 13 | 0.06 | 0.20 | 1987 Whittier | 45 |

Footnote: * -- Building is identified by CSMIP station serial number (SN).