TORSIONAL RESPONSE OF THREE INSTRUMENTED BUILDINGS
DURING THE 1984 MORGAN HILL EARTHQUAKE

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ABSTRACT

Torsional motion was derived from the strong-motion records obtained at three high-rise buildings in San Jose shaken during the Morgan Hill earthquake of April 24, 1984. The buldings include a moment-resistant steel-frame building and two reinforced concrete buildings, all 10-13 stories in height. The steel frame building exhibited clear torsional motion, with approximately 25% of the displacement at the exterior walls at the roof level being due to torsion. One of the reinforced concrete buildings exhibited torsional motion of approximately the same percentage of lateral displacement as the steel frame building, the second exhibited much less. For the two buildings exhibiting torsional response, the torsional motion at the upper floors of the structure was significantly greater than that at the base. The amplification ratio, roof to base, was greater than a factor of five for both buildings. Thus, the torsional motion is not simply due to compliance of the building with a torsional component of the incoming wave field, but rather represents a torsional response of the building to lateral motion at the base.

INTRODUCTION

The 6.2 ML Morgan Hill earthquake occurred on April 24, 1984 on the Calaveras fault southeast of San Jose, California. The earthquake triggered the strong-motion accelerographs at nearly 50 stations instrumented by the California Strong Motion Instrumentation Program (CSMIP). The stations include twenty-three extensively-instrumented structures and twenty-five ground-response stations. The accelerograms obtained at these stations are given in a report on the CSMIP strong motion records from the Morgan Hill earthquake [1]. Additional records obtained at USGS ground-response and structural stations are outlined in [2]. This paper deals specifically with the records from three buildings in San Jose. The building displacements and differential motion studied here are from the CSMIP processed-data report on the Morgan Hill structural records [3].

Three extensively-instrumented high-rise buildings are located within 2 kilometer of each other in San Jose, approximately 20 kilometers from the earthquake epicenter. A sufficient number of strong-motion sensors (13-22) were located in these buildings to allow estimation of the torsional and lateral motion at each of several levels in the building. Because of the

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simple geometry of the sensor layout, the torsional motion of a given floor can be estimated through analysis of the differential motion between sensors on that floor. The three buildings considered here include 1) the Santa Clara County Office building, a 13-story, moment-resistant steel frame building; 2) the Town Park Towers Apartment building, a 10-story, concrete shear wall building; and 3) the Great Western Savings building, a 10-story building with concrete frame and shear walls. These three buildings are shown in Fig. 1. During the Morgan Hill earthquake, peak accelerations of approximately 5% g were recorded at the ground level of these buildings and about 20% g at the top. The concrete buildings did not suffer structural damage; the steel-frame building suffered very limited structural damage [4].

On selected floors in the three buildings a pair of sensors are located at opposing end walls to record the motion in the transverse direction. This arrangement allows the estimation of the torsional motion at that level by subtracting the motion at one end wall from that at the other. Although the floor slab may undergo in-plane as well as other deformation in addition to simple torsion, the results presented here are based on the differences in the horizontal motion measured at the slab ends.

Santa Clara County Building

The 13-story Santa Clara County Office building, shown in Fig. 1a, is 167 by 167 feet in plan and 187 feet in height. The exterior cores at the west and south ends of the building extend from the lower level to 24 feet above the roof. The lateral force-resisting system of the building is composed of moment-resisting steel frames. The vertical load-carrying system consists of concrete floor slabs overlying decks supported by the steel framing. The foundation is a concrete mat.

A total of twenty-two accelerometers were installed at locations throughout the building; the sensor locations are shown in Fig. 2. Sensors 1 - 3, on the lower level, are mounted vertically to record the vertical motion at the base as well as to indicate the presence of any foundation rocking. Sensors 20 and 21 record the east-west translational motion of the foundation at the north and south ends. This east-west pair of sensors is repeated on the 2nd, 7th and 12th floors and on the roof. These sensor pairs allow analysis of the translational as well as torsional motions at these levels. These pairs are complemented by pairs sensing north-south motion on the same levels.

During the Morgan Hill earthquake, the Santa Clara County Office building vibrated for nearly 80 seconds, and there was nonstructural and content damage as well as very limited structural damage in the building [4]. The people working in the building were evacuated after the earthquake. The processed data indicate that the maximum relative displacement between the roof and the ground at this building was about 16 centimeters. This is 5 to 6 times that at the other two buildings.

To illustrate computation of the torsional motion from the motion recorded by a pair of sensors, Fig. 3a shows the displacements obtained from the accelerations recorded by sensors 4 and 5 on the roof, the average east-west translational displacement at the roof level (Ch. 4 + Ch. 5)/2, and the torsional displacement (Ch. 4 - Ch. 5)/2. The maximum amplitude of the

(a) Santa Clara County Office Bldg.
13-story steel frame
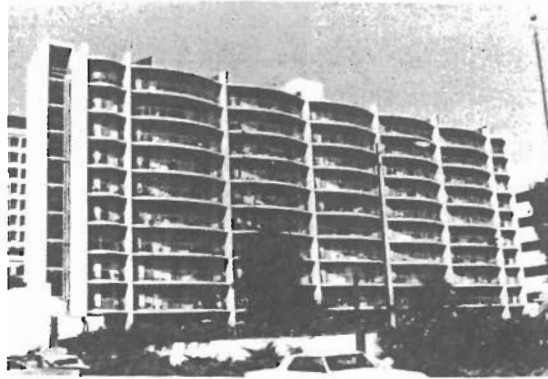
(b) Town Park Towers Apartment Bldg.
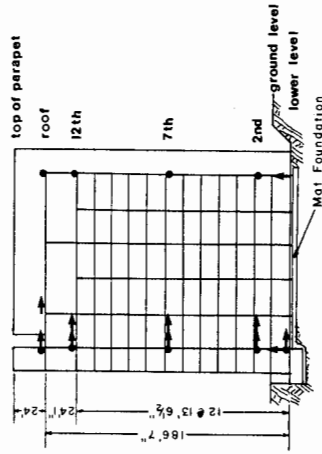11-story reinforced concrete
shear walls

(c) Great Western Savings & Loan Bldg.
10-story reinforced concrete frame
and shear walls

Fig. 1. Three instrumented buildings in San Jose, California.

SENSOR LAYOUT

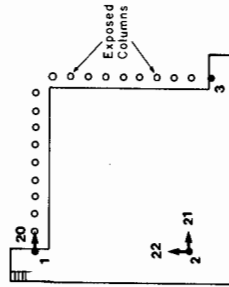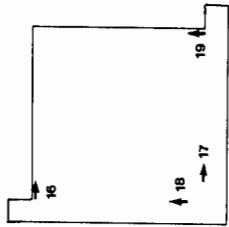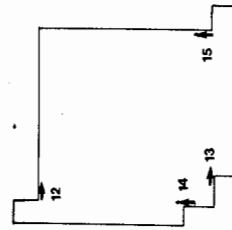## San Jose-Santa Clara County Bldg.
CSMIP Station No. 57357
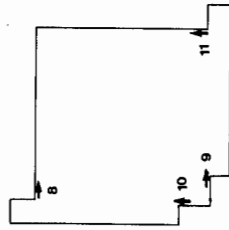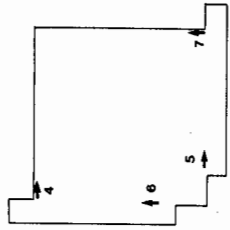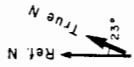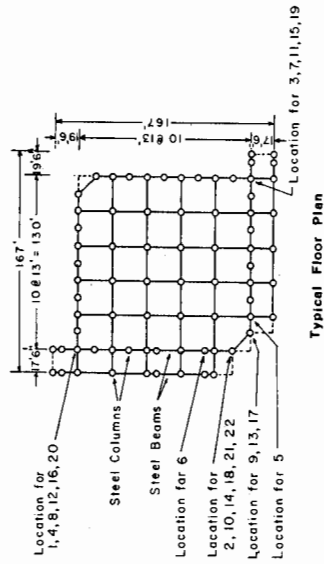
Fig. 2. Sensor layout in Santa Clara County Office Building.

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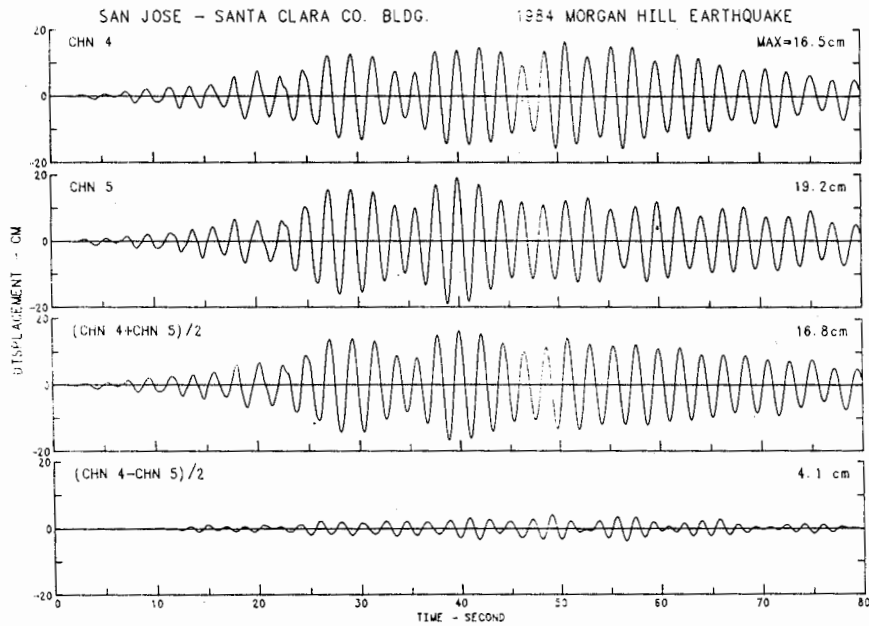Fig. 3a. Top Traces: EW displacements from sensors at N (Chn 4) and S (Chn 5) edge of roof. 3rd Trace: Average EW displacement at roof, obtained from Chns 4 and 5. 4th Trace: Torsional displacement at roof.
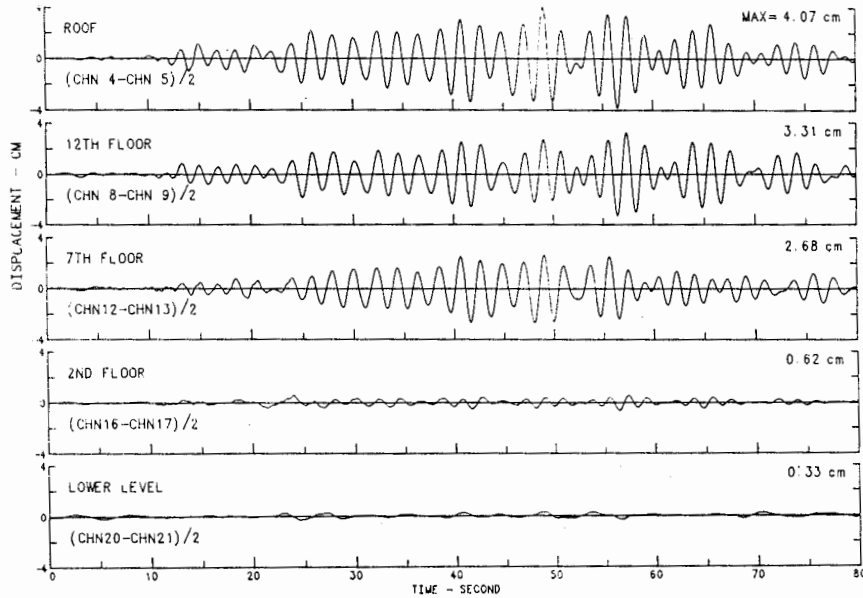

Fig. 3b. Torsional displacement profile, Santa Clara County Office Building, showing the torsional displacements obtained from EW sensors on the roof, 12th, 7th, and 2nd floor and lower level.

lateral displacement at the roof level is about 17 cm; the maximum amplitude of the displacement at the end wall due to torsional motion is about 4 cm. The predominant period of the torsional displacement is very close to that of the lateral displacement, which is about 2 seconds.

Fig. 3b shows the torsional displacements computed for the roof, 12th floor, 7th floor, 2nd floor and foundation level. The amplitude varies from about 0.3 cm at the base to 4.0 cm at the roof, an amplification factor of near 10. The torsional displacements obtained from the north-south sensor pairs on the roof, 12th, 7th, and 2nd floors are very similar to those obtained from the east-west pairs.

Town Park Towers Apartment Building

The 10-story Town Park Towers Apartment building, shown in Fig. 1b, is 210 by 64 feet in plan and 96 feet in height. The lateral force-resisting system consists of reinforced concrete shear walls at regular intervals in the transverse direction and reinforced concrete shear walls along interior corridors in the longitudinal direction (stepped at the 6th floor). The typical floor system is a one-way post-tensioned flat slab on reinforced concrete bearing walls. The foundation consists of precast-prestressed concrete piles under all bearing walls.

Thirteen accelerometers were installed in this building. The locations of the accelerometers are shown in Fig. 4. Sensors 11 and 12 record the translational motion of the foundation in the transverse direction. This pair of sensors is repeated at the 6th floor and the roof. Sensor 5 is mounted at the center of the roof to detect any in-plane motion of the roof diaphragm. In the longitudinal direction, one sensor is placed at each end of the ground floor, the 6th floor and the roof.

The computed torsional displacement and average transverse displacement at the roof level is shown in Fig. 5a. These results indicate that the torsional motion was quite different from the lateral motion. The predominant period of the torsional displacement is approximately 5 seconds, while the response spectra indicate that the first translational mode of the structure in the transverse direction has a period of approximately 0.5 second. Fig. 5b shows the torsional displacements obtained for the roof, 6th floor and ground floor. Like the Santa Clara County Building, the roof to ground floor amplification is quite large, near 6.

Great Western Savings Building

The 10-story Great Western Savings building, shown in Fig. 1c, has a basement and is 124 feet is height relative to ground level. The typical floor dimension is 190 by 82 feet. The lateral force-resisting system consists of end concrete shear walls in the transverse direction and a moment-resistant concrete frame in the longitudinal direction. The vertical load carrying system consists of concrete floor slabs over pan joists supported by the concrete frame. The foundation is a concrete mat.

Thirteen accelerometers were installed in this building. Their locations are shown in Fig. 6. Sensors 11 and 12 record the translational motion at opposite walls in the basement. This pair of sensors is repeated at the 5th

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SENSOR LAYOUT

San Jose—Town Park Towers Apartment Bldg.
CSMIP Station No. 57356

Roof Plan

6th Floor Plan

Concrete Shear Walls

One Way
Post-Tensioned
Concrete Slab

Ground Floor Plan

209'9"

5 # 36'0"

63'6"

Concrete Shear Walls

Concrete Piles

N—S Section
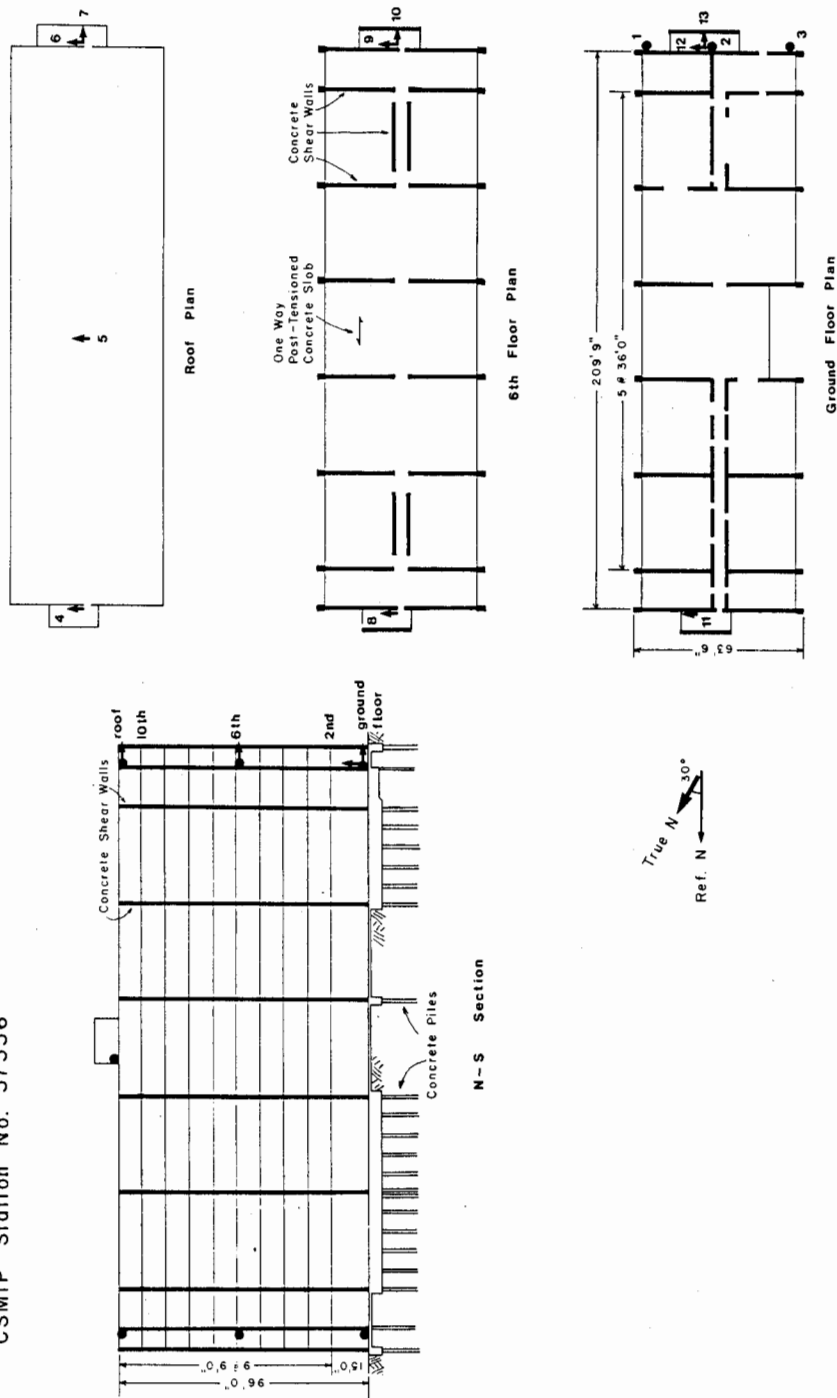
roof
10th
6th
2nd
ground floor

True N
30°
Ref. N

Fig. 4. Sensor layout in Town Park Towers Apartment Building.
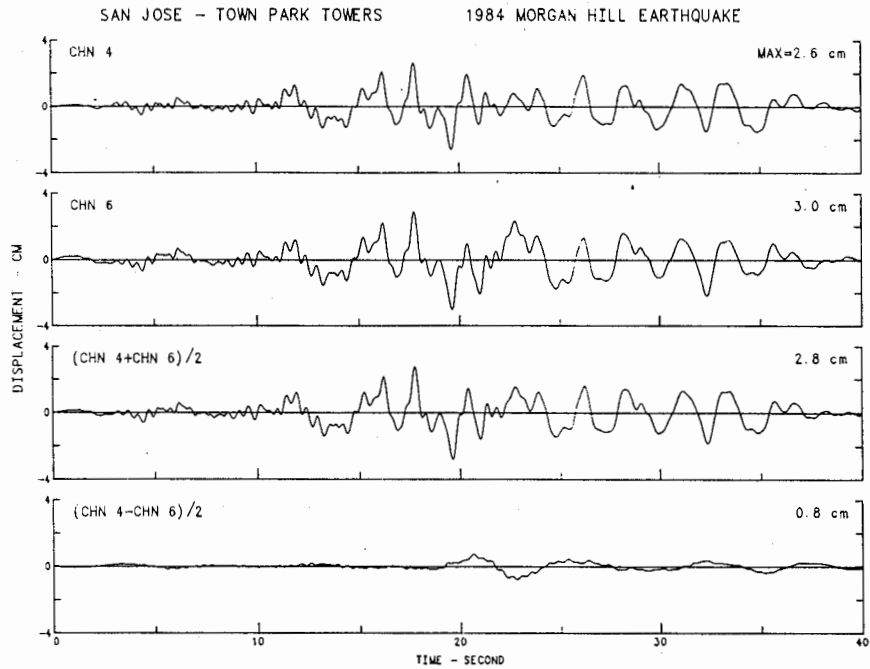
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Fig. 5a. Top Traces: EW displacements from sensors at N (Chn 4) and S (Chn 6) edge of roof. 3rd Trace: Average EW displacement at roof, obtained from Chns 4 and 6. 4th Trace: Torsional displacement at roof.
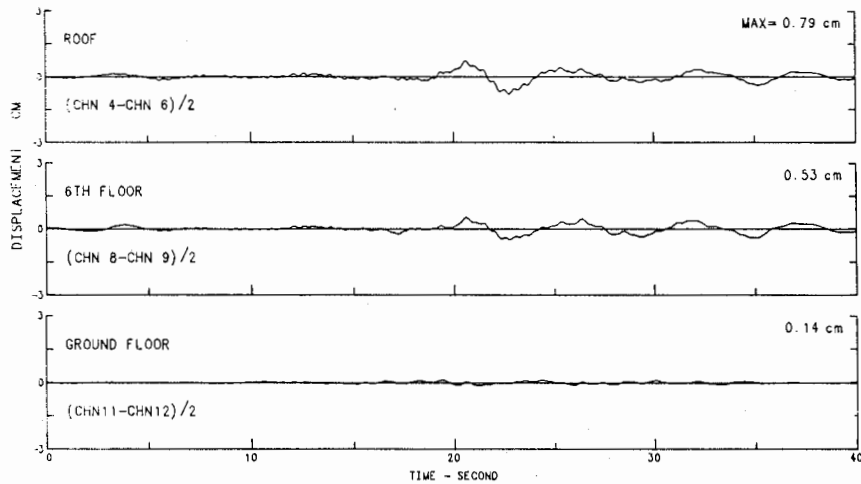

Fig. 5b. Torsional displacement profile, Town Park Towers Apartment Building, showing the torsional displacements obtained from EW sensors on the roof, 6th floor, and ground floor.

floor and the roof. Sensor 7 is mounted at the center of the 5th floor to detect any in-plane motion of the floor diaphragm. Sensors 13, 10, 9 and 5 in the longitudinal direction record the translational motion at the basement, 2nd floor, 5th floor and the roof, respectively.

The lateral and torsional displacement at the roof level are shown in Fig. 7a. In contrast with the two buildings considered previously, there is relatively little torsional motion indicated by the data from this building. The torsional displacements computed for the roof, 5th floor and base level are shown in Fig. 7b. These records do not show amplification of torsional motion at higher levels in the building. The sensor at the center of the 5th floor (no. 7) does indicate the presence of in-plane vibration of the floor slab, however.

DISCUSSION AND SUMMARY

The maximum torsional displacement at each floor level for the three San Jose buildings considered in this study have been plotted against floor level in Fig. 8. The torsional displacement profile for the Santa Clara County Office Building, obtained from the displacements shown in Fig. 3, is shown in Fig. 8a. The profile indicates significant amplification at the roof level relative to the base. Most of the amplification occurs between the 2nd and 7th floors. The torsional displacement at the roof is about 4 cm. In terms of angular measure, this converts to a maximum torsional rotation of the building at the roof level of approximately 0.002 radian (0.12 degree).

The torsional displacement profile for the Town Park Towers Apartment Building is shown in Fig. 8b, corresponding to the displacements plotted in Fig. 5b. The torsional displacement at the roof level, 0.8 cm, is much smaller than that at the County Building, although the roof-to-base amplification is similar to that of the County Building. As noted above, the predominant period of the torsional displacement is quite long, however. In terms of angular measure, the 0.8 cm torsional displacement is equivalent to 0.00025 radian (0.014 degree) maximum torsional rotation at the roof level.

The torsional displacement profile for the Great Western Building in Fig. 8c and the torsional records in Fig. 7b indicate little torsional response of this building, and little or no torsional amplification.

The Great Western building is quite symmetrical, and the shear walls, only two per floor, are located at the opposing endwalls (Fig. 6). The Town Park Towers Apartment Building, though similar to the Great Western building in overall dimensions (64 x 210 feet for Town Park, 82 x 190 feet for Great Western), has a much more complex distribution of shear walls in the interior of the building (Fig. 4). In addition, the distribution of shear walls is vertically discontinuous at the sixth floor.

The Town Park building and the Great Western building are located only about 0.5 km (0.3 mile) apart in a flat sedimentary valley about 10 km in width; the input to the two buildings, especially at long periods, must be similar. The torsional motion of the Town Park building is therefore not simply due to compliance of the building with a torsional component of the incoming wave field, but rather represents a torsional response of the building to lateral motion at the base.
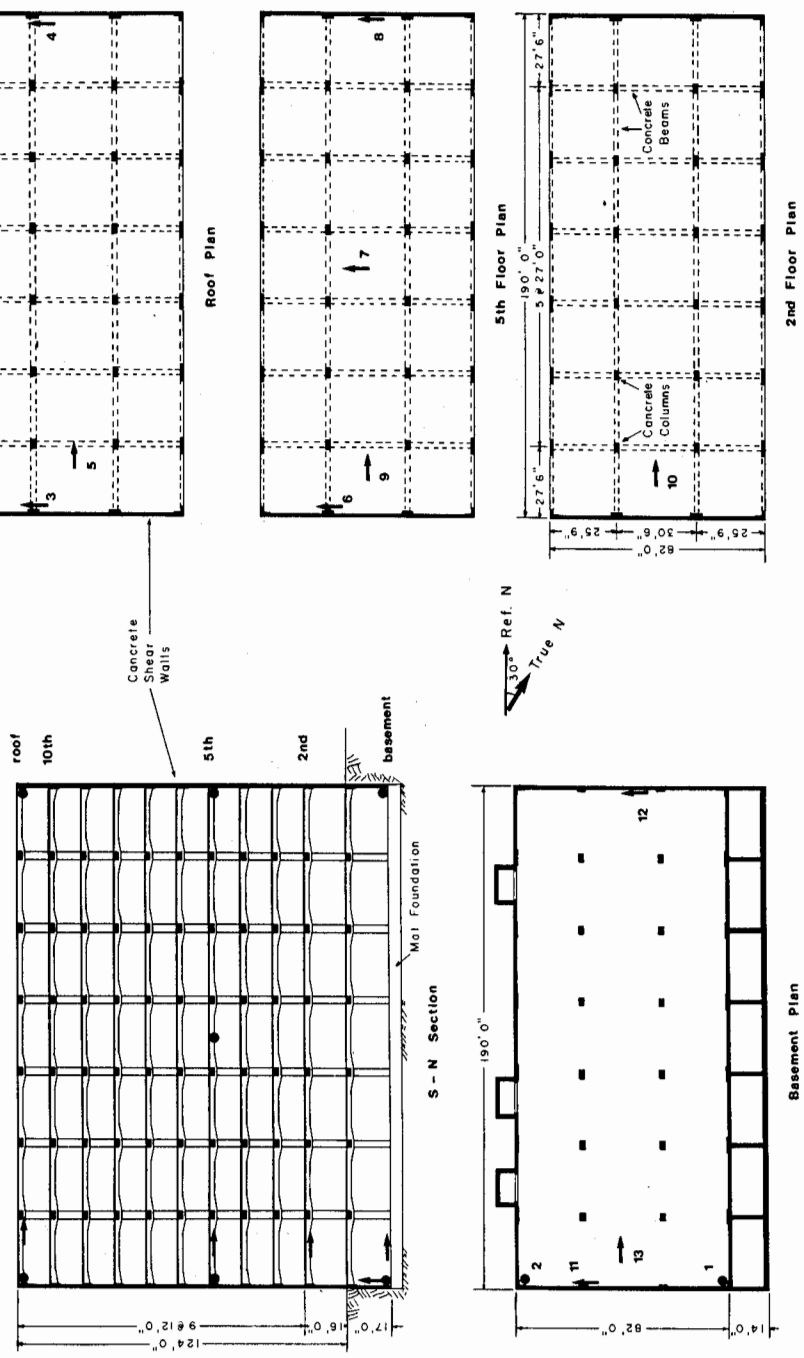
Fig. 6. Sensor layout in Great Western Savings and Loan Building.

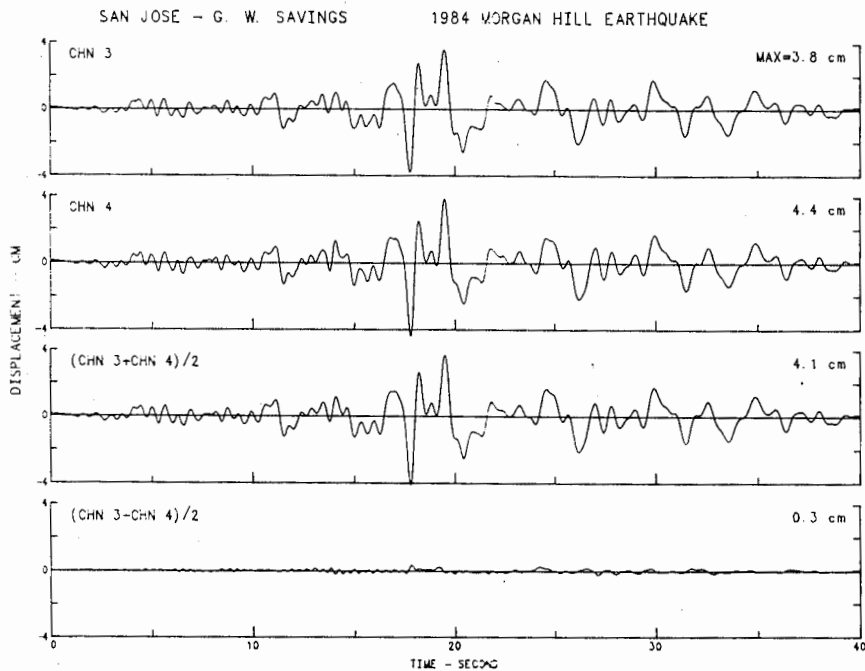SAN JOSE — G. W. SAVINGS   1984 MORGAN HILL EARTHQUAKE

Fig. 7a. Top Traces: EW displacements from sensors at S (Chn 3) and
N (Chn 4) edge of roof.   3rd Trace: Average EW displacement at roof,
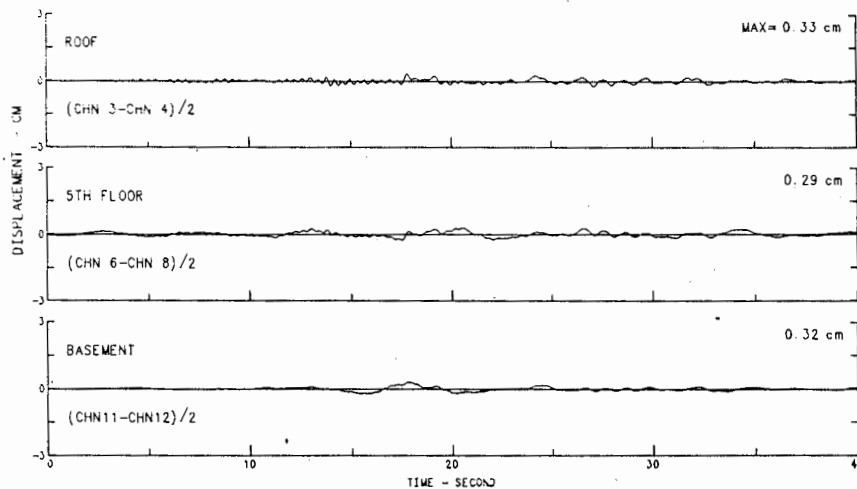obtained from Chns 3 and 4.   4th Trace: Torsional displacement at roof.

Fig. 7b. Torsional displacement profile, Great Western Savings
Building, showing the torsional displacements obtained from EW sensors
on the roof, 5th floor, and basement levels.

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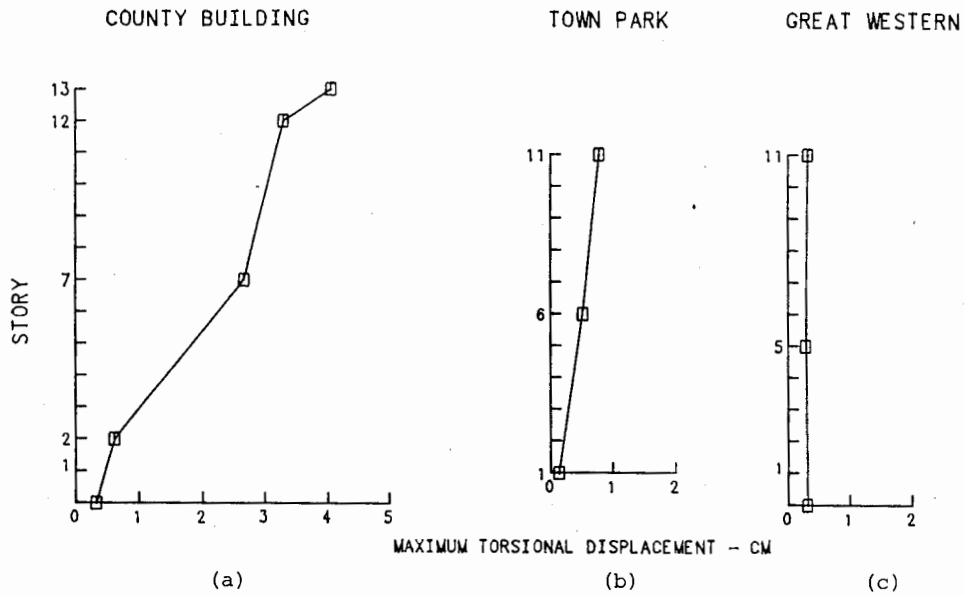COUNTY BUILDING   TOWN PARK   GREAT WESTERN

Fig. 8. Profile of torsional displacement in a) Santa Clara County
Building, b) Town Park Towers Apartment Building, and c) Great Western
Savings Building.

     This study of torsional displacements in three buildings suggests that
the addition of sensors to complement those at the end walls and floor centers
is necessary to fully understand the floor slab motion, especially in a
building as complex as the Town Park building. The addition of free-field
stations near the buildings is also necessary to more clearly define the input
to the buildings.

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[2] Brady, A.G., and A.F. Shakal, "The Morgan Hill Earthquake of April 24,
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     May 1985.

[3] Huang, M.J., A.F. Shakal, D.L. Parke, R.W. Sherburne, and R.V. Nutt,
     "Processed Data from the Strong-Motion Records of the Morgan Hill Earth-
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[4] Naaseh, S., "The Morgan Hill Earthquake of April 24, 1984 - Performance
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