Concentrated ground deformation and structural damage in the Monta Vista fault zone in the Los Altos Hills area, Santa Clara County, California

By D.H. Sorg and F.J. Groffie[1]

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[1] Terratech, Inc., 1365 Vander Way, San Jose, California, 95112

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ABSTRACT

Concentrated ground surface deformation and structural damage occurred in the Los Altos Hills area compared to the immediate surroundings during the Loma Prieta earthquake of October 17, 1989. The area is extensively laced with strands of the Monta Vista fault zone, suggesting a causal relationship between the presence of faults and the anomalously high levels of deformation and damage. Extensional and compressional cracking in pavements and in the ground surface were the most common types of observed ground deformation. Much of the ground deformation in the Los Altos Hills area was caused by the amplified ground shaking accompanying the Loma Prieta earthquake. However, the locations and types of some of the ground deformation features strongly suggest that they could have been caused by movement on one or more strands of the Monta Vista fault zone or by folding within a large fault-bounded block in the Monta Vista fault zone. Amplified ground shaking in the Los Altos Hills area (MM VIII) caused practically all of the structural damage. Speculation regarding a mechanism for the stronger ground shaking centers on three possibilities: (1) focusing of earthquake waves originating on the San Andreas fault due to underlying geologic structure, (2) different ground response caused by lithologic factors, or (3) seismogenic coseismic rupture on the Monta Vista fault zone. Variation in house orientation and design was responsible for the overwhelming majority of variation in levels of damage from one house to the next.

INTRODUCTION

Purpose

Concentrated ground surface deformation and structural damage occurred in the Los Altos Hills area of unincorporated Santa Clara County compared to the immediate surroundings during the Loma Prieta earthquake of October 17, 1989. Ground cracking was observed in this area to an extent not seen in the immediate surroundings. We also observed damage consistent with a Modified Mercalli intensity rating of VIII in the Los Altos Hills area, as indicated by numerous instances of damage to masonry, fall of stucco and chimneys, frame houses moved off foundations, and walls pushed out of plumb and sheared. In contrast, Stover and others (1990) assigned lesser Modified Mercalli ratings of VI and VII to the southern San Francisco Peninsula in general. The area attracted the special attention of both the Santa Clara County Department of Planning and Development and the U.S. Geological Survey. The purpose of this paper was to describe the heightened deformation and damage and to present possible explanations for their occurrence in the area.

Location and Description

The area we studied for deformation and damage is the oblong, irregularly shaped area shown in figure 3, measuring approximately 3.8 square km. It lies within an unincorporated part of Santa Clara County, California, adjacent to the cities of Los Altos and Los Altos Hills. The area lies at the northeastern base of the Santa Cruz Mountains, at the southwestern edge of the Santa Clara Valley (fig. 1). Topography consists of rolling hills incised by small watercourses that drain mostly to the northeast. Permanente Creek flows through the study area. Interstate Route 280, a freeway constructed in the 1960s, crosses the area in a northwest-southeast direction. The northern two-thirds of the study area is occupied mostly by one- and two-story, wood-frame, single-family homes built individually throughout the post-World War 2 period. Roads are essentially all paved with asphalt concrete; most lack curbs and sidewalks. The southern third of the study area consists of undeveloped parkland belonging to the Midpeninsula Regional Open Space District. [Figure 1 near here]

Previous Work

Original general geologic mapping of large areas that include the study area was performed by Dibblee (1966), Beaulieu (1970), and Rogers and Armstrong (1973). Helley and Brabb (1971) mapped late-Cenozoic deposits. Wright and Nilsen (1974) produced a map of landslide deposits. Rogers and Williams (1974) produced a geologic map of Santa Clara County that was a compilation of work by others but contains some modifications of the earlier work in the study area.

William Cotton and Associates (1978) produced maps of the geotechnical hazards of Los Altos Hills that covers the northwestern part of figure 3. Sorg and McLaughlin (1975) produced a geologic map of the Sargent-Berrocal fault zone that covers the southeastern part of figure 3. (New mapping by Sorg indicates that the Berrocal fault zone does not extend northward into the Los Altos Hills area, and, therefore, fault strands previously referred to as belonging to the Berrocal fault zone are here included in the Monta Vista fault zone.)

A large number of unpublished consultants' reports were produced for building sites within the study area, starting in the late 1960s. Geologic information from these reports were used as data points in creating the geologic map (fig. 3). Eleven positive fault locations, incorporated into figure 3, were obtained from consultant investigations performed by GEO-EKTA Laboratories and Goss & Associates, Inc. (1975), JCP (1988), William F. Jones, Inc. (1989), Nordmo Associates (1989), Rogers Johnson and Associates (1987, 1988), Rose (1978), Terrasearch (1977), Terratech (1976), United Soil Engineers (1975), and Upp Geotechnology (1990).

GEOLOGY

An understanding of the geology of the area is important to understanding the damage and deformation. [Fig. 3 near here]

Regional Geologic Setting

Rocks within the study area include strata as lithologically and temporally diverse as the Mesozoic Franciscan Complex and the Pliocene and Pleistocene Santa Clara Formation. Franciscan rocks in the Los Altos Hills region are part of the Permanente tectonostratigraphic terrane of Blake and others (1984), which extends from near Gilroy northwestward through the San Francisco Peninsula. The study area is located near the southwestern border of a structural block bounded by the Hayward and Calaveras faults on the northeast and the San Andreas fault on the southwest. The fundamental geologic structure of the study area is controlled by southwest-dipping thrust faults belonging to the Monta Vista fault zone. This fault zone is part of the Sargent-Berrocal thrust fault zone, which extends from San Juan Bautista to Palo Alto (Sorg and McLaughlin, 1975). This zone has formed in response to continuing crustal shortening being produced by the transpressive tectonic regime associated with the San Andreas fault system. Many geologists (e.g. McLaughlin and others, 1991) suspect that the zone of thrust faulting connects at depth with the San Andreas fault, several km to the southwest (see fig. 4).

Stratigraphy

Franciscan Complex and Serpentinite

The Franciscan Complex underlies the southwestern corner of the study area. Its age in this area is Jurassic and Cretaceous (Dibblee, 1966). The Franciscan Complex ranges from a broken formation to a melange, due to subduction-zone tectonic processes during the Mesozoic and early Cenozoic Eras. Lithic units of the Franciscan Complex mapped in the study area consist of greenstone, melange, chert, and limestone. The greenstone unit is composed of strongly sheared and altered submarine flows of basaltic composition. The melange unit is composed of different rock types mixed together so thoroughly that bodies of any one rock type are generally too small to be mapped, and includes greenstone, sandstone, limestone, chert, serpentinite, and blueschist. Several tectonically emplaced bodies of serpentinite of uncertain age are present between slabs of Franciscan rocks and along the thrust-fault contact separating Franciscan rocks from Miocene rocks.

Miocene Rocks

An unnamed sandstone unit of middle(?)-Miocene age (Beaulieu, 1970) is present in two small patches in the study area. Dibblee (1966), Beaulieu (1970), and Rogers and Armstrong (1973) differ in their mapping of the sandstone. We chose to map the patch in the northwestern corner of the study area in the manner of Rogers and Armstrong (1973) and the patch in the south-central part of the study area in the manner of Dibblee (1966). The Monterey Shale, of middle-Miocene age (Dibblee, 1966), is present locally as an irregular, roughly northwest-trending band in the central part of the study area. This unit in the study area consists mostly of thinly bedded, fractured, siliceous shale to chert. According to Beaulieu (1970), the Monterey Shale grades laterally and downward into the unnamed sandstone unit. The exposed contact between the Miocene rock units and the Franciscan Complex in the study area appears to be the central strand of the Monta Vista fault zone, as mapped by Dibblee (1966) and Beaulieu (1970), rather than a depositional contact, as mapped by Rogers and Armstrong (1973).

Santa Clara Formation

The Santa Clara Formation, of late-Pliocene and early-Pleistocene age (Dibblee, 1966), is present locally as an irregular, northwest-trending band on the northeast side of the study area. The unit's contact with the underlying Monterey Shale is an unconformity. The Santa Clara Formation in the study area consists of slightly lithified sandstone, conglomerate, and mudstone.

Surficial Deposits

Alluvial deposits, ranging in age from late Pleistocene into Holocene, is present along the streambeds of Permanente Creek and other major watercourses.

At least four significant landslide deposits are present within the study area. Three large, older landslide deposits, measuring about 300 m long, are present at the southern end of the study area. Two of these landslides are shown north of Permanente Creek on the maps by Rogers and Armstrong (1973) and Wright and Nilsen (1974). Sorg has mapped a third large older landslide just across the Permanente Creek canyon. Applied Soil Mechanics (1976) mapped a small, younger landslide adjacent to Ravensbury Avenue in the west-central part of the study area.

Ten large artificial fill deposits are shown in figure 3: eight beneath Route 280, a ninth at the Mora Drive overcrossing at Route 280, and a tenth beneath the slope between Partridge Lane and Eastbrook Avenue. The tenth deposit was placed to produce a level play field for the former Eastbrook School. Numerous small artificial fill deposits, not shown in figure 3, underlie individual residences and the edges of streets throughout the remainder of the study area.

Geologic Structure

Geologic structure in the Los Altos Hills area is characterized by southwest-dipping, slabs of deformed bedrock separated by thrust faults of the Monta Vista fault zone (fig. 4). The Monta Vista fault zone is dominated by three conspicuous strands in the Los Altos Hills area. The central strand of this fault zone has thrust Franciscan rocks up and over Miocene rocks. The northeastern strand has generally thrust Miocene rocks up and over the Pliocene and Pleistocene Santa Clara Formation. The Monta Vista fault zone, however, consists of numerous anastomosing fault strands, many of which are entirely within one rock unit. Probably only a small fraction of the many fault strands have been located. [Figure 4 near here]

Lawson (1908) mapped a fault he called the Black Mountain fault branching from the San Andreas fault at Portola Valley and ending in the vicinity of the southern end of the study area. The prominent, northwest-trending fault crossing the southwestern part of the study area, marked by large bodies of serpentinite, is probably the southeastern end of the Black Mountain fault. This fault is an extinct shear zone separating slabs of Franciscan rocks (Rogers and Armstrong, 1973).

Previous geologic mapping by Sorg and McLaughlin (1975) queried the continuation of the Berrocal fault as far northwest as the Los Altos Hills area. New geologic mapping in the study area by Sorg now suggests that the Berrocal fault does not extend as a continuous fault zone much farther northwestward than the Permanente Quarry; faults in the study area previously referred to as the Berrocal fault zone now are all included within the Monta Vista fault zone (fig. 3).

Attitudes of bedding in the rock units vary greatly across the study area. The Franciscan

Complex is intensely deformed. Most of the deformation in this unit occurred during the Mesozoic and early Cenozoic Eras and is unrelated to the present-day tectonic stress system. The Miocene units dip to the southwest. Dibblee (1966) classified bedding within the Miocene rocks as overturned, which we could not confirm. The Santa Clara Formation dips to the northeast (Dibblee, 1966; Sorg and McLaughlin, 1975).

Record of Faulting and Seismicity

The Monta Vista fault zone is generally considered to be at least potentially active. It has clearly ruptured the ground surface during the Quaternary Period, as it juxtaposes the Pliocene and Pleistocene Santa Clara Formation against older rock units (see also Hay and others, 1980). Some evidence for late-Quaternary offset exists. Several lines of geomorphic and soil-age evidence suggest late-Quaternary offset southeast of the study area (Sorg and McLaughlin, 1975). Rogers Johnson and Associates (1987, 1988) found a strand of the Monta Vista fault zone offsetting an "e" soil horizon on a property on Westbrook Avenue within the study area; while Rogers Johnson and Associates (1987, 1988) gave no opinion on the timing of this offset, it seems reasonable to place the event within the latest Pleistocene to Holocene Epochs. Earth Sciences Associates (1979) discovered faulting with offset on the order of 1 m that occurred 2,000 to 3,000 years ago about 600 m northeast of the known Monta Vista fault zone, on a property about 1.6 km southeast of the study area.

Lawson (1908, p. 104) reported the possibility of slight surface rupture along an unspecified part of the Black Mountain fault resulting from the 1906 San Francisco earthquake on the San Andreas fault. Rogers and Armstrong (1973) classified the Black Mountain fault as inactive. Rogers and Armstrong (1973) said that no other geologist besides Lawson has mapped an active fault where Lawson (1908) mapped the Black Mountain fault, and that the fault roughly coincides with one of the many unremarkable, extinct shear zones between rocks of the Franciscan Complex. A map in the Lawson (1908) report showing routes taken in studying effects of the 1906 earthquake suggests that the reported fault rupture, if in fact present and on the Black Mountain fault, was probably located well outside the study area, several km to the northwest. No apparent ground deformation occurred along the Black Mountain fault during the Loma Prieta earthquake.

Terratech (1990) studied earthquakes with $M \geq 2.0$ from 1969 through 1989 within a 62-square-km area surrounding the study area. The twenty-nine hypocenters ranged in depth from 5 to 8 km. Some of these earthquakes are temporally and spatially clustered and may represent small earthquake swarms. Although these earthquake hypocenters do not show a consistent southwesterly increase in depth as one might expect for earthquakes on a southwest-dipping fault zone, they do indicate that some type of seismic activity is occurring at depth.

Brabb and Olson (1986) studied earthquake epicenters over a larger part of the Los Altos Hills area and concluded that the Monta Vista fault system is a seismically active thrust fault.

Kovach and Beroza (1991) examined focal mechanisms for seismic events with M between 1.0 and 3.1 occurring from April 1967 to March 1991 in the Monta Vista fault zone. Their data also suggests that the Monta Vista fault system is active, with the majority of these seismic events having reverse (thrust) mechanisms, which corresponds with the compressional nature of the Monta Vista fault zone.

GEOLOGIC EFFECTS OF THE LOMA PRIETA EARTHQUAKE

Ground Deformation

Description

Coseismic ground deformation in the Santa Clara Valley associated with the Loma Prieta earthquake (there was abundant deformation elsewhere in the San Francisco Bay-Monterey Bay region) was focused along the southwestern edge of the valley along the Shannon and Sargent-Berrocal fault zones. This discontinuous zone of deformation begins in the Almaden Valley, approximately 8 km east of the town of Los Gatos, and extends for a distance of approximately 20 km to near Page Mill Road (Haugerud and Ellen, 1990). The three main areas of ground deformation were located in the Los Gatos area, near Regnart School in Cupertino, and in the Los Altos Hills area, where strands of the Monta Vista fault zone diverge to form a system of imbricate, southwest-dipping thrust faults (fig. 2). Within this northwest-trending zone, ground deformation was manifested by fresh compressional and extensional cracking in concrete sidewalks, curbs, gutters, asphalt pavement, and in soil. Much of the observed ground deformation, particularly in the Los Gatos area, was compressional, which Haugerud and Ellen (1990) attributed to northeast-southwest crustal shortening of unknown magnitude. [Figure 2 near here]

Within our area of investigation in the Los Altos Hills area (fig. 3), ground deformation was distributed through a northwest-trending zone approximately 2½ km long by 1 km wide, beginning at a point approximately 200 m west of St. Joseph Seminary and continuing northwestward within the Monta Vista fault zone to the vicinity of Magdalena Avenue, where ground deformation appeared to end. Ground deformation features within this zone consisted of compressional and extensional failures in asphalt pavement, concrete curbs, and soil.

Areas where significant ground deformation occurred, shown in figure 3, are described below.

Area 1. -- Compressional and extensional ground cracking formed within the Monta Vista fault zone where it passes through alluvium approximately 200 m west of St. Joseph Seminary. Ground deformation consisted of compressional and extensional cracking in soil, asphalt pavement, and a tennis court surface (figs. 5 through 8). [Figures 5-8 near here]

Area 2. -- Compression buckles and extension cracks formed along Route 280 between the Mora Drive and Magdalena Avenue overpasses. Prominent compression buckles formed in two areas of thick roadbed fill. Geologist Leslie Ransbottom (with JCP Geologists and Engineers, Inc.), who was driving northbound on Route 280 at the time of the earthquake, witnessed the formation of two of these compression buckles (written communication to U.S. Geological Survey geologist Steve Ellen, 12/20/90). After pulling over to the side of the freeway just south of the Magdalena Avenue exit, and while ground shaking continued, she witnessed the formation of two parallel, 30 to 46-cm-high compression buckles in the asphalt road surface where the freeway passes over an area of thick fill. Both of these compression buckles trended perpendicular to the road surface and were located about 9(?) m apart. By the time she returned with a camera the following morning, CalTrans had already removed and patched the compression buckles with fresh asphalt (figs. 9 through 12). These compression buckles formed at the same location where a soundwall under construction was extensively damaged (fig. 13). These compression buckles were not recorded in CalTrans reports of road surface damage in this area because there were probably no qualified observers at the site until the following day, by which time the road surface had already been repaired. Ms. Ransbottom also noted small compression buckles in the asphalt pavement of Magdalena Avenue between Route 280 and Foothill Expressway. [Figures 9-13 near here]

Another smaller, yet still significant, compression buckle appeared on Route 280 approximately 190 m north of the Mora Drive overpass. This compression buckle, which is located along a section of road bed cut into Monterey Shale bedrock rather than placed on artificial fill, trends nearly perpendicular to the road and crosses all lanes of the freeway. A remnant of this compression buckle, which was not entirely removed following the earthquake, remains as a hump in the southbound lanes at the time of this writing in November 1991 (fig. 14). [Figure 14 near here]

Area 3. -- Four prominent extension cracks cut the asphalt pavement of Mora Drive at Eastbrook Road. The cracks trend approximately N. 30°-45° W. and had a maximum opening of 1 cm. These cracks displayed no vertical or horizontal offset. An area of asphalt pavement at the intersection had already been patched with fresh asphalt on the day of observation, October 18, 1989. Based on the uneven nature of the patched road surface and the presence of slabs of former asphalt pavement nearby, small compression buckles probably also formed here. Significant shaking-induced settling and lateral spreading occurred in the fill underlying the western approach to the Mora Drive overpass (figs. 15 through 18). The northeastern trace of the Monta Vista fault zone, trending N. 10° W. here, passes through or close to this area. [Figures 15-18 near here]

Area 4. -- Five prominent extensional cracks cut the asphalt pavement of Mora Drive approximately 30 m northeast of the intersection with Sunhills Drive. The central trace of the

Monta Vista fault zone passes about 180 m northeast of this location. These cracks span a zone about 90 m wide. All five extensional cracks trend approximately N. 80° W., obliquely across Mora Drive, which trends approximately N. 25° E. at this location. The largest is 2 cm wide and cuts asphalt pavement and curbs, soil, and a stucco wall of an adjacent residence (figs. 19 through 22). Three of these extensional cracks show definite left-lateral offset with a cumulative offset of approximately 3 cm. Cumulative vertical offset across all five cracks measures approximately 1.5 cm, with the west side up. These cracks, being situated near the crest of a ridge, might have formed by ridge spreading, a mechanism Hart and others (1990) use to explain much of the ground deformation in the Summit Road and Skyland Ridge areas, about 30 km to the southeast. [Figures 19-22 near here]

Area 5. -- Four prominent extension cracks cut the asphalt pavement of Loyola Drive approximately 120 m northeast of the intersection with Eloise Circle. A strand of the Monta Vista fault zone passes through this area. The cracks trend N. 30° W. and vary in width from 1 to 2½ cm. These cracks displayed no vertical or horizontal offset.

Area 6. -- Two ½-cm-wide, extensional cracks, trending N. 40°-60° W., cut the asphalt pavement of Ravensbury Avenue where it makes a right-angle turn. Two strands of the Monta Vista fault zone converge in this area. The crack trending N. 40° W. shows approximately 3 mm of right-lateral offset. These cracks displayed no vertical offset.

Area 7. -- Four ½-cm-wide, extensional cracks, trending N. 70° W., cut the asphalt pavement of Camino Hermosa Drive about 30 m west of its intersection with Ravensbury Avenue. These cracks displayed no vertical or horizontal offset. Rogers and Armstrong (1973) mapped a strand of the Monta Vista fault zone crossing Camino Hermosa Drive near this location.

Area 8. -- Eight ½-cm-wide, extensional cracks, trending N. 45°-60° W., cut the asphalt pavement of Miller Avenue and Whitham Way. Several strands of the Monta Vista fault zone are present in this area. The cracks occupied a zone approximately 150 m across and did not display any vertical or horizontal offset.

Patterns

A few patterns emerge upon studying the ground deformation: Ground deformation in the Los Altos Hills area was restricted to areas underlain by the thrust-fault-bounded bedrock slab composed of Miocene rocks, and in some areas closely corresponded to mapped strands of the Monta Vista fault zone within and bounding this slab. All compressional ground deformation was restricted to the northeastern strand of the Monta Vista fault between St. Joseph Seminary and the Los Altos Country Club. All other areas of ground deformation exhibited only extensional types of failure.

Explanation

Some of the ground deformation features observed in the study area can be positively attributed to secondary effects of ground shaking, mainly fill deformation. The remainder are more difficult to explain with certainty. Explanations and speculation regarding the ground deformation features observed in the Los Altos Hills area center around the following three mechanisms:

(1) Folding. -- Folding within the thrust-fault-bounded, southwest-dipping slab of Miocene rocks offers a possible explanation for the extensional ground deformation observed in the Los Altos Hills area. Approximately 2 km south of the study area, Sorg and McLaughlin (1975)

interpreted this fault-bounded slab of Miocene rocks in the Monta Vista fault zone as an isoclinally folded anticline with its axial surface dipping about 45 degrees southwest. If this same compressed fold structure within the Monta Vista fault zone continues northwestward into the Los Altos Hills area, as shown in figure 4, then any additional tectonic shear compression of this fold caused by a seismic event might be expected to produce extensional deformation parallel to and across its axis, in the manner described by Yeats (1986). Additionally, any increased shear compression applied to an already highly deformed, isoclinally folded anticline might also cause slip along bedding planes and other shearing, including possible rupture along the axial surface of the fold (a blind thrust). With continued shear compression this could propagate to the ground surface as a new zone of thrust faulting. Such a style of deformation would probably not be confined to a narrow plane of failure, but would, more likely, be distributed across a wider zone, producing the type of ground deformation observed in the Los Altos Hills area. Strain partitioning, described by Lettis and others (1991), might have played a role. Strain partitioning results when oblique strain in the Earth's lower crust translates upward into tangential strain in the upper crust. This process commonly produces regions of folding, normal faulting, and thrust faulting that are subparallel to and flank large transform-fault systems (in this case, the San Andreas fault).

(2) Coseismic fault rupture. -- Some of the features that occurred within the Monta Vista fault zone strongly suggest that actual fault rupture might have been responsible for some of the observed ground deformation. Much of this deformation of the asphalt pavement along Route 280 between the Mora Drive overpass and Magdalena Avenue can be explained by failure of artificial fill; however, the extensiveness of the deformation, which includes compressional

buckling in an area where the roadbed is not constructed on artificial fill, suggests that some of this deformation might have been produced by thrust movement along the northeastern trace of the Monta Vista fault zone where it crosses Route 280. The discontinuous and varied intensity of ground deformation observed in the Los Altos Hills area suggests that if actual fault rupture did occur, it was more pronounced at depth, and fault rupture that propagated to the surface was discontinuous and diffuse.

(3) Ground shaking. -- At least part of the ground deformation features observed in the Los Altos Hills area can be attributed to secondary effects of the amplified ground shaking that occurred in the area (see *Structural Damage* section, below). Differential settlement and lurch cracking of large deposits of artificial fill probably caused most of ground deformation in Route 280 and in the approach to the Mora Drive overcrossing (Areas 2 and 3), and caused ground cracking in thick soil on one lot on Partridge Lane. The extensional cracks cutting across Mora Drive in Area 4 were located on a northeast-facing slope near the crest of a ridge and might have been formed by ridge spreading induced by strong ground shaking; Hart and others (1990) believe this mechanism best explains the extensive ridgetop fissuring in the Summit Road and Skyland Ridge areas, about 30 km to the southeast. However, almost all the ground deformation in the Los Altos Hills area was concentrated along a ridge flank, and is difficult to attribute to spreading, which is understood to generally produce ground deformation, instead, along the ridge *crest*.

Landsliding apparently did not contribute to the ground deformation: landslides are not abundant in the study area, and none of the features observed are on or near mapped landslides. Liquefaction, also, apparently did not occur.

Structural Damage

Description

Figure 3 shows the distribution of structural damage, which we divided into major, moderate, and minor classes. We classified tilting and tearing of walls, movement of superstructures off foundations, and heavy cracking of foundations as severe damage. We classified extensive damage to fireplaces and chimneys and cracking of foundations and walls as moderate damage. We classified cracking of stucco, roof tiles, fireplaces, and chimneys as minor damage.

A belfry at St. Joseph Seminary collapsed into the central courtyard, causing one fatality (figs. 23 and 24). The west wings of the four-story, unreinforced, concrete-and-masonry seminary building were extensively damaged and had to be demolished. A single-lane, wood-frame-and-steel-girder bridge that carries an extension of St. Joseph Avenue across Permanente Creek suffered severe damage and required extensive repair. [Figures 23 & 24 near here]

Density, age, and construction of residential development in the study area are similar to that of surrounding areas. Nevertheless, damage was significantly greater in the Los Altos Hills area than the immediate surroundings, based on the list of damage compiled by the Santa Clara County Planning and Development Department (1990). In the Los Altos Hills area, seventeen houses were severely damaged, about twenty-two were moderately damaged, and about twenty suffered minor damage from the Loma Prieta earthquake, according to the County's damage list. However, based on the flurry of construction activity that occurred soon after the earthquake and the great number of buildings that appeared to have been recently painted, we suspect that most of the residential buildings within the study area suffered at least some minor damage from the earthquake. Typical severe damage is shown in figures 25 through 30. Note that the performance of essentially all houses met the minimum intent of the applicable building code, the Uniform Building Code, which is designed to safeguard against collapse and loss of life rather than to make buildings "earthquake proof." [Figures 25-30 near here]

Two concrete-block soundwalls under construction or recently completed adjacent to Interstate Route 280 were damaged. Concrete slope paving on the Magdalena Avenue undercrossing spalled during the earthquake, and a 1½-cm space developed between the slope paving and an abutment wall (CalTrans, 1989a). The concrete pier column supporting the Mora Drive overcrossing over Route 280 was sheared completely through (Federal Highway Administration, 1989; CalTrans, 1989c) and the overcrossing abutments developed other, minor cracks, gaps, and spalling (CalTrans, 1989b).

Damage was consistent with a modified Mercalli intensity rating of VIII.

Patterns

Several patterns emerge upon examining individual structures and analyzing the general distribution of damage. Essentially none of the houses that incurred severe structural damage were on or near mapped fault traces, and practically none of the damage correlates with locations of ground deformation. Structural damage appeared to be confined almost entirely to areas underlain by the Monterey Shale and Santa Clara Formation, especially the Monterey Shale, and little damage occurred in areas underlain by the Franciscan Complex. Severely damaged houses were present on hilltops (seven houses), on hillsides (seven), and in swales and other low areas (three). Newer and older houses incurred about the same levels of damage. In all instances of severe damage, an undamaged or slightly damaged house could be found next door. All houses we examined showed that the strongest ground movement was in a north-south to northeast-southwest direction, which roughly agrees with findings by Reichle and others (1990) for polarizations of horizontal displacements in the San Francisco Bay and Monterey Bay areas. Nearly all severely damaged houses had their short (weaker) axes aligned more or less parallel to the direction of strongest ground movement, and many of the severely damaged buildings appeared to have few if any effective shear walls in the direction of strongest ground movement. Most house damage was to the superstructure or to the connection between superstructure and foundation; little damage was seen in foundations. Fireplace damage was extensive, and fireplaces located inside buildings, in particular, caused a significant part of the observable damage.

Explanation

Ground shaking appears to have caused nearly all the structural damage in the study area. For earthquake damage to occur, the earthquake has to have have some potentially damaging geologic effect, and construction has to be inadequate to withstand the effect or effects. We looked for all possible geologic effects when examining structural damage. Damaging effects can be divided into three broad groups: (1) ground shaking, (2) ground deformation (surface fault rupture, landsliding, settlement, lurching, etc.), and (3) water movements (dam failure, tsunami, etc.). After careful examination we ruled out ground deformation in almost all instances of damage (water movements, obviously, did not occur), leaving ground shaking as the cause of nearly all the structural damage.

Amplified ground shaking over the study area as a whole apparently caused the greater level of damage within the study area compared to the immediate surroundings. Building construction is not discernably weaker or different in the study area compared to the immediate surroundings, leaving no other possible explanation. While there were no motion-recording instruments in or near the Los Altos Hills area to confirm this greater level of shaking, "residents reported severe shaking" (Borchert and Donovan, 1990, p. 23).

Speculation regarding a mechanism responsible for the amplified ground shaking within the study area includes the following three possibilities:

(1) Focusing of seismic energy. -- Topography, reflection, and refraction are generally known to be factors in redirecting and focusing seismic energy. One intriguing possibility, which would be consistent with the distribution of damage, might be the trapping and channeling of seismic energy within low-velocity zones corresponding to the main strands of the Monta Vista fault zone or within a low-velocity zone corresponding to much or all of the fault zone. Such a mechanism would operate by channeling energy in much the same way that a fiber-optic cable channels light, as described by Li and others (1990). Another possibility might involve the role of deep structure. Geophysical work by Catchings and Fuis (1991) seems to indicate that energy released at the Loma Prieta epicenter is focused by reflections from deep crustal layers and from the Moho. This suggests amplified ground shaking could be expected along arcs with radii extending from the fault rupture, and, in fact, the geophysical work seems to show that amplified ground shaking occurs at points the same distance from the epicenter as the cities of Los Gatos, Los Altos Hills, and San Francisco (Catchings, pers. comm., 1992). These three areas experienced anomalously high levels of damage during the Loma Prieta earthquake.

(2) Lithologic variations. -- Nearly all the damage was in areas underlain by the Monterey Shale, which could have responded in some unusual, unknown way to seismic waves, perhaps

due to its low density or extensive fracturing.

(3) Seismogenic coseismic fault rupture. -- Shaking during the Loma Prieta earthquake could have momentarily added enough dynamic strain to an already statically strained Monta Vista fault zone to cause rupture simultaneous with the Loma Prieta earthquake, generating enough additional seismic energy to produce higher levels of damage in the study area. Examples of recent California earthquakes where coseismic rupture was documented include the Borrego Mountain earthquake of 1968 (Allen and others, 1972), the Westmorland earthquake of 1981 (Sharp and others, 1982), and the Loma Prieta earthquake, which caused minor coseismic movement on the Calaveras fault (McClellan and Hay, 1989). However, we know of no examples of *seismogenic* coseismic rupture in the literature, and this mechanism appears to be a less likely explanation for the amplified ground shaking than other explanations, for reasons suggested by Allen and others (1972, p. 101-102) in their discussion of the Borrego Mountain earthquake.

Variation in house orientation and design, apparently, was by far the most important factor in the variations in levels of damage to houses *within* the study area. A possible minor contributing factor might have included variations in levels of ground shaking. Such variations in ground shaking could have been caused by variations in thickness of underlying regolith, or by some houses straddling distinct soil-rock contacts, though there is not enough data to test either hypothesis. We do not know whether the numbers relating damage to topographic position (seven severely damaged houses on hilltops, seven on hillsides, and three in swales) are statistically significant enough to indicate that local topography was a factor in the distribution of structural damage.

Most of the severely damaged houses performed worse than other houses in the area because of some combination of the following four factors: (1) House orientation was such that the house's short (weaker) axis was aligned more or less in the direction of the strongest applied force, which was north-south to northeast-southwest. (2) Effective shear walls oriented in the direction of strongest ground movement were absent. (3) Heavy interior fireplaces placed high stresses on the building. (4) The house had poor connections between building components.

Similarities to Past and Future Earthquakes

We do not know if effects of the Loma Prieta earthquake in the Los Altos Hills area are a repeat of effects of the 1906 earthquake on the San Andreas fault. Reports on the effects of the 1906 earthquake (Lawson, 1908; Youd and Hoose, 1978; Nason, 1980) do not describe significant damage or deformation in the Los Altos Hills area, and contain insufficient detail to show a difference in the level of damage and deformation between this area and surrounding areas. The area was sparsely settled at the time of the 1906 earthquake. However, it seems possible that concentrated ground deformation and amplified ground shaking occurred in the Los Altos Hills area during the 1906 earthquake, and could occur again with another large earthquake on the San Andreas fault. The latter possibility is noteworthy due to the prediction by the Working Group on California Earthquake Probabilities (1990) that the San Francisco Peninsula segment of the San Andreas fault has about a 1-in-4 chance of rupturing with a magnitude-7 earthquake by the year 2020 (this fault segment is the adjoining segment north of the south Santa Cruz Mountains segment, which was responsible for the Loma Prieta earthquake).

CONCLUSIONS

Much of the ground deformation in the Los Altos Hills area was caused by the amplified ground shaking accompanying the Loma Prieta earthquake. However, the locations and types of some of the ground-deformation features strongly suggest that they could have been caused by movement on one or more strands of the Monta Vista fault zone, which crosses the area, or by folding within the fault-bounded block in the Monta Vista fault zone.

Ground shaking in the area caused practically all of the structural damage, and amplified ground shaking caused the concentration of damage in the area. Speculation regarding a mechanism for the amplified ground shaking centers on three possibilities: (1) focusing of earthquake waves originating on the San Andreas fault, due to underlying geologic structure, (2) different ground response caused by lithologic factors, or (3) seismogenic coseismic rupture on the Monta Vista fault zone. It appears that variation in house design was responsible for the majority of variation in levels of damage from one house to the next. The report by Terratech (1990) presents general suggestions that structural engineers might find useful in reducing future earthquake losses to this sort of construction in this type of terrain and geologic environment.

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