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Gennaro G. Marino
Engineering Consultants, Champaign, Illinois

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SYNOPSIS Significant damage to house foundations has resulted from the Loma Prieta earthquake. In some cases the cost to repair the foundation and to make the necessary seismic upgrades exceeded the market value of the house. This level of foundation damage was found at various distances from the epicenter and in different geologic settings. Presented in this paper are observations made on the foundation responses to various ground effects from the earthquake shaking. Also pointed out is the difference in performance of various affected foundation systems.

INTRODUCTION

Presented herein are overall observations made by the author on the response of residential foundations to the Loma Prieta earthquake. These observations are based on field inspections across the entire damage area affected by the quake, reviews of numerous engineering investigations and repair recommendations, and many detailed interviews conducted with geotechnical and structural engineers with extensive experience in the EQ damage to the residential structures.

Foundation damage was observed as a result of both structural shaking and in response to subjacent EQ induced ground movement. Differential ground movement that resulted in residential damage was related to faulting, ridge spreading, landsliding, soil densification, and liquefaction. Foundation response to structural shaking and the induced ground movement will be discussed after information is presented on the earthquake characteristics, the geologic settling, and the types of foundations affected. This paper concentrates on not those catastrophic failures, but the more common and severe damages.

THE LOMA PRIETA EARTHQUAKE

The Loma Prieta earthquake occurred in the Santa Cruz Mountains about 60 miles south of San Francisco on October 17, 1989 at 5:04pm. The quake registered 7.1 on the Richter Scale and was located between the towns of Boulder Creek to the northwest and Watsonville to the southeast (see Figure 1).

Although this quake was of significant size its duration of strong ground shaking was only 8 to 10 seconds which is much shorter than would be expected based on empirical data. In the area of the epicenter the induced damage was classified to reach an intensity of VIII based on the Modified Mercalli Intensity table (Stover, et al, 1990, and Wood and Neumann, 1931). But, because of ground and structural susceptibility, certain localized damage in San Francisco and Oakland reached intensities of IX. Mapping of the affected area showed the

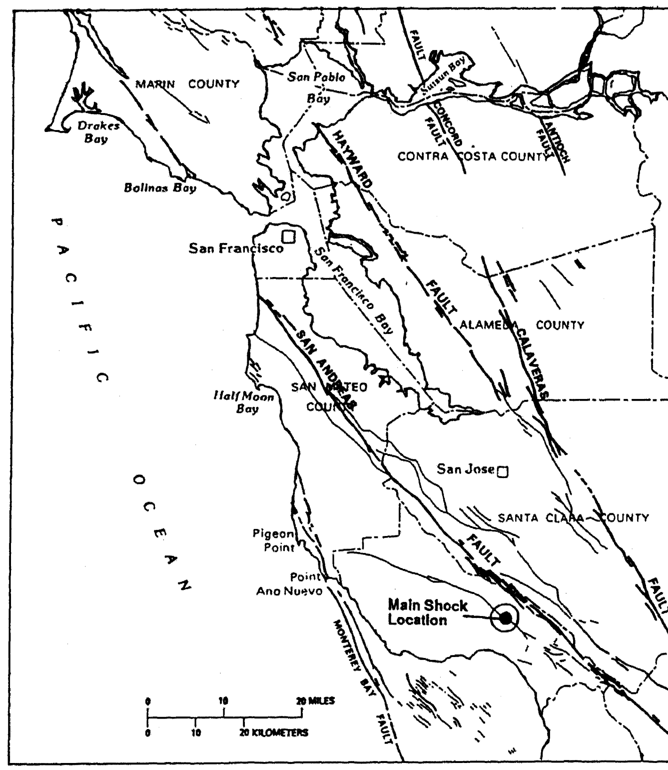

FIGURE 1 LOCATION OF THE LOMA PRIETA EARTHQAUKE AND THE REGIONAL FAULTING CHARACTERISTICS (AFTER STOVER, ETAL, 1990)

damage intensities generally extended (outward from the epicenter) about 2 to 4 times further along the northwest-southeast trending faults than perpendicular to them. It was found the amount of damage sustained depended on a number of factors including distance from the epicenter, geological/geotechnical characteristics, and construction of the foundation and superstructure. Distinctive differences in response were especially observed where the house was constructed to modern code standards versus those which were not (e.g., older, poorly maintained homes), the latter sustaining significantly more damage. It should be noted when viewing Isoseismal maps of Modified Mercalli Intensities that they are generally based upon maximum observed damages in the area. Therefore, areas of greater site susceptibility can be expected to have sustained the mapped intensity level, whereas, seismic resistant sites would be less affected.

An interesting correlation was drawn by Stover, et al, 1990 with the Loma Prieta earthquake and an 1865 quake which registered 6.3. Based on published reports, they discovered similar damage patterns between this older quake and the Loma Prieta. The 1865 quake was located about 8 miles north of the Loma Prieta quake.

GEOLOGIC SETTING

The areas significantly affected by ground motions caused by the Loma Prieta earthquake were quite diverse. Located in the Santa Cruz Mountains, the Loma Prieta earthquake waves propagated through the uplands down into the lowlands of the San Francisco Bay area. The lowland materials consist of 1. alluvial deposits originally from the uplands and transported down generally in the direction of the San Francisco Bay area; and 2. marine deposited materials along the Pacific coast (Brown and Kockelman, 1983). The distribution of the various alluvial materials, of course, is related to the carrying capacity of transporting water. Consequently, generally coarse unsorted soils are in abundance closer to the uplands while sorted and finer materials (including sands) exist down in the bay (or estuarine) area. Also playing an important part in the resultant residential damage were uncontrolled fills which were artificially placed in both the lowlands and uplands.

In the uplands or hillsides, residual soil profiles are found above sedimentary and igneous rocks. The nature of the bedrock and its structure varies considerably because of the intense degree of faulting in the area.

The specific geologic and geotechnical conditions found to be related to the foundation damage are discussed in the later sections on foundation behavior.

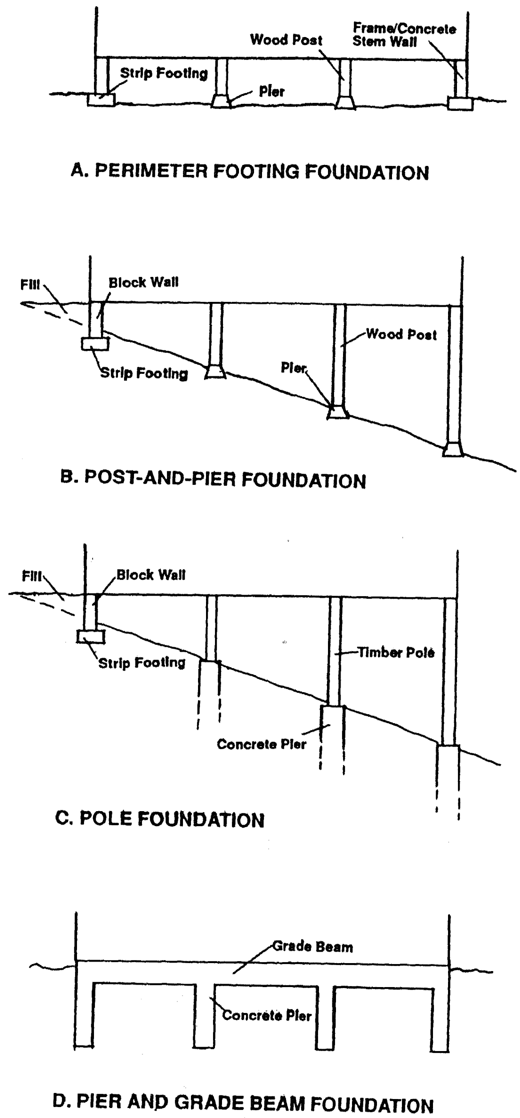

FIGURE 2 TYPICAL RESIDENTIAL FOUNDATION TYPES

FOUNDATION TYPES

The basic types of foundations more common to the San Francisco area include:

- ☞ perimeter footings,
- ☞ post-and-pier foundations,
- ☞ pole foundations, and
- ☞ pier and grade beam foundations.

The residential structures resting on concrete perimeter footings typically have interior post-and-pier foundations (see Figure 2A). Many times these perimeter footing foundations (especially in the Bay area) existed on the ground level making up the garage and "basement" areas. Because there was no concern for frost penetration these footings and piers are commonly placed near or on the ground surface. Above the perimeter footings are commonly either wood framing (called stem or cripple walls) or concrete bearing walls which directly support the first floor structure. The concrete perimeter footings are usually unreinforced.

Post-and-pier foundations are constructed in significant ground slope situations. Typically the upslope sides of the houses are supported on a below ground perimeter wall. The perimeter wall is usually made of block and rests on a concrete strip footing. This wall also serves the purpose of retaining soil fill that is used to level off the lot immediately in front of the house (see Figure 2B). Above this bearing-retaining wall may exist a short cripple wall to floor level on the floor. The downslope wood post and concrete piers (or pedestals) can achieve significant heights with only cursory wood bracing. The concrete piers are small and usually placed directly on the ground surface. The proliferation of this type of foundation was obviously as a result of its inexpensive costs.

Pole foundations also exist in significantly sloped ground areas. These timbers extended upwards to directly support the wood floor. The depth of these piles is typically not known but appear to terminate in stable bedrock in most cases. As with the post-and-pier system a retaining-bearing wall exists on the upslope side.

Although not so common in older construction, pier and grade beam foundations are a recent more popular means of construction. It is probably the most expensive of all the systems mentioned above. For this system the piers may consist of drilled-in concrete piers, driven pipe piers or screwed-in helix steel piers. Underpinning and installation of a pier-and-grade-beam system was commonly recommended by geotechnical engineers as a repair to stabilize the foundation below damaged ground, or as a mitigation measure for ground susceptible to damage from earthquake shaking. For sites susceptible to future liquefaction in the Bay area mat foundations were recommended when abutting neighboring houses exist (e.g., row houses).

FOUNDATION RESPONSE TO SHAKING

As discussed earlier, foundation damage from the Loma Prieta Earthquake was observed as the result of induced movement as well as from literally shaking. Although the shaking damage was less significant than the ground induced damage, there were certain more prominent damage scenarios including:

- ☞ tensile cracking of concrete stem walls and footings,
- ☞ sliding of floor on foundation,
- ☞ racking of cripple walls, and
- ☞ racking post-and-pier foundations.

The vertically-oriented tensile cracking observed in foundations was apparently caused by out-of-phase inertia forces in different foundation sections. This foundation damage was not severe consisting generally of racks of hairline widths. Where shaking was severe enough and the floor was not bolted to the foundation, the floor displaced laterally relative to the foundation. In the Loma Prieta earthquake some houses were knocked completely off the foundation (see Figure 3). Even with bolting, however, lateral shifting of the floor relative to the foundation still occurred when the floor was elevated off the concrete foundation by wood-stud-bearing wall (see Figure 4). This type of shifting results from the out-of-plane moment couple created by inertia forces in the floor structure and the foundation at the top and bottom of the stud wall, respectively. In order to mitigate this type of damage, knee braces could be installed to prevent out-of-plane rotation of the cripple wall.

Racking of cripple walls from EQ shaking is well celebrated damage condition from past earthquakes. This condition was again observed in the Loma Prieta quake. Since the Loma Prieta, awareness of the susceptibility of this condition to severe damage has been significantly raised in the bay area and the post-quake efforts in shear walling of these cripple walls has been significant.

Hillside homes resting on post-and-pier foundations present a structural situation where shaking is accentuated. This condition results because the entire residential structure is top heavy likened to a heavy weight on a stick that is shook at its base. Consequently, because the posts are typically not sufficiently braced nor fixed into the ground (as they typically

FIGURE 3 HOUSE THAT WAS NOT BOLTED DOWN WAS KNOCKED OFF IT'S FOUNDATION DURING THE LOMA PRIETA EARTHQUAKE

FIGURE 4 LATERAL SHIFTING OF THE FLOOR STRUCTURE OVER THE FOUNDATION CREATED BY A LACK OF BRACING OF THE CRIPPLE WALL

founded on small, shallow; concrete piers (or pedestals) they become significantly racked and displaced as the house shook. Figure 5 is a photograph of this type of racking damage. It is interesting to compare the behavior of the post-and-pier foundations to pole foundations under similar circumstances (i.e., supporting house on hillside). Pole foundations sustained less damage. Pole foundations being fixed into the ground behaved like moment-resisting structures when shook. Where damage to pole foundations occurred, floor diaphragm distortions and fracturing of the pole-floor connections resulted due to the different response of various length poles and the upslope wall foundation.

FOUNDATION RESPONSE TO FAULTING AND RIDGE SPREADING

Faulting beneath residential foundations resulted in complete failure of all foundation systems. It is not feasible to

FIGURE 5 RACKING OF POST-AND-PIER FOUNDATION ON MOUNTAIN SIDE FROM SHAKING

reconstruct over such faulted sites.

Although not common residential structures were affected by extensional fissures as a result of ridge spreading. Because ground stabilization is not feasible in this situation homes may be moved away from areas of ground movements, or shallow structural slab foundations are recommended which can resist some level of subjacent ground extension.

FOUNDATION RESPONSE TO LANDSLIDING

Shaking from the Loma Prieta earthquake resulted in dramatic to subtle landsliding effects. This phenomenon was observed in the uplands of the Santa Cruz Mountains. Those landsliding scenarios which caused significant residential damage were related to activation of old landslides, slides in undisturbed materials, and exacerbation of slope creep. Residential structures affected by movement of large earth masses were mainly associated with ancient landslides. In these cases EQ-induced displacements were most evident by fissuring which occurred mainly along the crest and sides of the pre-existing slide area. Many of the houses affected by massive slides did not exhibit significant foundation damage from the ground movement yet little could be done to economically stabilize the hillside. Without taking such stabilization measures area building officials would not sanction reconstruction and occupancy of the house.

More subtle and repairable damage conditions were related to sites where shifting of downslope fill or exacerbation of slope creep occurred. EQ instability of wedge-fill was typically attributed to uncontrolled placement. Although the sliding of the fill were commonly in the range of inches, cases of more extensive sliding also occurred (see Figure 6). In addition to fill these displacements, downslope movements subjacent to foundations on hillside fill sites were attributed to EQ-induced shifting of slope creep materials.

Since foundations rested partly on stable cut ground as well as unstable fill on the hillside, ground displacements with hogging curvatures and extension resulted beneath the house. Foundations most affected by this movement were perimeter foundation systems which have little resistance to this movement and are very flexible. Drilled-in concrete piers socketed into underlying stable ground with sufficient fixity and rigidity performed the best. Pipe piles also used in wedge fill situations were found to be too flexible to resist bending from lateral earth pressures due to sliding.

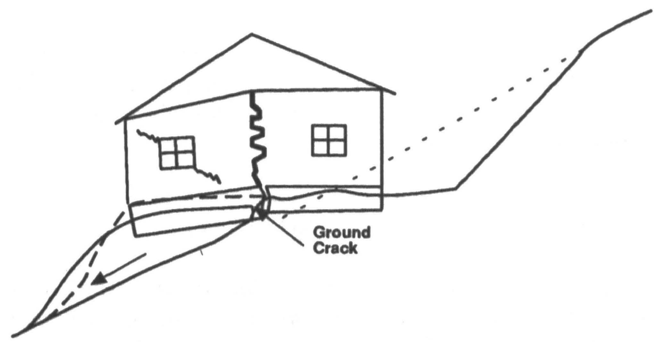

FIGURE 6 CROSS-SECTION OF SLIDING OF WEDGE FILL FROM EQ.

For exacerbated slope creep on hillside sites without fill, the post-and-pier systems were most susceptible to damage. Ground movement affecting these foundation systems were extensional and downslope but more translatory in nature than in the wedge fill scenario. Because of this downslope shift of these shallow creeping soils some of the post would lose the footing and others would be dragged downslope. This would occur concurrently with any racking damage to the post-and-pier system from shaking, as mentioned above.

In addition to foundation stabilization measures necessary to correct the above landsliding damage (which many times included underpinning), the induced downslope tilt required that the house be releveled.

Hillside houses resting on pole and drilled-in pier foundation were not displaced by these slope-creep-like movements because of the shallow depth of these movements, the rigidity of the foundation elements, and sufficient socketing into the underlying ground.

No detailed information was acquired by the author on homes damaged by lateral spreading although it was reported in the Marina District of San Francisco (Stover, et al, 1990).

FOUNDATION RESPONSE TO SOIL DENSIFICATION

During the Loma Prieta earthquake, differential settlement of foundations and associated damage from densification or compaction of granular soils was a more common scenario for residential structures. This type of damage occurred in the uplands as well as the lowlands and was most prevalent because loose sandy deposits are present throughout the EQ affected area. In the hillside sites, loose granular soils (mainly sands and silts) were typically present in wedge fills. In the lowlands these materials are mainly found in the flood plains, and dredge (and other) fills placed over bay mud in reclaimed areas. Foundations most susceptible to differential settlement were shallow perimeter footings. Where grade beam and pier or pipe pile foundations sufficiently extend below the zone of densification nominal damage results.

Underpinning was a common recommendation to stabilize and relevel the foundation over such ground conditions. Figure 7 shows a manometer survey performed on the first floor of house which settlement from some sliding and densification of the wedge fill.

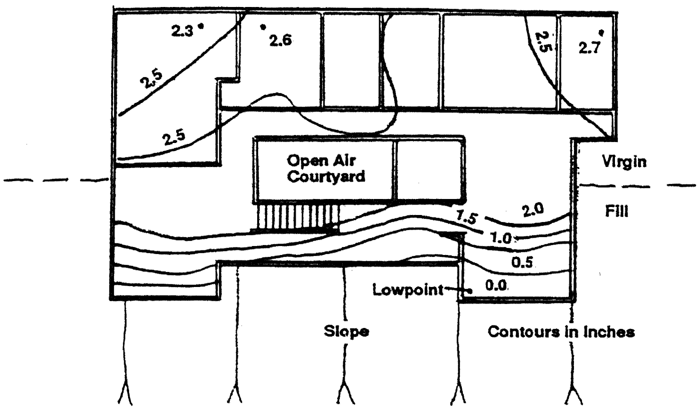

FIGURE 7 MANOMETER SURVEY OF FIRST FLOOR OF HOUSE WHICH IS OUT OF LEVEL DUE TO SLIDING AND SETTLING OF WEDGE FILL

FOUNDATION RESPONSE TO LIQUEFACTION

Liquefaction occurred in saturated loose sand and silts in lowland areas. The most dramatic accounts of this phenomenon were in the hydraulic fills in the Marina District of San Francisco approximately 60 miles away from the epicenter. Engineering investigations of foundation damage also noted liquefaction to occur in sand/silt lenses and seams deposited by river flood plains.

Houses on perimeter foundation systems were most susceptible to damage from liquefaction. These foundation responded to subjacent liquefaction by willingly bending and breaking. Resultant differential settlements were evident by the induced racking in the house frame and irregular tilting of floor areas. In Figure 8 a manometer survey is presented of the floor of the house in the Marina District where the subjacent soil have undergone liquefaction. Common foundation repair recommendations where liquefaction resulted involved compaction grouting of the loose sands or installation of a mat foundation.

CONCLUSIONS

Foundation damage from the Loma Prieta earthquake was observed as a result of structural shaking as well as from ground movements. EQ-induced ground movements which most commonly resulted in residential foundation damage were the result of landsliding, soil densification, and liquefaction. The occurrence of these different phenomena mainly depended on geologic setting, geotechnical properties of the affected ground, and the magnitude of the shake. Overall, perimeter foundation systems were found to be most sensitive to damage.

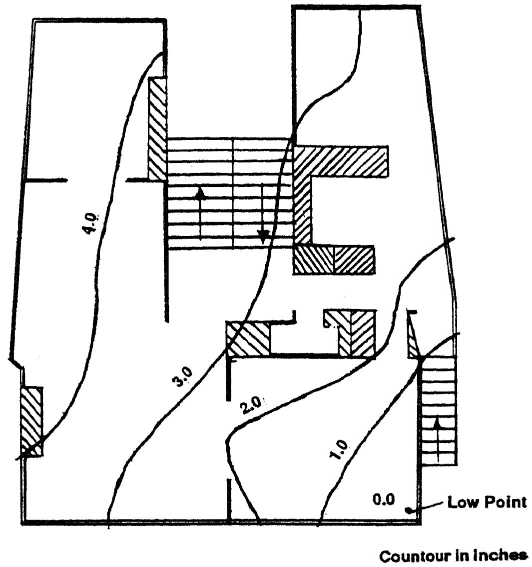

FIGURE 8 MANOMETER SURVEY OF FIRST FLOOR OF HOUSE IN MARINA DISTRICT OF SAN FRANCISCO WHERE SUBJACENT LIQUEFACTION OCCURED

ACKNOWLEDGEMENTS

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