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THE ROLE OF GEOTECHNICAL FACTORS IN NORTHRIDGE EARTHQUAKE RESIDENTIAL DAMAGE

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ABSTRACT

On three projects, one a class action law suit and two involving readjustment of insurance claims, we evaluated the impact of the 1994 M_w 6.7 Northridge, California earthquake on over 1,600 residential properties. For each of the properties, we reviewed previous reports on the condition of the site immediately after the earthquake, undertook a site visit to observe current conditions, undertook site-specific geotechnical investigations, as appropriate, and documented our findings on the impact of long-term and earthquake-related geotechnical factors on property damage. We have identified the following significant geotechnical factors that contribute to residential earthquake damage: (a) *hillside sites*; (b) *cut/fill transitions*; (c) *expansive soils*; (d) *liquefied sandy soils*; and (e) *deep soft soils*. This paper summarizes and presents our findings regarding these factors for five representative case histories of residential damage in the Northridge earthquake.

INTRODUCTION

General

This paper describes representative case histories of numerous site visits undertaken by the authors and their associates over a four-year period to observe conditions at Northridge earthquake-impacted houses in the greater Los Angeles area. The site visits were conducted as a part of re-adjustment of earthquake insurance claims. Our focus was the role of earthquake-related geotechnical factors in causing or contributing to geotechnical, structural and cosmetic damage at the properties.

The Northridge Earthquake and Limitations of our Study

The Northridge earthquake occurred on 17 January 1994 approximately 18 km below the surface of the northwestern end of the San Fernando Valley. The Moment Magnitude (M_w) 6.7 earthquake generated intense shaking that, although lasting only about nine seconds in the epicentral region, caused widespread damage and enormous economic loss.

Our site visits started in early 1999, approximately five years after the earthquake and were completed in mid 2003. None of the sites inspected were red-tagged (i.e., deemed unsafe to occupy) after the earthquake. Only 15 out of over 1600 sites inspected had been yellow-tagged (i.e., limited entry was allowed). A typical single-story house inspected is shown in Figure 1. A representative hillside site is shown in Figure 2.

Fig. 1. Typical Single-Story House in the Northridge Earthquake Epicentral Area

Fig. 2. Representative Hill-Side Site in the Northridge Earthquake Epicentral Area

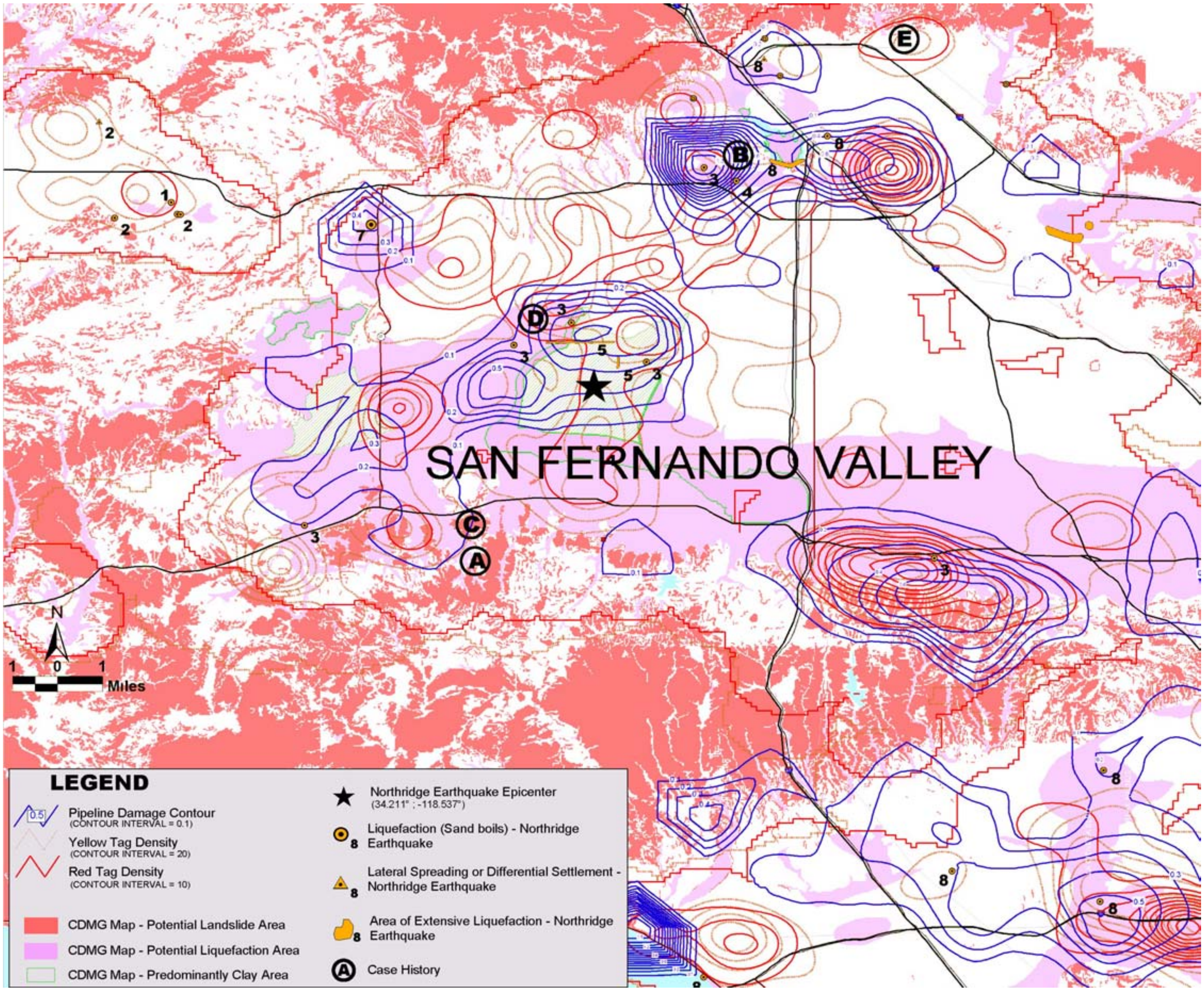

Fig. 3. Partial Presentation of GIS Database Developed for the Project (see also a Color Version of this Figure on CD)

The range of free-field horizontal accelerations encompassed at the sites visited in this study is 0.05 g to 0.9 g. However, due to the topographic amplification, hanging wall, focusing, and basin edge effects, it is possible that some of the properties were subjected to even higher acceleration levels. We use the term "expansive soils" for soils with Expansion Index (EI) exceeding 75. We note that compaction of fills and observation of bottoms of excavations was not supervised by the City of Los Angeles until 1964. Details on the past and present grading standards in southern California are described in detail in Stewart et al. (2001).

Geotechnical Site Visit Protocols

The following protocol was implemented for each property visited: (i) review previous reports and documentation on the condition of the site immediately after the earthquake; (ii) visit the site to observe current property condition; (iii) interview the property owners for their observations and personal accounts of damage; (iv) as appropriate, undertake site-specific geotechnical investigations; (v) as appropriate, evaluate site-specific strong ground shaking parameters (for the Northridge and previous earthquakes); and (vi) document observations and report findings on the impact of long-term and earthquake-related geotechnical factors on property damage.

A Geographic Information System (GIS) database was developed for the first project. The database, one layer of which is shown in Figure 3, contained information on regional and local geologic conditions (not shown in Figure 3 for clarity), areas prone to soil liquefaction and landsliding as established by the California Division of Mines and Geology (CDMG), Peak Horizontal Ground Acceleration (PHGA) contours as established by Stewart et al. (1994) (not shown in Figure 3), peak horizontal ground velocity as established by SAC Joint venture (1995) (not shown in Figure 3), contours of red- and yellow-tagged houses per California Office of Emergency Services (OES, 1994) and the pipeline damage contours as presented by O'Rourke and Toprak (1997). Generic GIS maps, covering a 1.6-km radius of the property, were generated prior to each site visit and distributed to the team members.

CASE HISTORIES

General

Table 1 summarizes the observations we made at the many sites we visited. We emphasize that the table lists actual observations, not theoretical considerations. We could quote a case history to support each and every statement in the table; however, because it is not possible to document so many case histories, we choose five representative case histories as follows to illustrate the points we make in Table 1.

(a) Hill-Side Site

The house is a single-story wood-framed structure founded on perimeter and interior concrete stem walls with cripple walls and isolated interior footings consisting of concrete pedestals, wooden caps, and wooden posts. The house was constructed circa 1920. An approximate location of the property is indicated in Figure 3 (Case History "A"). A plan view and a cross section through the property are shown in Figure 4.

According to the property owner, as a result of the earthquake, the stem walls cracked, the floor level was "changed," the flatwork cracked, the front retaining wall broke and leaned over, the exterior stucco cracked, and interior wall and ceiling finishes were damaged. According to the property owner, after the earthquake, new stem walls were installed on the north and east sides on the house, floors were re-leveled, and some stucco and interior surface cosmetic damage was repaired.

Table 1. Characteristic Pre-Earthquake Impacts, Site and Structure Responses in Earthquake, and Post-Earthquake Performance

Factor	Pre-Earthquake Impact(s)	Site Response	Structural Response	Post-Earthquake Performance
(a) Hill-Side Sites	• Long-Term Slope Creep • Structural Deformation and Tilting • Retaining Wall Tilting • Flatwork Movement	• Transient Shaking • Downslope Soil Movement • Minor Slope Cracking • Retaining Wall/Fill Lateral Movement	• Retaining Wall Damage • Foundation Cracking • Downslope Foundation Movement • Tilt-Exacerbated Structure Shaking and Cosmetic Damage	• Continued Downslope Deformation of Affected Soil Mass(es) • Increased Tilting and Movement of Retaining Walls • Increased Tilting and Deformation of Weakened Structures
(b) Cut-Fill Sites	• Differential Settlement Across Cut/Fill Line • Foundation Cracking • Structural Tilting • Flatwork Cracking	• Differential Transient Shaking of Cut vs. Fill • Differential Soil Settlement of Cut vs. Fill	• Slab Foundation, Structural and Cosmetic Damage Focus at Cut/Fill Line • Increase Floor Slopes and Wall Tilts	• Increased Structural and Cosmetic Finishes Susceptibility to Normal On-Going Deformation From Thermal, Wind, and Subsequent Small Earthquakes Cause Repeated Damage to Poorly-Executed Repairs
(c) Expansive Soil Sites	• Seasonal Soil Swelling and Shrinkage • Foundation Cracking and Stressing • Structural Weakening • Flatwork Cracking and Deformation	• Soil "Column" Shaking Exaggerates Surface Grade Movement (i.e., soil column separated by desiccation, cracks increase surface lateral movement)	• Foundation Cracking • Crack Exacerbation • Focused Structural and Cosmetic Damage at Most Expansive Soil Areas • Flatwork Slab Uplift at Cracked Areas Underlain by Expansive Soils	• Increase Moisture Entry Through Cracked Flatwork, Hence Increased Soil Swelling and Slab Deformation • Increase Entry of Surface Water to Crawl Spaces Through Cracked Stem Wells, Hence On-Going Foundation Deformation • Cracked and Weakened Foundation No Longer Resists Soil Expansion, Further Exacerbating Poorly-Executed Structural and Cosmetic Repairs
(d) Liquefaction Susceptible Sites	• Differential Settlement • Earthquake-Induced Deformation from Previous Earthquakes	• Surface Differential Movement • Loss of Soil Bearing Capacity • Linear fissures in soil	• Floor and Foundation Cracking • House Deformation • Cosmetic Damage	• Immediate Post-Earthquake Ongoing Soil Movement
(e) Deep Soft Soils (usually of varying depth across the site)	• Differential Settlement Due to Structural Loads and Water Table Dropping • Foundation Cracking and Stressing • Structural Tilting and Floor Sloping • Flatwork Sagging	• Differential Soil Shaking • Lateral Regional Deformation of Soft Soils	• Increased Floor Slopes and Wall Tilts • Foundation Cracking and Crack Exacerbation • Pool Shell out of Level • Focused Structural and Cosmetic Damage Associated with Abrupt Changes in Bedrock Topography	• Long-Term On-Going Differential Soil and Structural Deformation From Regional Water-Table Lowering

Based upon the property owner interview and our observation of site conditions, we concluded that there was no plausible geotechnical mechanism by which the earthquake caused a change in the bearing capacity of the soils at this site, the ability of the soils to support the house foundations, or of the rate of soil creep at the property. We recognized that the damage to the front retaining walls, and increase of moisture ingress through cracked flatwork, and leaking pipes were earthquake impacts that could, however, have resulted in increased localized soil creep. In conjunction with a structural engineer, we concluded that the stem wall cracks predated the earthquake and that both the stem wall cracking and pre-earthquake soil creep probably rendered the house susceptible to earthquake-induced structural and cosmetic damage. Furthermore, replacement of the downslope stem wall after the earthquake probably introduced a relatively rigid and unmoving foundation member that caused further cosmetic damage to the house. A subsequent visit revealed that cracked foundations continued to move downslope and push the house flooring and other structural components against the relatively unyielding components above the new stem walls.

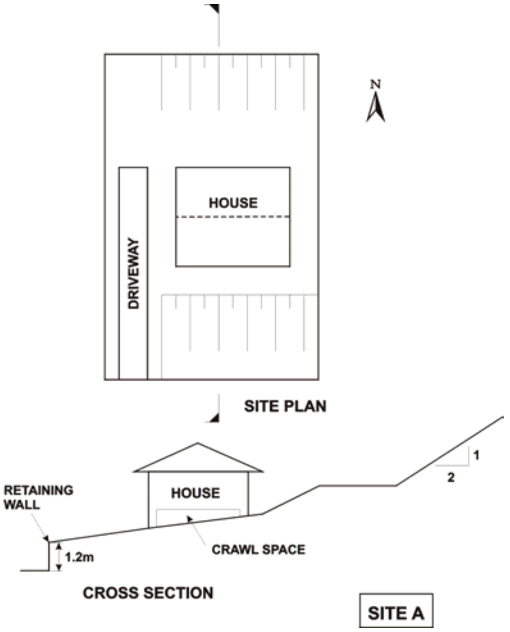

Fig. 4. Representative Hill-Side Site

Some of the conditions at this property were typical of many we saw where long-term slope creep had affected the position and level of the house and the integrity of foundation components. In the earthquake, such structures were more vulnerable than otherwise to seismic-induced disturbance as a result of their distortion and compromised foundations. In many cases post-earthquake soil creep appeared to have been accelerated by leakage from pipes broken by the earthquake, cracked flatwork and retaining walls, and the fact that post-earthquake precipitation was generally higher than in the decade or so before the earthquake. We also saw properties where post-earthquake partial replacement of old or earthquake-damaged foundations appeared to have resulted in more damage or exacerbation of earthquake-induced damage.

(b) Cut/Fill Site

The house is a single-story wood-framed structure constructed in 1957. The house foundation is a concrete perimeter footing and concrete slab-on-grade floor. An approximate location of the property is indicated in Figure 3 (Case History "B"). A plan view and a cross section through the property are shown in Figure 5.

The property owner told us that the house floor became unlevel as a result of the earthquake, that the courtyard paving to the north of the house was "deformed" after the earthquake, and that the pool shell "went down" to the southwest as a result of the earthquake. We lifted the carpets throughout the house during our site visit to inspect the slab-on-grade floor. In the west bedroom that straddles the reported change of grade of the floor, we observed a 10 to 15-mm wide crack with up to 5 mm of vertical offset across the crack. The crack had been filled with what appears to be a mortar grout; the grout filling had been placed in such a way to smooth out the vertical offset. The crack appeared to have opened no more than about 5 mm since the filling was placed. We noted that the slab crack appears to line up with the tile cracking in the entryway and the general floor slope changed along the slab crack.

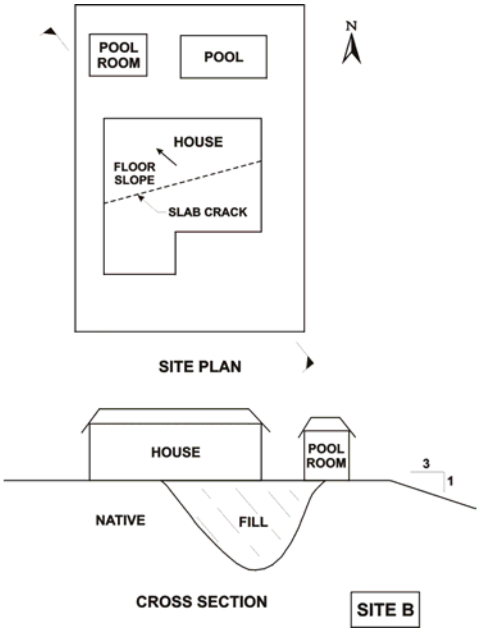

Fig. 5. Representative Cut/Fill Transition Site

On the basis of the property owner's statement that the carpets had been installed before the earthquake and not subsequently lifted, we concluded that the slab cracking clearly predated the earthquake and similarly that the slope of the floor to the northwest of the crack also predated the earthquake. On the basis of the reported cosmetic cracking of the tiles and wall finishes in the earthquake, we believe that some transient and possibly permanent fill deformation occurred as a result of the earthquake, but that this earthquake-induced deformation was not the predominant cause of the unlevel floors, the floor slab crack, or the vertical offset across the crack. We believe that the greater part of fill settlement and floor slope was the result of fill consolidation following original house construction.

We observed many other properties where there was an obvious correlation between the location of the cut/fill contact and earthquake-induced damage. On the basis of this case history and the many other sites we visited, we believe that as a general rule, differential cut/fill settlement preceding the earthquake rendered the house more vulnerable than otherwise to earthquake shaking. In particular, we believe that at many sites pre-earthquake differential cut/fill settlement induced, inter alia, floor slab cracks, unlevel floor, and focused strain in structural members and that in the earthquake the result was a focus of shaking, cosmetic damage, and additional crack exacerbation. Our observations are in general agreement with findings of Stewart et al. (2001) who studied in-depth performance of hillside fills in Northquake earthquake.

(c) Site on Expansive Soils

The house is a single-story wood-framed structure founded on perimeter and interior concrete stem walls with cripple walls and isolated interior footings consisting of concrete pedestals, wooden caps, and wooden posts. The house was constructed circa 1950. An approximate location of the property is indicated in Figure 3 (Case History "C"). A plan view and a cross section through the property are shown in Figure 6.

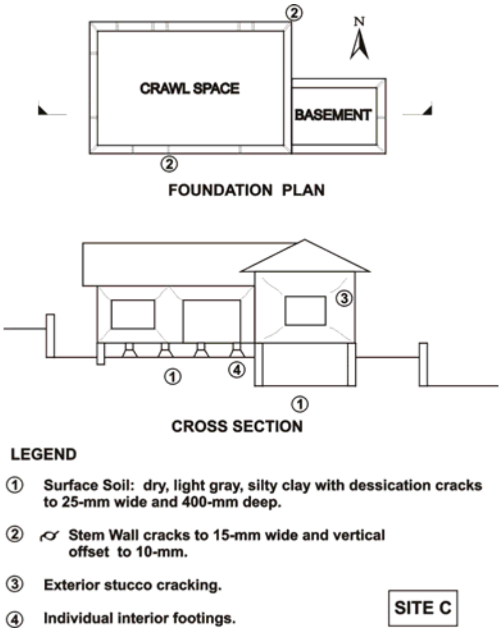

Fig. 6. Representative Site on Expansive Soils

We noted a direct correlation between the presence of expansive soils (EI ≥ 75) and damage to the structure and finishes of the house. At this site and many others that we visited that are founded on expansive soils, we noted significant stem wall cracking, deformation of the stem walls, and a correlation between reported interior cosmetic damage and the more desiccated soils at the site. For example, at the property shown in Figure 6, the structure and cosmetic finishes over the crawl space and particularly the north stem walls were significantly damaged in the earthquake.

The soil we observed beneath the stem walls of this house were dry and extensively desiccation cracked; the cracks were as wide as 25 mm, as deep as 400 mm, and were generally spaced at between 150 and 200 mm. It is as though the concrete stem walls were sitting on a series of isolated soil columns. Clearly, the long-term soil desiccation-induced deformation had stressed and in many instances cracked and displaced the stem walls relative to each other.

At this house, as at many we visited that are founded on expansive soils, the property owner had undertaken post-earthquake repair of cosmetic finishes only to be frustrated by the recurrence of stucco cracks, drywall plaster cracking, and deformed moldings. Obviously, ongoing seasonal soil swelling and shrinkage continue to move the foundations and to affect the structure and its cosmetic finishes. This process is exacerbated by the tendency to patch stucco and drywall cracks rather than remove and replace them – with even minimal seasonal movement of the foundation soil, the crack location makes itself known through paint and other overlays.

(d) Site on Liquefied Soils

The house is a single-story wood-framed structure constructed between 1950 and 1960. The house foundation is a concrete perimeter footing and concrete slab-on-grade floor. An approximate location of the property is indicated in Figure 3 (Case History "D"). A plan view and a cross section through the property are shown in Figure 7.

The property owner told us that he was sitting in the living room at the time of the earthquake, unable to sleep because of back pain. He told us that in the earthquake the living room floor appeared to "plunge and snap." He said that the width of the crack in the floor slab was about 50 mm immediately after the earthquake but appeared to close to about 30 mm in the days following the earthquake. Other earthquake damage described by the property owner included broken windows and door, cracking of exterior and interior wall finishes, and a significant "tilting" of the bathroom. He noted that as a general observation "most things fell to the south."

When we observed the crack its width was about 30 mm and the vertical offset across the crack was about 25 mm, with the north slab segment being higher than the south slab segment. We observed that house floor slab to the north of the living room floor crack was generally level. The floor slab to the south of the crack generally slopes down to the south at an inclination of approximately one vertical in 100 to 200 horizontal. Laboratory testing of soil samples from test pits indicated that the upper site soils are silty sand with a unit weight ranging from 14.6 to 16.5 kN/m^3. Boreholes indicate that the local water table is about 5 m below the surface and that the soils to about 20 m are interbedded silty sand and sandy silt. Soil liquefaction-induced sand boils were observed in relative vicinity of the site (see Figure 3). A site-specific soil liquefaction analysis showed that two 1.5-m thick layers at about 10 and 15 m below the ground surface may have liquefied in the earthquake and the estimated site-specific PHGA of 0.62 g. Calculations indicated that up to 74 mm of liquefaction-induced soil settlement could have occurred at the site.

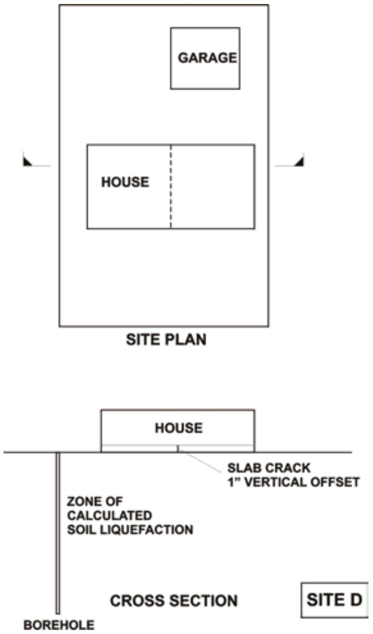

Fig. 7. Representative Site on Liquefied Soils

<u>(e) Deep Soft Soil of Varying Depth</u>

The house is a single-story wood-framed structure constructed in 1924. The house foundation was originally cast-in-place concrete slab on grade, large parts of which had been removed in 1960 and replaced with Concrete Masonry Unit (CMU) perimeter and interior footings. An approximate location of the property is indicated in Figure 3 (Case History "E"). A plan view and a cross section through the property are shown in Figure 8.

This house was unlevel, the walls tilted, and the ceilings sloped in the same direction and to the same degree as the floors. We advanced five CPT soundings with *discrete soil sampling*™. This established the upper three to five feet of soil was a variable mix of clayey silt and sand. Beneath this was a soft clay layer that varied from 5-m deep on the north side of the house to 8-m deep on the south side of the house. We concluded that the house had probably experienced considerable differential settlement ever since construction and that the Concrete Masonry Unit (CMU) stem walls had been installed before the earthquake in an attempt to correct house tilting. We believe that there was no significant earthquake-induced soil deformation at this site.

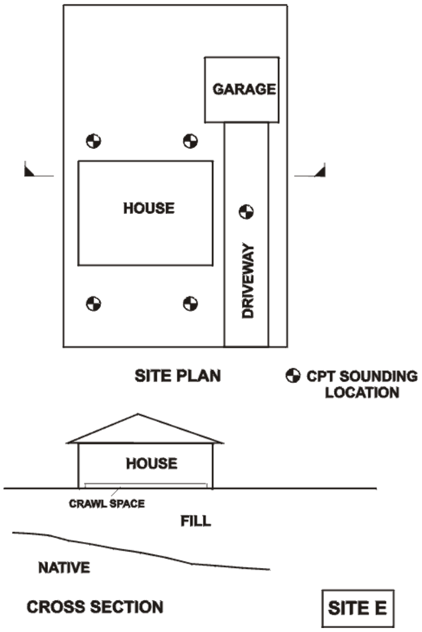

Fig. 8. Representative Site on Deep Fills of Variable Depth

CONCLUSIONS

On the basis of the representative case histories described in this paper and over 1,600 other sites visited, we conclude that the predominant impact of geotechnical factors in seismically-induced residential damage (green-tagged houses only) was the effect of long-term soil deformation in setting up structural conditions that rendered the house more than ordinarily susceptible to transient seismic shaking. There appears to be a general correlation of earthquake-induced structural and cosmetic damage and foci of long-term soil differential settlement regardless of whether that deformation is the result of downslope soil creep, differential cut/fill settlement, the highly variable nature of expansive soil swelling and shrinking, or variations in thickness of soft clays beneath the house.

While the foundations of the house may affect structural seismic response, we believe that differential long-term site settlement was a significant factor in structural damage regardless of whether the foundations were cast-in-place concrete, un-reinforced CMU, or perimeter strip footings with slab-on-grade floors. Surprisingly, the only foundation type that consistently appeared not to be associated with significant structural or cosmetic damage, regardless of soil conditions, were those involving exterior and interior stem walls and no isolated individual interior footings.

We observed many cases where the earthquake damaged concrete components such as flatwork and retaining walls, and subsequent to the earthquake, these damaged structural components lead to soil response and performance that resulted in additional post-earthquake damage. For example broken retaining walls were no longer able to adequately retain soil that experienced increased movement, flatwork cracks lead to increase percolation of precipitation runoff to underlying expansive soils that further lifted and damage concrete slabs and foundations, and cracked pools leaked resulting in rising groundwater levels, flooding of basements, increased moisture penetration through floors and ultimately to mold development – a topic that is beyond the scope of this paper.

We conclude by remarking that only at a few houses have the underlying geotechnical and foundation conditions that caused seismic-induced damage been fixed. In a future earthquake in this area, many of the houses we visited, and undoubtedly the many others of which they are representative, will be damaged and large property and human losses incurred.

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