SEISMIC HAZARD ZONE REPORT FOR THE SANTIAGO PEAK 7.5-MINUTE QUADRANGLE, ORANGE COUNTY, CALIFORNIA

2002

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EXECUTIVE SUMMARY

This report summarizes the methods and sources of information used to prepare the Seismic Hazard Zone Map for the Santiago Peak 7.5-minute Quadrangle, Orange County, California. The map displays the boundaries of Zones of Required Investigation for liquefaction and earthquake-induced landslides over an area of approximately 27 square miles at a scale of 1 inch = 2,000 feet.

Most of the land in the Santiago Peak Quadrangle lies within the Cleveland National Forest. Only the southwestern quarter has been evaluated where residential development is underway in the unincorporated communities of Rancho Santa Margarita, Coto de Caza, and Dove Canyon adjacent to narrow strips of the O'Neill Regional Park in Plano Trabuco and Tijeras Canyon. The area lies on the western slope of the Santa Ana Mountains and is characterized by rugged, deeply dissected terrain. The highest point in the quadrangle is 5,687-foot Santiago Peak. The lowest point is less than 800 feet above sea level in the southwestern corner in Plano Trabuco. The major drainage courses in the quadrangle include Trabuco Canyon and Arroyo Trabuco, which cross the entire quadrangle, Silverado Canyon, and Santiago Canyon. The gently sloping to nearly level land of Plano Trabuco, incised by Arroyo Trabuco within O'Neill Regional Park, contrasts with the surrounding brush-covered mountains. Access to the quadrangle is provided by roads that intersect the Foothill Transportation Corridor (State Highway 241) just west of the quadrangle. The primary access is via county road S19 (Live Oak Canyon Road/ Trabuco Canyon Road/ Plano Trabuco Road) and Santa Margarita Parkway, which services the Rancho Santa Margarita development south of Plano Trabuco.

The map is prepared by employing geographic information system (GIS) technology, which allows the manipulation of three-dimensional data. Information considered includes topography, surface and subsurface geology, borehole data, historical ground-water levels, existing landslide features, slope gradient, rock-strength measurements, geologic structure, and probabilistic earthquake shaking estimates. The shaking inputs are based upon probabilistic seismic hazard maps that depict peak ground acceleration, mode magnitude, and mode distance with a 10% probability of exceedance in 50 years.

In the Santiago Peak Quadrangle the liquefaction zone is restricted to portions of the bottoms of Arroyo Trabuco, Canada Gobernadora, Tijeras Canyon, Live Oak Canyon, Modjeska Canyon, Harding Canyon, Bell Canyon and the Oso Creek drainage area. The bedrock geology consists of a broad range of rock types. Where slopes are steep and rocks are weak or fractured landslides are abundant. Such conditions contribute to an earthquake-induced landslide zone that covers about 41 percent of the evaluated area of the quadrangle.

How to view or obtain the map

Seismic Hazard Zone Maps, Seismic Hazard Zone Reports and additional information on seismic hazard zone mapping in California are available on the California Geological Survey's Internet page: http://www.conservation.ca.gov/CGS/index.htm

Paper copies of Official Seismic Hazard Zone Maps, released by CGS, which depict zones of required investigation for liquefaction and/or earthquake-induced landslides, are available for purchase from:

BPS Reprographic Services
945 Bryant Street
San Francisco, California 94105
(415) 512-6550

Seismic Hazard Zone Reports (SHZR) summarize the development of the hazard zone map for each area and contain background documentation for use by site investigators and local government reviewers. These reports are available for reference at CGS offices in Sacramento, San Francisco, and Los Angeles. **NOTE: The reports are not available through BPS Reprographic Services.**

INTRODUCTION

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate seismic hazard zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the seismic hazard zone maps in their land-use planning and permitting processes. They must withhold development permits for a site within a zone until the geologic and soil conditions of the project site are investigated and appropriate mitigation measures, if any, are incorporated into development plans. The Act also requires sellers (and their agents) of real property within a mapped hazard zone to disclose at the time of sale that the property lies within such a zone. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California State Mining and Geology Board (SMGB) (DOC, 1997). The text of this report is on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

The Act also directs SMGB to appoint and consult with the Seismic Hazards Mapping Act Advisory Committee (SHMAAC) in developing criteria for the preparation of the seismic hazard zone maps. SHMAAC consists of geologists, seismologists, civil and structural engineers, representatives of city and county governments, the state insurance commissioner and the insurance industry. In 1991 SMGB adopted initial criteria for delineating seismic hazard zones to promote uniform and effective statewide implementation of the Act. These initial criteria provide detailed standards for mapping regional liquefaction hazards. They also directed CGS to develop a set of probabilistic seismic maps for California and to research methods that might be appropriate for mapping earthquake-induced landslide hazards.

In 1996, working groups established by SHMAAC reviewed the prototype maps and the techniques used to create them. The reviews resulted in recommendations that 1) the process for zoning liquefaction hazards remain unchanged and 2) earthquake-induced landslide zones be delineated using a modified Newmark analysis.

This Seismic Hazard Zone Report summarizes the development of the hazard zone map. The process of zoning for liquefaction uses a combination of Quaternary geologic mapping, historical ground-water information, and subsurface geotechnical data. The process for zoning earthquake-induced landslides incorporates earthquake loading, existing landslide features, slope gradient, rock strength, and geologic structure. Probabilistic seismic hazard maps, which are the underpinning for delineating seismic hazard zones, have been prepared for peak ground acceleration, mode magnitude, and mode distance with a 10% probability of exceedance in 50 years (Petersen and others, 1996) in accordance with the mapping criteria.

This report summarizes seismic hazard zone mapping for potentially liquefiable soils and earthquake-induced landslides in the Santiago Peak 7.5-minute Quadrangle.

SECTION 1
LIQUEFACTION EVALUATION REPORT

Liquefaction Zones in the Santiago Peak 7.5-Minute Quadrangle, Orange County, California

By
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California Department of Conservation
California Geological Survey

PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use seismic hazard zone maps developed by CGS in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within seismic hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California State Mining and Geology Board (SMGB) (DOC, 1997). The text of this report is on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

Following the release of DMG Special Publication 117 (DOC, 1997), agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction hazards. The agencies made their request through the Geotechnical Engineering Group of the Los Angeles Section of the American Society of Civil Engineers (ASCE). This group convened an implementation committee under the auspices of the Southern California Earthquake Center (SCEC).

The committee, which consisted of practicing geotechnical engineers and engineering geologists, released an overview of the practice of liquefaction analysis, evaluation, and mitigation techniques (SCEC, 1999). This text is also on the Internet at: http://www.scec.org/

This section of the evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils in the Santiago Peak 7.5-minute Quadrangle. Section 2 (addressing earthquake-induced landslides) and Section 3 (addressing potential ground shaking), complete the report, which is one of a series that summarizes production of similar seismic hazard zone maps within the state (Smith, 1996). Additional information on seismic hazards zone mapping in California is on CGS's Internet web page: http://www.conservation.ca.gov/CGS/index.htm

BACKGROUND

Liquefaction-induced ground failure historically has been a major cause of earthquake damage in southern California. During the 1971 San Fernando and 1994 Northridge earthquakes, significant damage to roads, utility pipelines, buildings, and other structures in the Los Angeles area was caused by liquefaction-induced ground displacement.

Localities most susceptible to liquefaction-induced damage are underlain by loose, water-saturated, granular sediment within 40 feet of the ground surface. These geological and ground-water conditions exist in parts of southern California, most notably in some densely populated valley regions and alluviated floodplains. In addition, the potential for strong earthquake ground shaking is high because of the many nearby active faults. The combination of these factors constitutes a significant seismic hazard in the southern California region in general, including areas in the Santiago Peak Quadrangle.

METHODS SUMMARY

Characterization of liquefaction hazard presented in this report requires preparation of maps that delineate areas underlain by potentially liquefiable sediment. The following were collected or generated for this evaluation:

- Existing geologic maps were used to provide an accurate representation of the spatial distribution of Quaternary deposits in the study area. Geologic units that generally are susceptible to liquefaction include late Quaternary alluvial and fluvial sedimentary deposits and artificial fill

- Construction of shallow ground-water maps showing the historically highest known ground-water levels

- Quantitative analysis of geotechnical data to evaluate liquefaction potential of deposits

- Information on potential ground shaking intensity based on CGS probabilistic shaking maps

The data collected for this evaluation were processed into a series of geographic information system (GIS) layers using commercially available software. The liquefaction zone map was derived from a synthesis of these data and according to criteria adopted by the SMGB (DOC, 2000).

SCOPE AND LIMITATIONS

Evaluation for potentially liquefiable soils generally is confined to areas covered by Quaternary (less than about 1.6 million years) sedimentary deposits. Such areas within the Santiago Peak Quadrangle consist mainly of alluviated valleys and canyons. CGS's liquefaction hazard evaluations are based on information on earthquake ground shaking, surface and subsurface lithology, geotechnical soil properties, and ground-water depth, which is gathered from various sources. Although selection of data used in this evaluation was rigorous, the quality of the data used varies. The State of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data obtained from outside sources.

Liquefaction zone maps are intended to prompt more detailed, site-specific geotechnical investigations, as required by the Act. As such, liquefaction zone maps identify areas where the potential for liquefaction is relatively high. They do not predict the amount or direction of liquefaction-related ground displacements, or the amount of damage to facilities that may result from liquefaction. Factors that control liquefaction-induced ground failure are the extent, depth, density, and thickness of liquefiable materials, depth to ground water, rate of drainage, slope gradient, proximity to free faces, and intensity and duration of ground shaking. These factors must be evaluated on a site-specific basis to assess the potential for ground failure at any given project site.

Information developed in the study is presented in two parts: physiographic, geologic, and hydrologic conditions in PART I, and liquefaction and zoning evaluations in PART II.

PART I

PHYSIOGRAPHY

Study Area Location and Physiography

The Santiago Peak Quadrangle covers an area of about 60 square miles in easternmost Orange County. Most of the land in the quadrangle lies within the Cleveland National Forest. In the southwestern quarter, however, residential development is underway in the unincorporated communities of Rancho Santa Margarita, Coto de Caza, and Dove

Canyon. Older development in the quadrangle is restricted to scattered clusters of residences in the canyons. The area evaluated for seismic hazard zoning covers about 27 square miles.

The study area lies on the western slope of the Santa Ana Mountains in the Peninsular Ranges geomorphic province of southern California. Rugged, deeply dissected terrain characterizes the topography in the quadrangle. The highest point in the quadrangle is Santiago Peak, at 5,687 feet. The lowest point is less than 800 feet above sea level in the southwestern corner of the quadrangle where Arroyo Trabuco and Tijeras Canyon deeply incise the gently sloping Plano Trabuco. Trabuco Creek provides the main drainage through both Trabuco Canyon and Arroyo Trabuco, which together cross the entire quadrangle. Other canyons within the quadrangle included Silverado, Santiago, Live Oak, Hickey, Rose, Dove, and Tijeras. Access to the Santiago Peak Quadrangle is provided by roads that intersect the Foothill Transportation Corridor (State Highway 241) just west of the quadrangle. The primary access is via county road S19 (Live Oak Canyon Road/ Trabuco Canyon Road/ Plano Trabuco Road) and Santa Margarita Parkway. Numerous canyon-bottom roads connect with unpaved motorways and truck trails that provide access to parts of the national forest.

GEOLOGY

Bedrock and Surficial Geology

Geologic units generally susceptible to liquefaction include late Quaternary alluvial and fluvial sedimentary deposits and artificial fill. For this evaluation, the geologic map for the Santiago Peak Quadrangle was compiled and digitized by the Southern California Areal Mapping Project [SCAMP] (Morton and Kennedy, 1989) from 1:12,000-scale mapping (Miller and Morton, 1984). Nomenclature for the Quaternary geologic units follows that applied by SCAMP. Additional linework and nomenclature modifications were done by CGS. Plate 1.1 shows the generalized Quaternary geology of the Santiago Peak Quadrangle map that was used in combination with other data to evaluate liquefaction potential and develop the Seismic Hazard Zone Map.

Approximately 15 percent of the quadrangle is covered by alluvial deposits of Quaternary age. These Pleistocene through Holocene surficial deposits are summarized in Table 1.1 and discussed below. The remainder of the quadrangle consists of Jurassic through Cretaceous igneous, sedimentary and metamorphic bedrock overlain by sedimentary rocks that range in age from Cretaceous to late Miocene. Refer to the earthquake-induced landslide portion, Section 2, of this report for further details on the bedrock.

Older alluvial channel and valley fill deposits of early to middle Pleistocene age (Qvoa) occur on ridges above the modern drainages and on the mesa-like Plano Trabuco. The remaining younger alluvial units consist of channel deposits (Qya), slopewash and colluvial debris (Qc), landslide debris, and artificial fill materials (af). Landslides are not shown on the generalized geologic map (Plate 1.1) but are specifically addressed in Section 2.

The late Pleistocene through Holocene channel deposits (Qya) include active wash and alluvial valley deposits. They occur within the Trabuco Canyon/Arroyo Trabuco drainage area, narrow canyons and in the downstream portions of smaller drainages. Colluvium, also known as slope wash, occurs in small drainages, upstream portions of major drainages, and along gentle to moderate slopes. This unit is gradational with other alluvial units. Colluvium ranges from late Pleistocene to Holocene. Artificial fill resulting from grading and construction activities is present within the study area. On Plate 1.1, however, only one area of artificial fill is shown due to the limits of the map scale.

Map Unit	Environment of Deposition	Age
Qvoa	channel/valley deposits	early to middle Pleistocene
Qya	channel/valley deposits	late Pleistocene and Holocene
Qc	Colluvium/ slopewash	late Pleistocene and Holocene

Table 1.1. Quaternary Units of the Southern California Areal Mapping Project (SCAMP) Nomenclature used in the Santiago Peak Quadrangle.

Structural Geology

The Santiago Peak Quadrangle lies within the foothills of the southern Santa Ana Mountains, which are part of the Peninsular Ranges geomorphic province of southern California. This province is cut by several large regional northwest-trending faults. The study area lies within a block bound on the northeast by the Elsinore Fault and on the southwest by the offshore extension of the Newport-Inglewood Fault. Exposed in the area within the regional fault zone is a sequence of mostly west-dipping strata of Jurassic, Cretaceous, and Tertiary age. Relatively thin, flat-lying Quaternary terrace deposits occur adjacent to modern drainages, and as isolated remnants in upland areas. A more detailed discussion of the structural geology is presented in Section 2.

ENGINEERING GEOLOGY

CGS conducted a subsurface investigation of Quaternary sedimentary deposits in the Santiago Peak Quadrangle using borehole and trench logs from the files of the following agencies and organizations: Orange County Planning and Development; California Department of Transportation; California Department of Water Resources; Leighton and Associates; and Goffman, McCormick & Urban, Inc. The locations of the exploratory boreholes and trenches used in this investigation are shown on Plate 1.2.

Out of the approximately 100 logs that were collected and reviewed for this evaluation, data from 60 logs were entered into the CGS's GIS. This database allowed effective examination of subsurface geology through the construction of software-generated cross sections. Staff examined the nature and distribution of various depositional units in the subsurface, correlated soil types where feasible, extrapolated geotechnical data into outlying areas containing similar soils, and evaluated historical ground-water depths.

Eleven of the 60 logs evaluated contained Standard Penetration Test (SPT) results or normalized SPT results that provided information on the density, or compactness of Quaternary sedimentary layers penetrated by the borehole. This test, along with the results of other engineering tests (dry density, moisture content, sieve analysis, etc.) are used in the Seed-Idriss Simplified Procedure (Seed and Idriss, 1971) to evaluate liquefaction potential of a site (see Part II - Quantitative Liquefaction Analysis). The results of the liquefaction analysis performed on the geotechnical data were posted onto the cross sections and aided in the overall three-dimensional evaluation of the Quaternary deposits.

Standard Penetration Tests (SPTs) provide a standardized measure of the penetration resistance of geologic deposits and are commonly used as an index of soil density. This in-field test consists of counting the number of blows required to drive a split-spoon sampler (1.375-inch inside diameter) one foot into the soil at the bottom of a borehole at chosen intervals while drilling. The driving force is provided by dropping a 140-pound hammer weight 30 inches. The SPT method is formally defined and specified by the American Society for Testing and Materials in test method D1586 (ASTM, 1999). Recorded blow counts for non-SPT geotechnical sampling where the sampler diameter, hammer weight or drop distance differ from those specified for an SPT (ASTM D1586), are converted to SPT-equivalent blow counts. The actual and converted SPT blow counts are normalized to a common-reference, effective-overburden pressure of one atmosphere (approximately one ton per square foot) and a hammer efficiency of 60% using a method described by Seed and Idriss (1982) and Seed and others (1985). This normalized blow count is referred to as $(N_1)_{60}$.

It is important to note that the Seed-Idriss Simplified Procedure was developed primarily for clean sand and silty sand, and results depend greatly on accurate measurement of in-situ soil density. However, the cross sections generated in this study show that some of the young Quaternary alluvial deposits contain a significant amount of gravel. In the past, gravelly soils were considered not to be susceptible to liquefaction because the high permeability of these soils presumably would allow the dissipation of pore pressures before liquefaction could occur. However, liquefaction in gravelly soils has been observed during earthquakes, and recent laboratory studies have shown that gravelly soils are susceptible to liquefaction (Ishihara, 1985; Harder and Seed, 1986; Budiman and Mohammadi, 1995; Evans and Zhou, 1995; and Sy and others, 1995).

SPT-derived density measurements in gravelly soils are unreliable and generally too high. They are likely to lead to overestimation of the density of the soil and, therefore, result in an underestimation of the liquefaction susceptibility. To identify potentially liquefiable units where the N values appear to have been affected by gravel content, correlations are made with boreholes in the same unit where the N (blow count) values do not appear to be affected by gravel.

GROUND-WATER CONDITIONS

Liquefaction hazard may exist in areas where depth to ground water is 40 feet or less. This is because saturated conditions in near-surface sediments reduce the effective normal stress thereby increasing the likelihood of earthquake-induced liquefaction (Youd, 1973). CGS liquefaction evaluations incorporate the historically highest known ground-water levels since depth to ground water during an earthquake cannot be anticipated because of the unpredictable fluctuations caused by natural processes and human activities. Thus, CGS develops a hypothetical ground-water table map within alluviated areas based on the estimated shallowest depths that have occurred during historic time. These maps differ from conventional ground-water contour maps that show the measured water table for a particular year or season.

The ground-water evaluation of the Santiago Peak Quadrangle was based on first-encountered water noted in geotechnical borehole and water well logs. Sources for this information include those mentioned in the previous section for boreholes and trenches, as well as information provided by the Trabuco Canyon Water District, Santa Margarita Water District, and City of San Juan Capistrano for ground-water information within the Arroyo Trabuco. The depths to first-encountered water, free of piezometric influences, were evaluated by CGS to develop a map of the project area showing depths to historically shallowest ground water (Plate 1.2).

Borehole, trench and water-well data collected for this study indicate measured water levels in alluviated canyon areas that range from a few feet to more than 40 feet below the ground surface. A hydrograph from a water well near the confluence of Arroyo Trabuco and Hickey Canyon shows water as shallow as 4 feet with seasonal variations of 15 to 20 feet over a 17 year period (DWR, 1972). Due to limited records in the other canyon areas, historically high ground water was assumed to be from 0 to 10 feet based upon expected seasonal influences. Within the very old alluvium in the Trabuco Plano area the shallowest water encountered was at depths of 18 to 26 feet.

PART II

LIQUEFACTION POTENTIAL

Liquefaction may occur in water-saturated sediment during moderate to great earthquakes. Liquefied sediment loses strength and may fail, causing damage to buildings, bridges, and other structures. Many methods for mapping liquefaction hazard have been proposed. Youd (1991) highlights the principal developments and notes some of the widely used criteria. Youd and Perkins (1978) demonstrate the use of geologic criteria as a qualitative characterization of liquefaction susceptibility and introduce the mapping technique of combining a liquefaction susceptibility map and a liquefaction opportunity map to produce a liquefaction potential map. Liquefaction susceptibility is a function of the capacity of sediment to resist liquefaction. Liquefaction opportunity is a function of the potential seismic ground shaking intensity.

The method applied in this study for evaluating liquefaction potential is similar to that of Tinsley and others (1985). Tinsley and others (1985) applied a combination of the techniques used by Seed and others (1983) and Youd and Perkins (1978) for their mapping of liquefaction hazards in the Los Angeles region. CGS's method combines geotechnical analyses, geologic and hydrologic mapping, and probabilistic earthquake shaking estimates, but follows criteria adopted by the SMGB (DOC, 2000).

LIQUEFACTION SUSCEPTIBILITY

Liquefaction susceptibility reflects the relative resistance of a soil to loss of strength when subjected to ground shaking. Physical properties of soil such as sediment grain-size distribution, compaction, cementation, saturation, and depth govern the degree of resistance to liquefaction. Some of these properties can be correlated to a sediment's geologic age and environment of deposition. With increasing age, relative density may increase through cementation of the particles or compaction caused by the weight of the overlying sediment.

Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is treated as liquefiable in this investigation. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may be vulnerable to strength loss with remolding and represent a hazard that is not addressed in this investigation. Soil characteristics and processes that result in higher measured penetration resistances generally indicate lower liquefaction susceptibility. Thus, blow count and cone penetrometer values are useful indicators of liquefaction susceptibility.

Saturation is required for liquefaction, and the liquefaction susceptibility of a soil varies with the depth to ground water. Very shallow ground water increases the susceptibility to liquefaction (soil is more likely to liquefy). Soils that lack resistance (susceptible soils) typically are saturated, loose and sandy. Soils resistant to liquefaction include all soil types that are dry, cohesive, or sufficiently dense.

CGS's map inventory of areas containing soils susceptible to liquefaction begins with evaluation of geologic maps and historical occurrences, cross-sections, geotechnical test data, geomorphology, and ground-water hydrology. Soil properties and soil conditions such as type, age, texture, color, and consistency, along with historical depths to ground water are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on similar soil observations, liquefaction susceptibility maps typically are similar to Quaternary geologic maps. CGS's qualitative relations between geologic map unit and susceptibility are summarized in Table 1.2.

Discussion of Map Units

Most Holocene materials where water levels are within 30 feet of the ground surface have susceptibility assignments of high to very high. Although some Holocene units may be fine grained, many contain lenses of material with higher liquefaction susceptibility. Within the Santiago Peak Quadrangle the young channel/alluvial valley deposits (Qya) are considered highly susceptible. Borehole and trench logs for these materials generally record intervals of clean-sorted sands with intervals of gravelly, silty and clayey sand, silt and clay. Materials are generally loose to medium dense as recorded in both descriptions and blow-count data.

Colluvium (Qc) is extensive throughout the Santiago Peak Quadrangle. However, for this study only the colluvial units mapped in canyon bottoms and swales were considered for liquefaction evaluation. Borehole and trench logs collected show that the colluvium within these areas is laterally and vertically transitional with, and sometimes indistinguishable from, Qya deposits.

Compositionally, colluvium is highly variable and reflects adjacent bedrock sources. Within the Santiago Peak Quadrangle, borehole logs within colluvium encountered loose to medium dense gravel, sand, silt and clay. Liquefaction susceptibility for this unit is low to high.

In the Santiago Peak Quadrangle the very old channel/alluvial valley deposits (Qvoa) are generally considered not susceptible to liquefaction due largely to age-related processes that act to densify the materials. Logs penetrating this unit record materials consisting of dense to weakly cemented, clayey sand, silt, and gravel.

Subsurface data were not collected for any fill units. Artificial fill areas consist of engineered fill for residential and commercial sites. Since these fills are generally considered to be properly engineered, zoning for liquefaction susceptibility in such areas depends on soil conditions in underlying strata.

Geologic Map Unit	Sediment Type	Consistency	Age	Susceptible to Liquefaction?*
Qvoa	Gravel, sand, silt, clay	Weakly cemented	early to middle Pleistocene	no
Qya	Gravel, sand, silt, clay	Loose to medium dense	late Pleistocene and Holocene	yes
Qc	Gravel, sand, silt, clay	Loose to medium dense	late Pleistocene and Holocene	yes

Table 1.2. Quaternary Map Units used in Santiago Peak 7.5-Minute Quadrangle and Their Geotechnical Characteristics and Liquefaction Susceptibility (*when saturated).

LIQUEFACTION OPPORTUNITY

Liquefaction opportunity is a measure, expressed in probabilistic terms, of the potential for strong ground shaking. Analyses of in-situ liquefaction resistance require assessment of liquefaction opportunity. The minimum level of seismic excitation to be used for such purposes is the level of peak ground acceleration (PGA) with a 10% probability of exceedance over a 50-year period (DOC, 2000). The earthquake magnitude used in CGS's analysis is the magnitude that contributes most to the calculated PGA for an area.

For the Santiago Peak Quadrangle, PGAs of 0.33 to 0.45g, resulting from an earthquake of magnitude 6.8 were used for liquefaction analyses. The PGA and magnitude values were based on de-aggregation of the probabilistic hazard at the 10% in 50-year hazard level (Petersen and others, 1996; Cramer and Petersen, 1996). See the ground motion portion (section 3) of this report for further details.

Quantitative Liquefaction Analysis

CGS performs quantitative analysis of geotechnical data to evaluate liquefaction potential using the Seed-Idriss Simplified Procedure (Seed and Idriss, 1971; Seed and others, 1983; National Research Council, 1985; Seed and others, 1985; Seed and Harder, 1990; Youd and Idriss, 1997). Using the Seed-Idriss Simplified Procedure one can calculate soil resistance to liquefaction, expressed in terms of cyclic resistance ratio (CRR), based on SPT results, ground-water level, soil density, moisture content, soil type, and sample depth. CRR values are then compared to calculated earthquake-generated shear stresses expressed in terms of cyclic stress ratio (CSR).

The Seed-Idriss Simplified Procedure requires normalizing earthquake loading relative to a M7.5 event for the liquefaction analysis. To accomplish this, CGS's analysis uses the Idriss magnitude-scaling factor (MSF) (Youd and Idriss, 1997). It is convenient to think in terms of a factor of safety (FS) relative to liquefaction, where: FS = (CRR / CSR) * MSF. FS, therefore, is a quantitative measure of liquefaction potential. CGS uses a factor of safety of 1.0 or less, where CSR equals or exceeds CRR, to indicate the presence of potentially liquefiable soil. While an FS of 1.0 is considered the "trigger" for liquefaction, for a site specific analysis an FS of as much as 1.5 may be appropriate depending on the vulnerability of the site and related structures.

The CGS liquefaction analysis program calculates an FS for each geotechnical sample where blow counts were collected. Typically, multiple samples are collected for each borehole. The program then independently calculates an FS for each non-clay layer that includes at least one penetration test using the minimum $(N1)_{60}$ value for that layer. The minimum FS value of the layers penetrated by the borehole is used to determine the liquefaction potential for each borehole location. The reliability of FS values varies according to the quality of the geotechnical data. FS, as well as other considerations such as slope, presence of free faces, and thickness and depth of potentially liquefiable soil, are evaluated in order to construct liquefaction potential maps, which are then used to make a map showing zones of required investigation.

Of the 100 geotechnical borehole logs reviewed in this study, 60 were entered into the database (Plate 1.2), and among these, 11 include blow-count data from SPTs or from penetration tests that allow reasonable blow count translations to SPT-equivalent values. Non-SPT values, such as those resulting from the use of 2-inch or 2½-inch inside-diameter ring samplers, were translated to SPT-equivalent values if reasonable factors could be used in conversion calculations. The reliability of the SPT-equivalent values varies. Therefore, they are weighted and used in a more qualitative manner. Few borehole logs, however, include all of the information (e.g. soil density, moisture content, sieve analysis, etc.) required for an ideal Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed using recorded density, moisture, and sieve test values or using averaged test values of similar materials.

LIQUEFACTION ZONES

Criteria for Zoning

Areas underlain by materials susceptible to liquefaction during an earthquake were included in liquefaction zones using criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (DOC, 2000). Under those guideline criteria, liquefaction zones are areas meeting one or more of the following:

1. Areas known to have experienced liquefaction during historical earthquakes

2. All areas of uncompacted artificial fill containing liquefaction-susceptible material that are saturated, nearly saturated, or may be expected to become saturated

3. Areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable

4. Areas where existing geotechnical data are insufficient

In areas of limited or no geotechnical data, susceptibility zones may be identified by geologic criteria as follows:

a) Areas containing soil deposits of late Holocene age (current river channels and their historic floodplains, marshes and estuaries), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.10 g and the water table is less than 40 feet below the ground surface; or

b) Areas containing soil deposits of Holocene age (less than 11,000 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.20 g and the historical high water table is less than or equal to 30 feet below the ground surface; or

c) Areas containing soil deposits of latest Pleistocene age (11,000 to 15,000 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.30 g and the historical high water table is less than or equal to 20 feet below the ground surface.

Application of SMGB criteria to liquefaction zoning in the Santiago Peak Quadrangle is summarized below.

Areas of Past Liquefaction

In the Santiago Peak Quadrangle, no areas of documented historical liquefaction are known. Areas showing evidence of paleoseismic liquefaction have not been reported.

Artificial Fills

In the Santiago Peak Quadrangle, an artificial fill area large enough to show at the scale of mapping consists of engineered fill for a graded residential/commercial site. Since the fill is considered to be properly engineered, zoning for liquefaction was dependent on soil conditions in the underlying strata. Non-engineered fills are commonly loose, uncompacted and the material varies in size and type.

Areas with Sufficient Existing Geotechnical Data

Borehole logs that include penetration test data and sufficiently detailed lithologic descriptions were used to evaluate liquefaction potential. Areas with sufficient geotechnical data were evaluated for zoning based on the liquefaction potential determined by the Seed-Idriss Simplified Procedure. In Holocene alluvial deposits, most of the borehole logs that were analyzed using the Seed-Idriss Simplified Procedure contain sediment layers that may liquefy under the expected earthquake loading. Areas containing saturated potentially liquefiable material (Table 1.2) are included in the zone. These areas include portions of Arroyo Trabuco, Canada Gobernadora, Tijeras Canyon, Live Oak Canyon, Modjeska Canyon, Harding Canyon, Bell Canyon and the Oso Creek drainage area.

Areas with Insufficient Existing Geotechnical Data

Younger alluvium deposited in tributary canyon areas generally lacks adequate geotechnical borehole information. The soil characteristics and ground-water conditions within these deposits are assumed to be similar to deposits where subsurface information is available. Stream channel deposits in the Santiago Peak Quadrangle, therefore, are zoned for liquefaction for reasons presented in criteria item 4a above.

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REFERENCES

American Society for Testing and Materials, 1999, Standard test method for penetration test and split-barrel sampling of soils, Test Method D1586-99, *in* Annual Book of ASTM Standards, v. 4.08.

Budiman, J.S. and Mohammadi, Jamshid, 1995, Effect of large inclusions on liquefaction of sands, *in* Evans, M.D. and Fragaszy, R.J., *editors*, Static and Dynamic properties of Gravelly Soils: American Society of Civil Engineers Geotechnical Special Publication no. 56, p. 48-63.

California Department of Conservation, Division of Mines and Geology, 1997, Guidelines for evaluating and mitigating seismic hazards in California, Special Publication 117, 74 p.

California Department of Conservation, Division of Mines and Geology, 2000, Recommended criteria for delineating seismic hazard zones in California, Special Publication 118, 12 p.

California Department of Water Resources, 1972, Planned utilization of water resources in the San Juan Creek Basin area: Bulletin no. 104-7, p 52.

Cramer, C.H. and Petersen, M.D., 1996, Predominant seismic source distance and magnitude maps for Los Angeles, Orange, and Ventura counties, California: Bulletin of Seismological Society of America, v. 86, no. 5, p. 1,645-1,649.

Evans, M.D. and Zhou, Shengping, 1995, Liquefaction behavior of sand-gravel composites: American Society of Civil Engineers, Journal of Geotechnical Engineering, v. 121, no. 3, p. 287-298.

Harder, L.F. and Seed, H.B., 1986, Determination of penetration resistance for coarse-grained soils using the Becker hammer drill: University of California at Berkeley, College of Engineering, Earthquake Engineering Research Center, report no. UCB/EERC-86/06, 126 p.

Ishihara, Kenji, 1985, Stability of natural deposits during earthquakes, *in* Proceedings of the Eleventh International Conference on Soil Mechanics and Foundation Engineering, San Francisco, v. 1, p. 321-376.

Miller, R.V. and Morton, P.K., 1984, Engineering geology of part of the western half of the Santiago Peak Quadrangle, Orange County, California: California Division of Mines and Geology Open-File Report 84-58, 62 p., map scale 1:12,000.

Morton, D.M. and Kennedy, M.P., 1989, A southern California digital 1:100,000-scale geologic map series: The Santa Ana Quadrangle, The first release: Geological Society of America Abstracts with Programs v. 21, no. 6, p. A107-A108.

National Research Council, 1985, Liquefaction of soils during earthquakes: National Research Council Special Publication, Committee on Earthquake Engineering, National Academy Press, Washington, D.C., 240 p.

Petersen, M.D., Bryant, W.A., Cramer, C.H., Cao, Tianqing, Reichle, M.S., Frankel, A.D., Lienkaemper, J.J., McCrory, P.A. and Schwartz, D.P., 1996, Probabilistic seismic hazard assessment for the State of California: California Department of Conservation, Division of Mines and Geology, Open-File Report 96-08; also U.S. Geological Survey Open-File Report 96-706, 33 p.

Seed, H.B. and Idriss, I.M., 1971, Simplified procedure for evaluating soil liquefaction potential: Journal of the Soil Mechanics and Foundations Division of ASCE, v. 97: SM9, p. 1,249-1,273.

Seed, H.B. and Idriss, I.M., 1982, Ground motions and soil liquefaction during earthquakes: Monograph Series, Earthquake Engineering Research Institute, Berkeley, California, 134 p.

Seed, H.B., Idriss, I.M. and Arango, Ignacio, 1983, Evaluation of liquefaction potential using field performance data: Journal of Geotechnical Engineering, v. 109, no. 3, p. 458-482.

Seed, H.B., Tokimatsu, Kohji, Harder, L.F. and Chung, R.M., 1985, Influence of SPT procedures in soil liquefaction resistance evaluations: Journal of Geotechnical Engineering, ASCE, v. 111, no. 12, p. 1,425-1,445.

Seed, R.B. and Harder, L.F., 1990, SPT-based analysis of cyclic pore pressure generation and undrained residual strength: Proceedings of the H. Bolton Seed Memorial Symposium, v. 2, p. 351-376.

Smith, T.C., 1996, Preliminary maps of seismic hazard zones and draft guidelines for evaluating and mitigating seismic hazards: California Geology, v. 49, no. 6, p. 147-150.

Southern California Earthquake Center, 1999, Recommended procedures for implementation of DMG Special Publication 117 guidelines for analyzing and mitigating liquefaction in California: Southern California Earthquake Center, University of Southern California, 63 p.

Sy, Alex, Campanella, R.G. and Stewart, R.A., 1995, BPT-SPT correlations for evaluations of liquefaction resistance in gravelly soils, *in* Evans, M.D. and Fragaszy, R.J., *editors*, Static and Dynamic Properties of Gravelly Soils: American Society of Civil Engineers Geotechnical Special Publication no. 56, p. 1-19.

Tinsley, J.C., Youd, T.L., Perkins, D.M. and Chen, A.T.F., 1985, Evaluating liquefaction potential, *in* Ziony, J.I., *editor*, Evaluating earthquake hazards in the Los Angeles region — An earth science perspective: U.S. Geological Survey Professional Paper 1360, p. 263-316.

Youd, T.L., 1973, Liquefaction, flow and associated ground failure: U.S. Geological Survey Circular 688, 12 p.

Youd, T.L., 1991, Mapping of earthquake-induced liquefaction for seismic zonation: Earthquake Engineering Research Institute, Proceedings, Fourth International Conference on Seismic Zonation, v. 1, p. 111-138.

Youd, T.L. and Idriss, I.M., 1997, *editors*, Proceedings of the NCEER workshop on evaluation of liquefaction resistance of soils: National Center for Earthquake Engineering Research Technical Report NCEER-97-0022, 276 p.

Youd, T.L. and Perkins, D.M., 1978, Mapping liquefaction-induced ground failure potential: Journal of Geotechnical Engineering, v. 104, p. 433-446.

SECTION 2
EARTHQUAKE-INDUCED LANDSLIDE EVALUATION REPORT

Earthquake-Induced Landslide Zones in the Santiago Peak 7.5-Minute Quadrangle, Orange County, California

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PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use seismic hazard zone maps prepared by CGS in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (DOC, 1997). The text of this report is on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

Following the release of DMG Special Publication 117 (DOC, 1997), agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing landslide hazards. The agencies made their request through the Geotechnical Engineering Group of the Los Angeles Section of the American Society of Civil Engineers (ASCE). This group convened an implementation committee in 1998 under the auspices of the Southern California Earthquake Center (SCEC). The committee, which consisted of practicing geotechnical engineers and engineering geologists, released an overview of the practice of landslide analysis, evaluation, and mitigation techniques (SCEC, 2002). This text is also on the Internet at: http://www.scec.org/

This section of the evaluation report summarizes seismic hazard zone mapping for earthquake-induced landslides in the Santiago Peak 7.5-minute Quadrangle. Section 1 (addressing liquefaction) and Section 3 (addressing earthquake shaking), complete the report, which is one of a series that summarizes the preparation of seismic hazard zone maps within the state (Smith, 1996). Additional information on seismic hazard zone mapping in California can be accessed on CGS's Internet web page: http://www.conservation.ca.gov/CGS/index.htm

BACKGROUND

Landslides triggered by earthquakes historically have been a significant cause of earthquake damage. In California, large earthquakes such as the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes triggered landslides that were responsible for destroying or damaging numerous structures, blocking major transportation corridors, and damaging life-line infrastructure. Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks, areas underlain by loose, weak soils, and areas on or adjacent to existing landslide deposits. These geologic and terrain conditions exist in many parts of California, including numerous hillside areas that have already been developed or are likely to be developed in the future. The opportunity for strong earthquake ground shaking is high in many parts of California because of the presence of numerous active faults. The combination of these factors constitutes a significant seismic hazard throughout much of California, including the hillside areas of the Santiago Peak Quadrangle.

METHODS SUMMARY

The mapping of earthquake-induced landslide hazard zones presented in this report is based on the best available terrain, geologic, geotechnical, and seismological data. If unavailable or significantly outdated, new forms of these data were compiled or generated specifically for this project. The following were collected or generated for this evaluation:

- Digital terrain data were used to provide an up-to-date representation of slope gradient and slope aspect in the study area

- Geologic mapping was used to provide an accurate representation of the spatial distribution of geologic materials in the study area. In addition, a map of existing landslides, whether triggered by earthquakes or not, was prepared

- Geotechnical laboratory test data were collected and statistically analyzed to quantitatively characterize the strength properties and dynamic slope stability of geologic materials in the study area

- Seismological data in the form of CGS probabilistic shaking maps and catalogs of strong-motion records were used to characterize future earthquake shaking within the mapped area

The data collected for this evaluation were processed into a series of GIS layers using commercially available software. A slope stability analysis was performed using the Newmark method of analysis (Newmark, 1965), resulting in a map of landslide hazard potential. The earthquake-induced landslide hazard zone was derived from the landslide hazard potential map according to criteria developed in a CGS pilot study (McCrink and Real, 1996; McCrink, 2001) and adopted by the State Mining and Geology Board (DOC, 2000).

SCOPE AND LIMITATIONS

The methodology used to make this map is based on earthquake ground-shaking estimates, geologic material-strength characteristics and slope gradient. These data are gathered from a variety of outside sources. Although the selection of data used in this evaluation was rigorous, the quality of the data is variable. The State of California and the Department of Conservation make no representations or warranties regarding the accuracy of the data gathered from outside sources.

Earthquake-induced landslide zone maps are intended to prompt more detailed, site-specific geotechnical investigations as required by the Act. As such, these zone maps identify areas where the potential for earthquake-induced landslides is relatively high. Due to limitations in methodology, it should be noted that these zone maps do not necessarily capture all potential earthquake-induced landslide hazards. Earthquake-induced ground failures that are not addressed by this map include those associated with ridge-top spreading and shattered ridges. It should also be noted that no attempt has been made to map potential run-out areas of triggered landslides. It is possible that such run-out areas may extend beyond the zone boundaries. The potential for ground failure resulting from liquefaction-induced lateral spreading of alluvial materials, considered by some to be a form of landsliding, is not specifically addressed by the earthquake-induced landslide zone or this report. See Section 1, Liquefaction Evaluation Report for the Santiago Peak Quadrangle, for more information on the delineation of liquefaction zones.

The remainder of this report describes in more detail the mapping data and processes used to prepare the earthquake-induced landslide zone map for the Santiago Peak Quadrangle. The information is presented in two parts. Part I covers physiographic, geologic and engineering geologic conditions in the study area. Part II covers the preparation of landslide hazard potential and landslide zone maps.

PART I

PHYSIOGRAPHY

Study Area Location And Physiography

The Santiago Peak Quadrangle covers an area of about 60 square miles in easternmost Orange County. Most of the land in the quadrangle lies within the Cleveland National Forest. In the southwestern quarter, however, residential development is underway in the unincorporated communities of Rancho Santa Margarita, Coto de Caza, and Dove Canyon adjacent to narrow strips of the O'Neill Regional Park in Plano Trabuco and Tijeras Canyon. Only about 27 square miles of the quadrangle have been evaluated because that is the area subject to development.

The study area lies on the western slope of the Santa Ana Mountains in the Peninsular Ranges geomorphic province of southern California. Rugged, deeply dissected terrain characterizes the topography in the quadrangle. The highest point in the quadrangle is Santiago Peak, at 5,687 feet. The lowest point is less than 800 feet above sea level in the southwestern corner in Plano Trabuco. The major drainage courses in the quadrangle include Trabuco Canyon and Arroyo Trabuco, which together cross the entire quadrangle, Silverado Canyon, and Santiago Canyon. The gently sloping to nearly level land of Plano Trabuco, incised by Arroyo Trabuco within O'Neill Regional Park, contrasts with the surrounding brush-covered mountains.

Access to the Santiago Peak Quadrangle is provided by roads that intersect the Foothill Transportation Corridor (State Highway 241) just west of the quadrangle. The primary access is via county road S19 (Live Oak Canyon Road/ Trabuco Canyon Road/ Plano Trabuco Road) and Santa Margarita Parkway, which services the Rancho Santa Margarita development south of Plano Trabuco. Numerous canyon-bottom roads connect with unpaved motorways and truck trails that provide access to parts of the national forest. Development in the quadrangle is restricted to scattered clusters of residences in Silverado Canyon, Modjeska in Santiago Canyon, and the rapidly developing area south of Plano Trabuco.

Digital Terrain Data

The calculation of slope gradient is an essential part of the evaluation of slope stability under earthquake conditions. To calculate slope gradient for the terrain within the Santiago Peak Quadrangle, a Level 2 digital elevation model (DEM) was obtained from the USGS (U.S. Geological Survey, 1993). This DEM, which was prepared from the 7.5-minute quadrangle topographic contours, based on 1954 topography, has a 10-meter horizontal resolution and a 7.5-meter vertical accuracy.

Areas that have undergone large-scale grading in the hilly portions of the quadrangle since 1954 were updated to reflect the new topography. A DEM reflecting this recent grading was obtained from an airborne interferometric radar platform flown in 1998, with an estimated vertical accuracy of approximately two meters (Intermap Corporation). An interferometric radar DEM is prone to creating false topography where tall buildings, metal structures, or trees are present. Due to the low lying chaparral vegetation and relatively small-structure/residential construction types present, this type of DEM is appropriate for use in the Santiago Peak Quadrangle. Nevertheless, the final hazard zone map was checked for potential errors of this sort and corrected. Graded areas where the radar DEM was applied are shown on Plate 2.1.

A slope map was made from the DEM using a third-order, finite difference, center-weighted algorithm (Horn, 1981). The DEM was also used to make a slope aspect map. The manner in which the slope and aspect maps were used to prepare the zone map will be described in subsequent sections of this report.

GEOLOGIC CONDITIONS

Bedrock and Surficial Geology

The geologic map for the Santiago Peak Quadrangle was digitized by the Southern California Areal Mapping Project [SCAMP] (Morton and Kennedy, 1989) from 1:12,000-scale mapping (Miller and Morton, 1984). The mapping was modified during this project to reflect field observations and the most recent mapping in the area. In the field, observations were made of exposures, aspects of weathering, and general surface expression of the geologic units. In addition, the relation of the various geologic units to development and abundance of slope failures was noted. The geologic unit descriptions below are taken from Miller and Morton (1984). The U.S. Geological Survey (Schoellhamer and others, 1981) also described the geologic units in the northern Santa Ana Mountains. The Quaternary geologic map of the Santiago Peak Quadrangle is reproduced as Plate 1.1.

The oldest rocks exposed in the Santiago Peak Quadrangle belong to the Middle Jurassic Bedford Canyon Formation (Jbc). This formation consists of slightly metamorphosed thin-bedded shale, thin to moderately thick, interbedded sandstone and shale of possible turbidite origin, and thick-bedded sandstone and conglomerate. Bedford Canyon Formation underlies the elevated terrain in the eastern part of the map area and much of the northern Santa Ana Mountains. The Santiago Peak Volcanics of Upper Jurassic and Lower Cretaceous age rest unconformably upon Bedford Canyon Formation rocks at many places within the quadrangle, especially around Santiago Peak, for which the unit is named. Santiago Peak Volcanics (Jsp, Kvsp) consist of a mixture of slightly metamorphosed, andesitic and dacitic, volcanic flows, flow breccia, tuff, volcanic sedimentary rocks and local intrusive bodies (Jspi, Kvspi).

A westward-thickening sequence of Upper Cretaceous and Tertiary sedimentary units covers the Bedford Canyon Formation and Santiago Peak Volcanics in the western part of the quadrangle. The oldest of these units is the Trabuco Formation (Kt, Ktr) of Late Cretaceous age. It consists of a deeply weathered reddish upper member (Ktu) and a grayish lower member (Ktl), both of which are bouldery nonmarine fanglomerates.

Within the map area the Upper Cretaceous Ladd Formation consists of the conglomeratic Baker Canyon Member (Klb, Klbc), with interlayered shale (Klb-sh) or sandstone (Klb-s) beds, and the Holz Shale Member (Klh, Klhs), with interbedded sandstone and conglomerate (Klh-sc).

The Williams Formation, also of Late Cretaceous age, rests on top of the Ladd Formation. The Williams Formation contains three members: the Starr Member (Kwst) nonmarine conglomerate; the Schulz Ranch Member (Kws, Kwsr) marine (?) sandstone and conglomerate; and the Pleasants Sandstone Member (Kwp, Kwps) marine silty sandstone.

The oldest Tertiary unit, the Silverado Formation (Tsi) of Paleocene age, consists of predominantly nonmarine arkosic sandstone, multi-colored kaolinitic clay beds (Tsi-c) and a basal conglomerate (Tsi-cg).

Resting conformably upon the Silverado Formation is the Santiago Formation (Tsa) of Eocene age, which consists of sandstone and siltstone. Poorly bedded, multi-hued nonmarine silty sandstone, sandstone and conglomerate (Ts-cg) of the Sespe Formation (Ts) of Oligocene age overlies the Santiago Formation. It is widespread on both sides of Plano Trabuco.

The return to marine conditions following the deposition of the Sespe Formation resulted in the deposition of a variety of shales, siltstones, sandstones, and pebbly sandstones. These marine deposits comprise the Vaqueros Formation (Tv) of Oligocene to early Miocene age, the Topanga Formation (Tt) of middle Miocene age, and the Monterey Formation (Tm) of middle to late Miocene age. In some areas it is difficult to distinguish Vaqueros Formation from Sespe Formation due to their lithologic and textural similarities. In those areas Miller and Morton (1984) used the map symbol Tvs.

Quaternary surficial deposits are scattered across parts of the quadrangle, especially in places that are elevated above the modern drainage courses. Old (Pleistocene) stream terrace deposits (Qtr, Qvoaga) occur on ridge tops north and south of Plano Trabuco. Within mesa-like Plano Trabuco itself stream terrace deposits have been designated as Qtr1 (oldest) through Qtr4 (youngest) to indicate their relative position above the modern drainage level. Other older Quaternary deposits include very old alluvial valley deposits (Qvoaa, Qvoaar) and very old alluvial fan deposits (Qvofa).

Other surficial deposits include general alluvium (Qal), slopewash (Qsw), young alluvial valley deposits (Qya, Qyaa, Qyaga), young alluvial fan deposits (Qyfa), active stream wash (Qywg, Qw), colluvium (Qc), and landslide deposits (Qls, Qyls). Landslides are widely distributed in the area. They are especially abundant west of Live Oak Canyon, north of Plano Trabuco, in areas underlain by Vaqueros Formation bedrock. Landslides are discussed in more detail in a following section of this report.

Structural Geology

The structural framework of Orange County is one that reflects a broad regional crustal shortening from a southwest to northeast direction. Southern Orange County is bounded on the northeast by the Elsinore fault and on the south by the offshore Newport-Inglewood fault. Exposed in the area between the two northwest trending right-lateral strike-slip faults are a homoclinal sequence of mostly westerly dipping rocks of Jurassic, Cretaceous, and Tertiary age. The western margin of the homocline is gently warped into a north-trending broad syncline, comprised primarily of Tertiary age sedimentary bedrock, generally referred to as the Capistrano syncline, which occurs to the west of the Santiago Peak Quadrangle.

Structures within the quadrangle include a number of north- to northwest-trending faults that dip steeply to the west and appear to have normal displacements; one of those faults, the Mission Viejo fault, has a normal displacement on the order of 1000-feet (Miller and Morton, 1984). These faults interrupt the homoclinal sequence of Cretaceous to Tertiary sedimentary rocks that are superadjacent to the metamorphic and igneous rocks of the Upper Cretaceous and Jurassic.

Landslide Inventory

As a part of the geologic data compilation, an inventory of existing landslides in the Santiago Peak Quadrangle was prepared by field reconnaissance, analysis of stereo-paired aerial photographs and a review of previously published landslide mapping (Miller and Morton, 1984). Landslides were mapped at a scale of 1:24,000. For each landslide included on the map a number of characteristics (attributes) were compiled. These characteristics include the confidence of interpretation (definite, probable and questionable) and other properties, such as activity, thickness, and associated geologic unit(s). Landslides rated as definite and probable were carried into the slope stability analysis. Landslides rated as questionable were not carried into the slope stability analysis due to the uncertainty of their existence. The completed landslide map was scanned, digitized, and the attributes were compiled in a database. A version of this landslide inventory is included with Plate 2.1.

The area mapped for landslides within the Santiago Peak Quadrangle consists of two separate portions of the quadrangle. The smaller of the two is an area of about three square miles along Silverado Canyon in the northwest corner of the quadrangle. The Bedford Canyon Formation (Jbc) and the Santiago Peak Volcanics (Jsp, Kvsp) underlie this area and these units support very steep slopes bordering deeply incised drainages. Four large rock slides are included in the landslide inventory for this area. Miller and Morton (1984) mapped most of these, and several additional landslides that they considered questionable. These questionable landslides were not readily identifiable and consequently were not included in this inventory.

Rock falls, debris flows and debris slides are common modes of slope failure in Silverado Canyon, but are often difficult to identify due to typically narrow debris tracks and a thick vegetative cover that appears to regenerate rather quickly. The track of a debris flow that killed five people at the Silverado Canyon fire station in 1969 is not discernable on the 1970 air photos used for this study, and without knowledge of this event, would not be readily identified in the field. Two large debris slides, visible on both the 1970 and 1998 air photos, are present in Pine Canyon near the eastern margin of the mapped area.

The second area mapped in the Santiago Peak Quadrangle comprises the southwest quadrant of the quadrangle, plus Sections 28 and 33 of T5S, R7W, and a strip one-half mile wide that extends into National Forest lands on the north and east sides of the quadrant. Landslides of several types, ranging in size from small to very large, are distributed throughout the mapped area. The larger landslides are old rock slides, and they tend to be more common along the northern and eastern boundaries of the mapped area, in part due to the greater elevations and steeper slopes there. Nearly all of the large, deep landslides occur in the Santiago Peak Volcanics (Jsp, Kvsp), and the Ladd (Klh, Klhs, Klb, Klbc) and Vaqueros (Tv) formations.

Debris flows and debris slides were observed to be abundant throughout the mapped area on the 1970 air photos, particularly within the Sespe (Ts) and Silverado (Tsi) formations. Observations made from 1998 air photos and recent field reconnaissance indicate that many of these shallow slope failures have either re-vegetated or have been eliminated by grading for urban development. Others were not mapped due to their limited size and extent.

Landslides mapped for this inventory correspond reasonably well with those mapped earlier by Miller and Morton (1984). Many of the slides considered questionable by Miller and Morton were not included in this inventory, while others not shown on their map have been included. Landslide boundaries shown in this inventory are often somewhat different than the boundaries delineated by Miller and Morton because they mapped only the landslide deposit while the source area has been included in this inventory.

Because it is not within the scope of the Act to review and monitor grading practices to ensure past slope failures have been properly mitigated, all documented slope failures, whether or not their surface expression currently exists, are included in the landslide inventory. However, some landslides were removed from the inventory if it was determined from recent stereo aerial photographs that they were either completely covered or completely removed by grading activities, with no remaining slopes.

ENGINEERING GEOLOGY

Geologic Material Strength

To evaluate the stability of geologic materials under earthquake conditions, they first must be ranked based on their overall shear strength. Generally, the primary source for shear-strength measurements is geotechnical reports prepared by consultants on file with local government permitting departments. Shear strength data for the units identified on the geologic map were obtained from the Orange County Office of Planning and Development Services (see Appendix A). When available, shear tests from adjacent quadrangles were used to augment data for geologic formations that had little or no shear test information; these other quadrangles include the San Juan Capristrano, Canada

Gobernadora, El Toro, and Black Star Canyon quadrangles. The locations of rock and soil samples taken for shear testing in the Santiago Peak Quadrangle are shown on Plate 2.1.

Shear strength data gathered from the above sources were compiled for each geologic map unit. Geologic units were grouped on the basis of average angle of internal friction (average phi) and lithologic character. Average (mean and median) phi values for each geologic map unit and corresponding strength group are summarized in Table 2.1. For most of the geologic strength groups in the map area, a single shear strength value was assigned and used in our slope stability analysis. A geologic material strength map was made based on the groupings presented in Tables 2.1 and 2.2, and this map provides a spatial representation of material strength for use in the slope stability analysis.

Several geologic map units were subdivided further, as discussed below.

Adverse Bedding Conditions

Adverse bedding conditions are an important consideration in slope stability analyses. Adverse bedding conditions occur where the dip direction of bedded sedimentary rocks is roughly the same as the slope aspect, and where the dip magnitude is less than the slope gradient. Under these conditions, landslides can slip along bedding surfaces due to a lack of lateral support.

To account for adverse bedding in our slope stability evaluation, we used geologic structural data in combination with digital terrain data to identify areas with potentially adverse bedding, using methods similar to those of Brabb (1983). The structural data, derived from the geologic map database, was used to categorize areas of common bedding dip direction and magnitude. The dip direction was then compared to the slope aspect and, if the same, the dip magnitude and slope gradient categories were compared. If the dip magnitude category was less than or equal to the slope gradient category, but greater than 25% (4:1 slope), the area was marked as a potential adverse bedding area.

The formations that contain interbedded sandstone and shale were subdivided based on shear strength differences between coarse-grained (higher strength) and fine-grained (lower strength) lithologies. Shear strength values for the fine- and coarse-grained lithologies were then applied to areas of favorable and adverse bedding orientation, which were determined from structural and terrain data as discussed above. It was assumed that coarse-grained material strength dominates where bedding dips into a slope (favorable bedding) while fine-grained material strength dominates where bedding dips out of a slope (adverse bedding). The geologic material strength map was modified by assigning the lower, fine-grained shear strength values to areas where potential adverse bedding conditions were identified. The favorable and adverse bedding shear strength parameters for the formations are included in Table 2.1.

Adverse bedding conditions were considered for geologic units Kws, Kwst, Kwsr, Klh, Klhs, Kwp, Kwps, Ts, Tt, Tsi, Tsa, Tv, and Tvs. Adverse bedding conditions were not considered for Tm because it is predominantly fine-grained in texture (siltstone and shale). Over 90% of the test samples tallied for this formation, in quadrangles around the Santiago Peak Quadrangle, were of a fine-grained nature and, therefore, indicate relatively low shear strength values throughout this unit.

The results of the grouping of geologic materials in the Santiago Peak Quadrangle are in Tables 2.1 and 2.2.

Existing Landslides

As discussed later in this report, the criteria for landslide zone mapping state that all existing landslides that are mapped as definite or probable are automatically included in the landslide zone of required investigation. Therefore, an evaluation of shear strength parameters for existing landslides is not necessary for the preparation of the zone map. However, in the interest of completeness for the material strength map, to provide relevant material strength information to project plan reviewers, and to allow for future revisions of our zone mapping procedures, we have collected and compiled shear strength data considered representative of existing landslides within the quadrangle.

The strength characteristics of existing landslides (Qls) must be based on tests of the materials along the landslide slip surface. Ideally, shear tests of slip surfaces formed in each mapped geologic unit would be used. However, this amount of information is rarely available, and for the preparation of the earthquake-induced landslide zone map it has been assumed that all landslides within the quadrangle have the same slip surface strength parameters. We collect and use primarily “residual” strength parameters from laboratory tests of slip surface materials tested in direct shear or ring shear test equipment. Back-calculated strength parameters, if the calculations appear to have been performed appropriately, have also been used. Within the Santiago Peak Quadrangle, four direct shear tests of landslide slip surface materials were obtained, and the results are summarized in Table 2.1.

SANTIAGO PEAK QUADRANGLE
SHEAR STRENGTH GROUPS

	Formation Name	Number Tests	Mean/Median Phi (deg)	Mean/Median Group Phi (deg)	Mean/Median Group C (psf)	No Data: Similar Lithology	Phi Values Used in Stability Analyses
GROUP 1	**Kwst(fbc)**	2	35/35	35/35	263/225	Jsp, Jspi, Kvsp	35
	Ts(fbc)	26	35/35			Kvspi, Klb, Klb-s	
	Tt(fbc)	6	37/36			Klbc, Klhs(fbc)	
	acf	7	35/35			Klh(fbc), Klh-sc	
						Kws(fbc), Kwsr(fbc)	
						Kwp(fbc), Kwps(fbc)	
GROUP 2	**Jbc**	5	31/30	32/32	286/193	Ktu, Ktl	32
	Kt	2	33/33			Ktr, Klb-sh	
	Klh(abc)	2	30/30			Klhs(abc)	
	Tsi(fbc)	8	33/31			Kwst(abc)	
	Tsa(fbc)	13	33/31			Kws(abc)	
	Tv(fbc)	4	31/31			Kwsr(abc)	
	Qt*	16	31/30			Tvs(fbc)	
	Qal	9	31/31			Qvoaa, Qvofa	
	Qsw	18	33/32			Qvoaar, Qyaga	
	af	11	31/30			Qya, Qyfa, Qywg	
						Qyaa, Qc, Qw	
GROUP 3	**Tsa(abc)**	10	27/28	27/28	519/420	Kwp(abc)	28**
	Ts(abc)	8	27/27			Kwps(abc)	
	Tv(abc)	10	28/27			Tsi(abc)	
						Tvs(abc), Tt(abc)	
GROUP 4	**Tm**	3	24/24	24/24	602/725		24
GROUP 5	**Qls**	4	12/10	12/10	130/110	Qyls	10**

Formational Subunits on Map Combined in Analysis

*** Qt = terrace deposits (Qvoaga, Qtr, Qtr1, Qtr2, Qtr3, and Qtr4)**

**** = The median values for GROUP 3 (28 degrees) and GROUP 5 (10 degrees) were used for the stability analysis because their sample population were too small to justify the use of the mean values.**

abc = adverse bedding condition, fine-grained material strength
fbc = favorable bedding condition, coarse-grained material strength

Table 2.1. Summary of the Shear Strength Statistics for the Santiago Peak Quadrangle.

SHEAR STRENGTH GROUPS FOR THE SANTIAGO PEAK 7.5-MINUTE QUADRANGLE

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5
Jsp, Jspi	Jbc, Kt, Ktu, Ktl	Kwp(abc)	Tm	Qls
Kvsp, Kvspi	Klb-sh, Klh(abc)	Kwps(abc)		Qyls
Klb, Klb-s	Klhs(abc), Kwst(abc)	Tsi(abc)		
Klbc, Klh(fbc)	Kws(abc), Kwsr(abc)	Tsa(abc)		
Klhs(fbc)	Tsi(fbc), Tsa(fbc)	Ts(abc)		
Klh-sc	Tv(fbc), Tvs(fbc)	Tv(abc)		
Kwst(fbc)	Qt, Qvoaga, Qtr	Tvs(abc)		
Kws(fbc)	Qtr1, Qtr2, Qtr3, Qtr4	Tt(abc)		
Kwsr(fbc)	Qvoaa, Qvofa			
Kwp(fbc)	Qvoaar, Qvofa			
Kwps(fbc)	Qal, Qya, Qyfa			
Ts(fbc)	Qsw, Qywg			
Tt(fbc)	Qyaa, Qc			
acf	Qw, af			

Table 2.2. Summary of the Shear Strength Groups for the Santiago Peak Quadrangle.

PART II

EARTHQUAKE-INDUCED LANDSLIDE HAZARD POTENTIAL

Design Strong-Motion Record

To evaluate earthquake-induced landslide hazard potential in the study area, a method of dynamic slope stability analysis developed by Newmark (1965) was used. The Newmark method analyzes dynamic slope stability by calculating the cumulative down-slope displacement for a given earthquake strong-motion time history. As implemented for the preparation of earthquake-induced landslide zones, the Newmark method necessitates the selection of a design earthquake strong-motion record to provide the "ground shaking opportunity." For the Santiago Peak Quadrangle, selection of a strong motion record was based on an estimation of probabilistic ground motion parameters for modal magnitude, modal distance, and peak ground acceleration (PGA). The parameters were estimated from maps prepared by CGS for a 10% probability of being exceeded in 50 years (Petersen and others, 1996; Cramer and Petersen, 1996). The parameters used in the record selection are:

Modal Magnitude:	6.80
Modal Distance:	5.3 to 17.1 km
PGA:	0.31 to 0.59g

The strong-motion record selected for the slope stability analysis in the Santiago Peak Quadrangle was the USC-14 (Trifunac and others, 1994) record from the modal magnitude 6.7 1994 Northridge Earthquake. This record had a source to recording site distance of 8.5 km and a peak ground acceleration (PGA) of 0.59g. The selected strong-motion record was not scaled or otherwise modified prior to its use in the analysis.

Displacement Calculation

The design strong-motion record was used to develop a relationship between landslide displacement and yield acceleration (a_y), defined as the earthquake horizontal ground acceleration above which landslide displacements take place. This relationship was prepared by integrating the design strong-motion record twice for a given acceleration value to find the corresponding displacement, and the process was repeated for a range of acceleration values (Jibson, 1993). The resulting curve in Figure 2.1 represents the full spectrum of displacements that can be expected for the design strong-motion record. This curve provides the required link between anticipated earthquake shaking and estimates of displacement for different combinations of geologic materials and slope gradient, as described in the Slope Stability Analysis section below.

The amount of displacement predicted by the Newmark analysis provides an indication of the relative amount of damage that could be caused by earthquake-induced landsliding. Displacements of 30, 15 and 5 cm are used as criteria for rating levels of earthquake-induced landslide hazard potential based on the work of Youd (1980), Wilson and Keefer (1983), and the CGS pilot study for earthquake-induced landslides (McCrink and Real, 1996; McCrink, 2001). Applied to the curve in Figure 2.1, these displacements correspond to yield accelerations of 0.076, 0.129 and 0.232g. Because these yield acceleration values are derived from the design strong-motion record, they represent the ground shaking opportunity thresholds that are significant in the Santiago Peak Quadrangle.

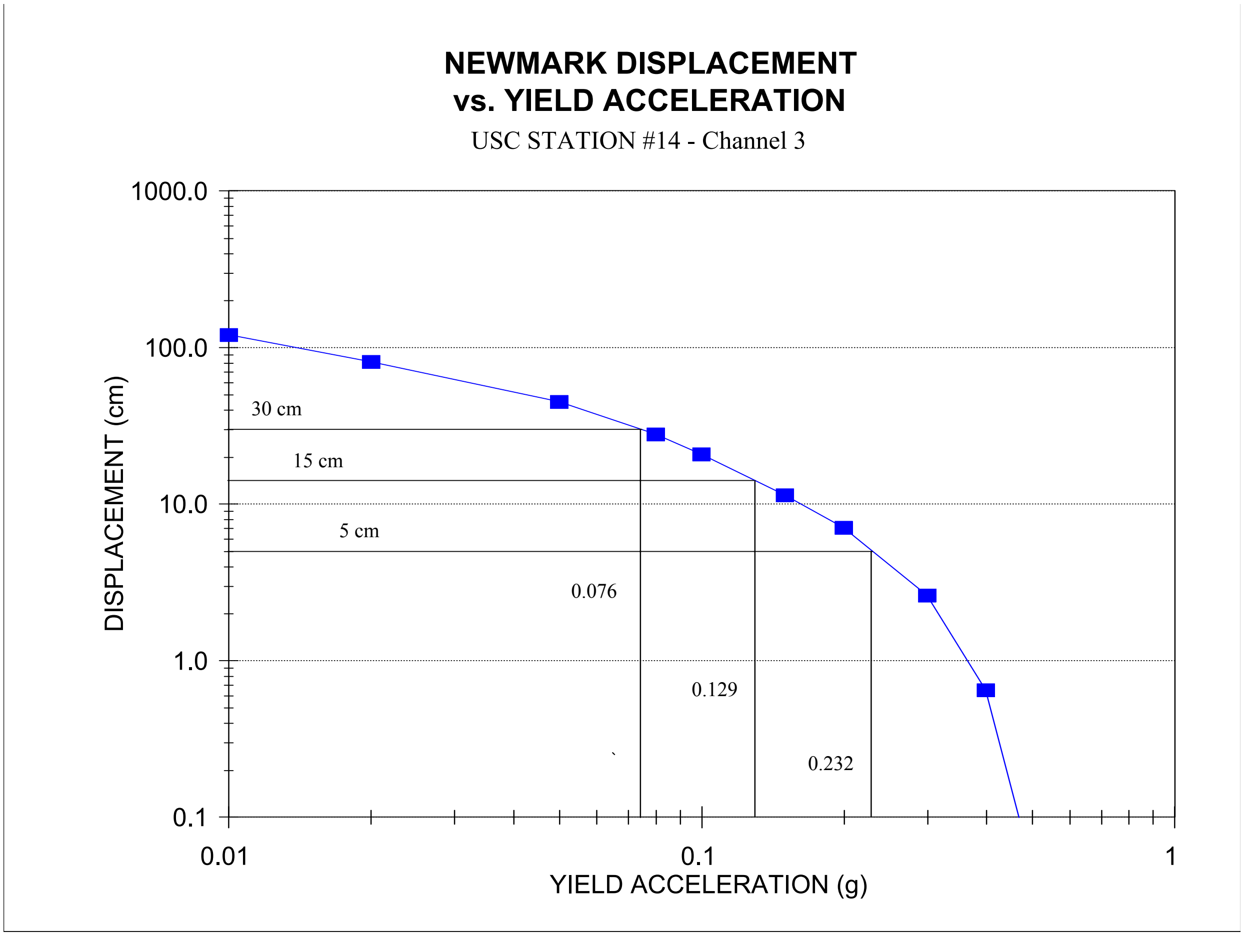

Figure 2.1. Yield Acceleration vs. Newmark Displacement for the USC Station # 14 Record from the 1994 Northridge Earthquake.

Slope Stability Analysis

A slope stability analysis was performed for each geologic material strength group at slope increments of 1 degree. An infinite-slope failure model under unsaturated slope conditions was assumed. A factor of safety was calculated first, followed by the calculation of yield acceleration from Newmark's equation:

$$a_y = (FS - 1)g \sin \alpha$$

where FS is the Factor of Safety, g is the acceleration due to gravity, and α is the direction of movement of the slide mass, in degrees measured from the horizontal, when displacement is initiated (Newmark, 1965). For an infinite slope failure, α is the same as the slope angle.

The yield accelerations resulting from Newmark's equations represent the susceptibility to earthquake-induced failure of each geologic material strength group for a range of slope gradients. Based on the relationship between yield acceleration and Newmark displacement shown in Figure 2.1, hazard potentials were assigned as follows:

1. If the calculated yield acceleration was less than 0.076g, Newmark displacement greater than 30 cm is indicated, and a HIGH hazard potential was assigned (H on Table 2.3).

2. If the calculated yield acceleration fell between 0.076g and 0.129g, Newmark displacement between 15 cm and 30 cm is indicated, and a MODERATE hazard potential was assigned (M on Table 2.3).

3. If the calculated yield acceleration fell between 0.129g and 0.232g, Newmark displacement between 5 cm and 15 cm is indicated, and a LOW hazard potential was assigned (L on Table 2.3).

4. If the calculated yield acceleration was greater than 0.232g, Newmark displacement of less than 5 cm is indicated, and a VERY LOW potential was assigned (VL on Table 2.3).

Table 2.3 summarizes the results of the stability analyses. The earthquake-induced landslide hazard potential map was prepared by combining the geologic material-strength map and the slope map according to this table.

SANTIAGO PEAK QUADRANGLE HAZARD POTENTIAL MATRIX

Geologic Material Group	Mean PHI	SLOPE CATEGORY (% SLOPE)								
		I	II	III	IV	V	VI	VII	VII	IX
		0 to 8%	9 to 13%	14 to 20%	21 to 31%	32 to 37%	38 to 47%	48 to 54%	55 to 61%	>62%
1	39	VL	VL	VL	VL	VL	VL	L	M	H
2	34	VL	VL	VL	VL	VL	L	M	H	H
3	29	VL	VL	VL	VL	L	M	H	H	H
4	25	VL	VL	VL	L	M	H	H	H	H
5	17	L	M	H	H	H	H	H	H	H

Table 2.3. Hazard Potential Matrix for Earthquake-Induced Landslides in the Santiago Peak Quadrangle. Shaded area indicates hazard potential levels included within the earthquake-induced hazard zone. H = High, M = Moderate, L = Low, VL = Very Low.

EARTHQUAKE-INDUCED LANDSLIDE ZONE

Criteria for Zoning

Earthquake-induced landslide zones were delineated using criteria adopted by the California State Mining and Geology Board (1996). Under those criteria, earthquake-induced landslide zones are areas meeting one or both of the following:

1. Areas identified as having experienced landslide movement in the past (including all mappable landslide deposits and source areas), and, where possible, areas known to have experienced earthquake-induced landsliding during historic earthquakes.

2. Areas where geologic and geotechnical data and analyses indicate that the earth materials may be susceptible to earthquake-induced slope failure.

Existing Landslides

Existing landslides typically consist of disrupted soils and rock materials that are generally weaker than adjacent undisturbed rock and soil materials. Previous studies indicate that existing landslides can be reactivated by earthquake movements (Keefer, 1984). Earthquake-triggered movement of existing landslides is most pronounced in steep head scarp areas and at the toe of existing landslide deposits. Although reactivation of deep-seated landslide deposits is less common (Keefer, 1984), a significant number of deep-seated landslide movements have occurred during, or soon after, several recent earthquakes. Based on these observations, all existing landslides with a definite or probable confidence rating are included within the earthquake-induced landslide hazard zone.

Geologic and Geotechnical Analysis

Based on the conclusions of a pilot study performed by CGS (McCrink and Real, 1996; McCrink,2001), it has been concluded that earthquake-induced landslide hazard zones should encompass all areas that have a High, Moderate or Low level of hazard potential (see Table 2.3). This would include all areas where the analyses indicate earthquake displacements of 5 centimeters or greater. Areas with a Very Low hazard potential, indicating less than 5 centimeters displacement, are excluded from the zone.

As summarized in Table 2.3, all areas characterized by the following geologic strength group and slope gradient conditions are included in the earthquake-induced landslide hazard zone:

1. Geologic Strength Group 5 is included for all slope gradient categories. (Note: Geologic Strength Group 5 includes all mappable landslides with a definite or probable confidence rating).

2. Geologic Strength Group 4 is included for all slopes steeper than 20 percent.

3. Geologic Strength Group 3 is included for all slopes steeper than 31 percent.

4. Geologic Strength Group 2 is included for all slopes steeper than 37 percent.

5. Geologic Strength Group 1 is included for all slopes greater than 47 percent.

This results in roughly 41% of the land in the quadrangle lying within the earthquake-induced landslide hazard zone for the Santiago Peak Quadrangle.

ACKNOWLEDGMENTS

The authors would like to thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project. Jeanette Brone and Carolyn Uribe of the Orange County Planning and Development Services were helpful in the collection of shear strength data. Ellen Sander, Ian Penney, and Bryan Caldwell digitized borehole locations and entered shear test data into the database. Terilee McGuire, Lee Wallinder, and Bob Moscovitz provided GIS support. Barbara Wanish and Ross Martin prepared the final landslide hazard zone maps and the graphic displays for this report.

REFERENCES

Brabb, E.E., 1983, Map showing direction and amount of bedding dip of sedimentary rocks in San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I-1257C, 1 sheet, scale 1:62,500.

California Department of Conservation, Division of Mines and Geology, 1997, Guidelines for evaluating and mitigating seismic hazards in California: California Department of Conservation, Division of Mines and Geology, Special Publication 117, 74 p.

California Department of Conservation, Division of Mines and Geology, 2000, Recommended criteria for delineating seismic hazard zones: California Department of Conservation, Division of Mines and Geology, Special Publication 118, 12 p.

Cramer, C.H. and Petersen, M.D., 1996, Predominant seismic source distance and magnitude maps for Los Angeles, Orange and Ventura counties, California: Bulletin of the Seismological Society of America, v. 85, no. 5, pp. 1645-1649.

Horn, B.K.P., 1981, Hill shading and the reflectance map: Proceedings of the IEEE, v. 69, no. 1, p. 14-47.

Intermap Corporation, 2002, Global terrain product handbook and quick start guide: http://www.intermap.com/images/handbook/producthandbook.pdf

Jibson, R.W., 1993, Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis: Transportation Research Board, National Research Council, Transportation Research Record 1411, 17 p.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, no. 4, p. 406-421.

McCrink, T.P., 2001, Mapping earthquake-induced landslide hazards in Santa Cruz County *in* Ferriz, H. and Anderson, R., *editors*, Engineering geology practice in northern California: California Geological Survey Bulletin 210 / Association of Engineering Geologists Special Publication 12, p.77-94.

McCrink, T.P. and Real, C.R., 1996, Evaluation of the Newmark method for mapping earthquake-induced landslide hazards in the Laurel 7-1/2 minute Quadrangle, Santa Cruz County, California: California Division of Mines and Geology Final Technical Report for U.S. Geological Survey Contract 143-93-G-2334, U.S. Geological Survey, Reston, Virginia, 31 p.

Miller, R.V. and Morton, P.K., 1984, Engineering geology of part of the western half of the Santiago Peak Quadrangle, Orange County, California: California Division of Mines and Geology Open-File Report 84-58, 62 p., map scale 1:12,000.

Morton, D.M. and Kennedy, M.P., 1989, A southern California digital 1:100,000-scale geologic map series: The Santa Ana Quadrangle, The first release: Geological Society of America Abstracts with Programs v. 21, no. 6, p. A107-A108.

Newmark, N.M., 1965, Effects of earthquakes on dams and embankments: Geotechnique, v. 15, no. 2, p. 139-160.

Petersen, M.D., Bryant, W.A., Cramer, C.H., Cao, T., Reichle, M.S., Frankel, A.D., Lienkaemper, J.J., McCrory, P.A. and Schwartz, D.P., 1996, Probabilistic seismic hazard assessment for the State of California: California Department of Conservation, Division of Mines and Geology, Open File Report 96-08; U.S. Geological Survey Open File Report 96-706, 33 p.

Schoellhamer, J.E., Vedder, R.G, Yerkes, R.F. and Kinney, D.M., 1981, Geology of the northern Santa Ana Mountains, California: U.S. Geological Survey Professional Paper 420-D, 70 p., map scale 1:24,000.

Smith, T.C., 1996, Preliminary maps of seismic hazard zones and draft guidelines for evaluating and mitigating seismic hazards: California Geology, v. 49, no. 6, p. 147-150.

Southern California Earthquake Center, 2002, Recommended procedures for implementation of DMG Special Publication 117 guidelines for analyzing and mitigating landslide hazards in California: Southern California Earthquake Center, University of Southern California, 108 p.

Trifunac, M.D., Todorovska, M.I. and Ivanovic, S.S., 1994, A note on distribution of uncorrected peak ground accelerations during the Northridge, California earthquake of 17 January 1994: Soil Dynamics and Earthquake Engineering, v. 13, no. 3, p. 187-196.

U.S. Geological Survey, 1993, Digital Elevation Models: National Mapping Program, Technical Instructions, Data Users Guide 5, 48 p.

Wilson, R.C. and Keefer, D.K., 1983, Dynamic analysis of a slope failure from the 1979 Coyote Lake, California, earthquake: Bulletin of the Seismological Society of America, v. 73, p. 863-877.

Youd, T.L., 1980, Ground failure displacement and earthquake damage to buildings: American Society of Civil Engineers Conference on Civil Engineering and Nuclear Power, 2d, Knoxville, Tennessee, 1980, v. 2, p. 7-6-2 to 7-6-26.

AIR PHOTOS

Robert J. Lung and Associates, dated July/August, 1970, Flight No. 239, Photo Nos. 14 - 15; Flight No. 24, Photo Nos. 14 - 17; Flight No. 25, Photo Nos. 9 - 19; Flight No.

26, Photo Nos. 8 - 19; Flight No. 27, Photo Nos. 6 - 17; Flight No. 28, Photo Nos. 4 – 14; Flight No. 29, Photo Nos. 10 – 15; Flight No. 30, Photo Nos. 12 – 14; Flight No. 31, Photo Nos. 13 – 14; scale 1 inch = 1164 feet.

I.K. Curtis Services, dated November 1998, Frames 328 and 329; scale 1 inch = 3500 feet.

APPENDIX A
SOURCE OF ROCK STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
ORANGE COUNTY PLANNING AND DEVELOPMENT SERVICES	164

SECTION 3
GROUND SHAKING EVALUATION REPORT

Potential Ground Shaking in the Santiago Peak 7.5-Minute Quadrangle, Orange County, California

By

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California Geological Survey
***Formerly with CGS, now with U.S. Geological Survey**

PURPOSE

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation (DOC), Division of Mines and Geology (DMG) [now called California Geological Survey (CGS)] to delineate Seismic Hazard Zones. The purpose of the Act is to reduce the threat to public health and safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. Cities, counties, and state agencies are directed to use the Seismic Hazard Zone Maps in their land-use planning and permitting processes. The Act requires that site-specific geotechnical investigations be performed prior to permitting most urban development projects within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines established by the California State Mining and Geology Board (DOC, 1997; also available on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

This section of the evaluation report summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential for zoning purposes. Included are ground motion and related maps, a brief overview on how these maps were prepared, precautionary notes concerning their use, and related references. The maps provided herein are presented at a scale of approximately 1:150,000 (scale bar provided on maps), and show the full 7.5-minute quadrangle and portions of the adjacent eight quadrangles. They can be used to assist in the specification of earthquake loading conditions ***for the analysis of ground failure*** according to the “Simple Prescribed Parameter Value” method (SPPV) described in the site investigation guidelines (California Department of Conservation, 1997). Alternatively, they can be used as a basis for comparing levels of ground motion determined by other methods with the statewide standard.

This section and Sections 1 and 2 (addressing liquefaction and earthquake-induced landslide hazards) constitute a report series that summarizes development of seismic hazard zone maps in the state. Additional information on seismic hazard zone mapping in California can be accessed on CGS’s Internet homepage:
http://www.conservation.ca.gov/CGS/index.htm

EARTHQUAKE HAZARD MODEL

The estimated ground shaking is derived from the statewide probabilistic seismic hazard evaluation released cooperatively by the California Department of Conservation, Division of Mines and Geology [California Geological Survey], and the U.S. Geological Survey (Petersen and others, 1996). That report documents an extensive 3-year effort to obtain consensus within the scientific community regarding fault parameters that characterize the seismic hazard in California. Fault sources included in the model were evaluated for long-term slip rate, maximum earthquake magnitude, and rupture geometry. These fault parameters, along with historical seismicity, were used to estimate return times of moderate to large earthquakes that contribute to the hazard.

The ground shaking levels are estimated for each of the sources included in the seismic source model using attenuation relations that relate earthquake shaking with magnitude, distance from the earthquake, and type of fault rupture (strike-slip, reverse, normal, or subduction). The published hazard evaluation of Petersen and others (1996) only considers uniform firm-rock site conditions. In this report, however, we extend the hazard analysis to include the hazard of exceeding peak horizontal ground acceleration (PGA) at 10% probability of exceedance in 50 years on spatially uniform conditions of rock, soft rock, and alluvium. These soil and rock conditions approximately correspond to site categories defined in Chapter 16 of the Uniform Building Code (ICBO, 1997), which are commonly found in California. We use the attenuation relations of Boore and others (1997), Campbell (1997), Sadigh and others (1997), and Youngs and others (1997) to calculate the ground motions.

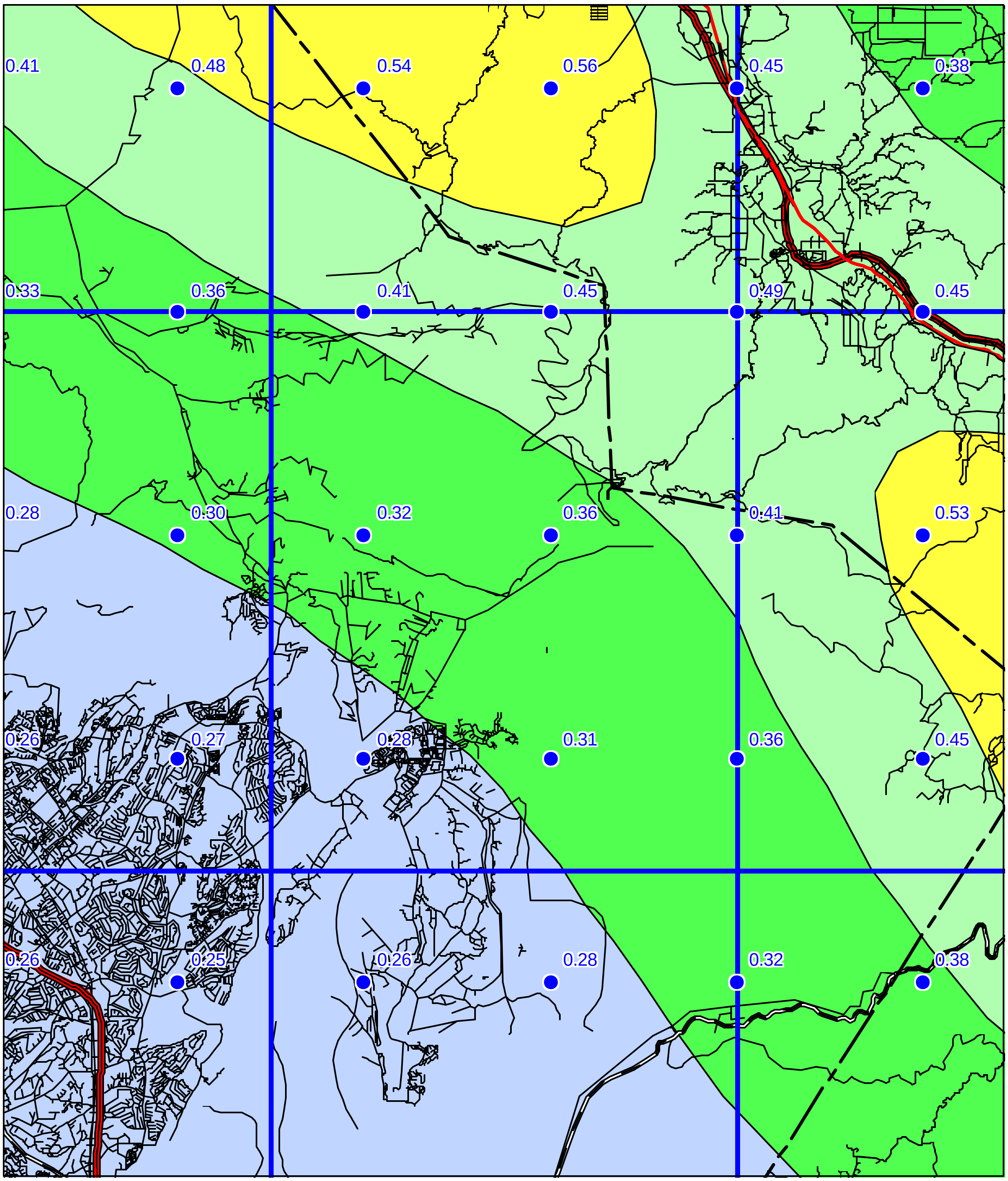
The seismic hazard maps for ground shaking are produced by calculating the hazard at sites separated by about 5 km. Figures 3.1 through 3.3 show the hazard for PGA at 10% probability of exceedance in 50 years assuming the entire map area is firm rock, soft rock, or alluvial site conditions respectively. The sites where the hazard is calculated are represented as dots and ground motion contours as shaded regions. The quadrangle of interest is outlined by bold lines and centered on the map. Portions of the eight adjacent

SANTIAGO PEAK 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

FIRM ROCK CONDITIONS



Base map modified from MapInfo StreetWorks © 1998 MapInfo Corporation

0 1.5 3

Miles

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California Geological Survey

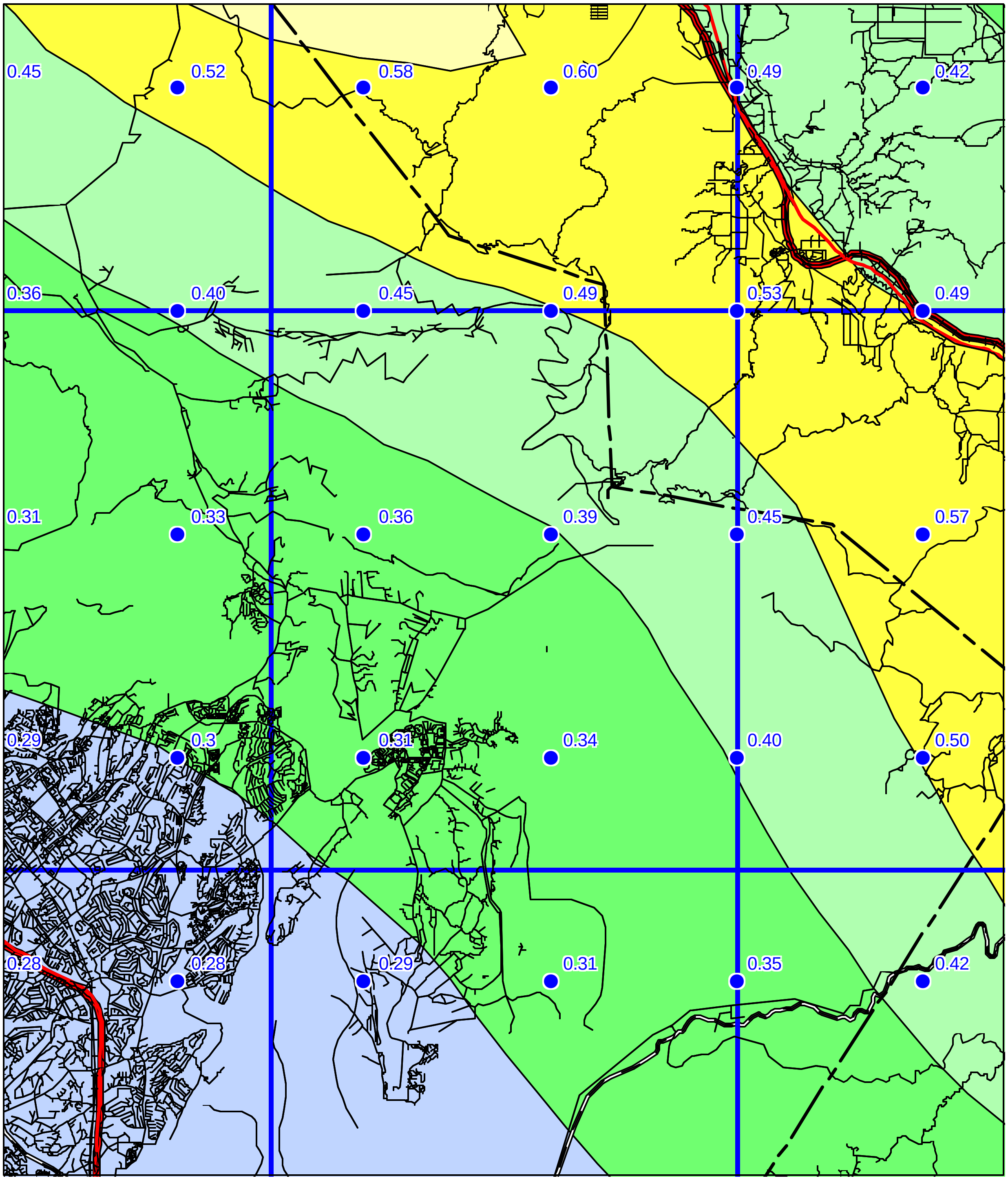
Figure 3.1

SANTIAGO PEAK 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

SOFT ROCK CONDITIONS



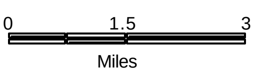


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Figure 3.2

SANTIAGO PEAK 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION (g)

1998

ALLUVIUM CONDITIONS

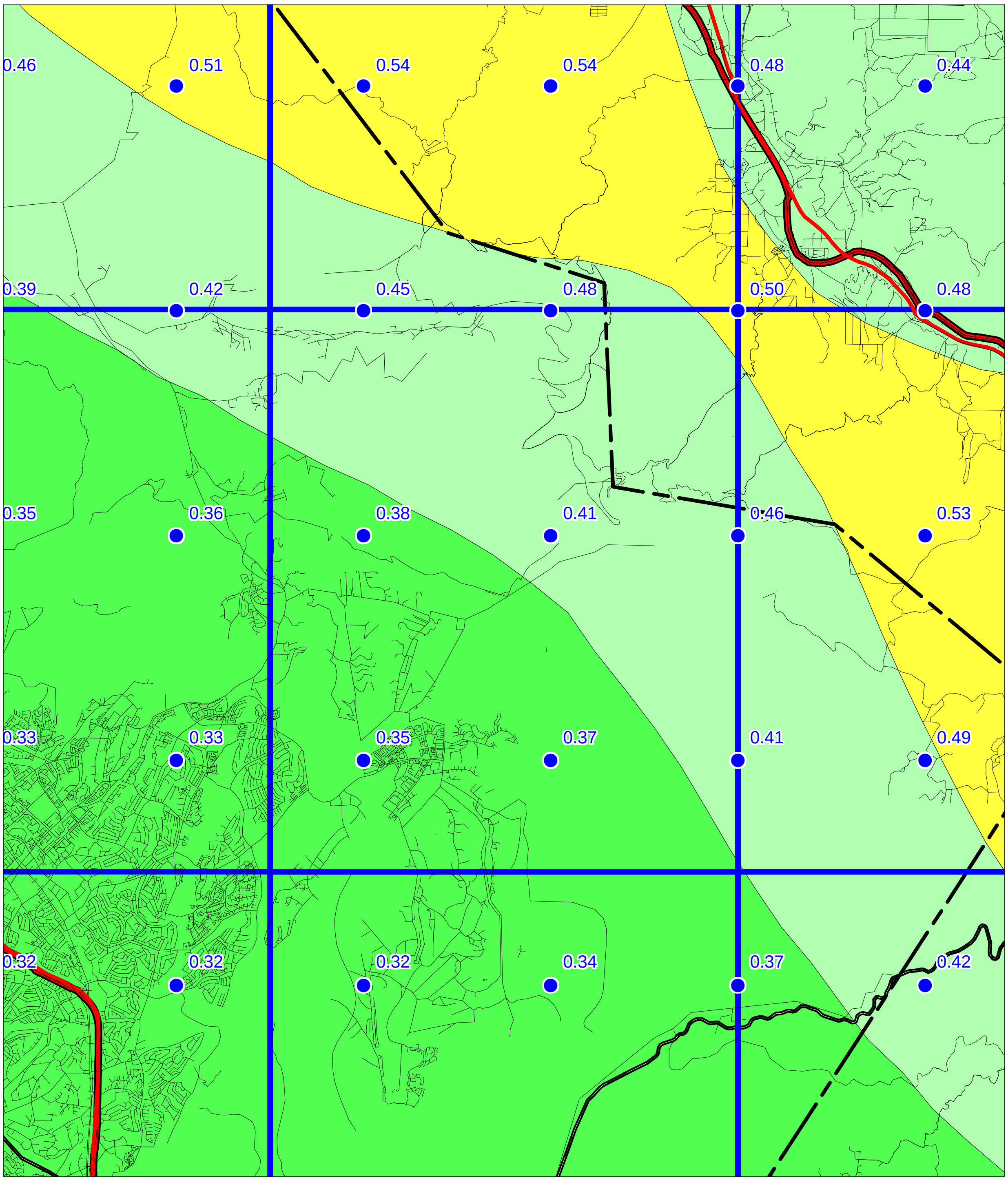

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Figure 3.3

quadrangles are also shown so that the trends in the ground motion may be more apparent. We recommend estimating ground motion values by selecting the map that matches the actual site conditions, and interpolating from the calculated values of PGA rather than the contours, since the points are more accurate.

APPLICATIONS FOR LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENTS

Deaggregation of the seismic hazard identifies the contribution of each of the earthquakes (various magnitudes and distances) in the model to the ground motion hazard for a particular exposure period (see Cramer and Petersen, 1996). The map in Figure 3.4 identifies the magnitude and the distance (value in parentheses) of the earthquake that contributes most to the hazard at 10% probability of exceedance in 50 years on alluvial site conditions (*predominant earthquake*). This information gives a rationale for selecting a seismic record or ground motion level in evaluating ground failure. However, it is important to keep in mind that more than one earthquake may contribute significantly to the hazard at a site, and those events can have markedly different magnitudes and distances. For liquefaction hazard the predominant earthquake magnitude from Figure 3.4 and PGA from Figure 3.3 (alluvium conditions) can be used with the Youd and Idriss (1997) approach to estimate cyclic stress ratio demand. For landslide hazard the predominant earthquake magnitude and distance can be used to select a seismic record that is consistent with the hazard for calculating the Newmark displacement (Wilson and Keefer, 1983). When selecting the predominant earthquake magnitude and distance, it is advisable to consider the range of values in the vicinity of the site and perform the ground failure analysis accordingly. This would yield a range in ground failure hazard from which recommendations appropriate to the specific project can be made. Grid values for predominant earthquake magnitude and distance should **not** be interpolated at the site location, because these parameters are not continuous functions.

A preferred method of using the probabilistic seismic hazard model and the “simplified Seed-Idriss method” of assessing liquefaction hazard is to apply magnitude scaling probabilistically while calculating peak ground acceleration for alluvium. The result is a “magnitude-weighted” ground motion (liquefaction opportunity) map that can be used directly in the calculation of the cyclic stress ratio threshold for liquefaction and for estimating the factor of safety against liquefaction (Youd and Idriss, 1997). This can provide a better estimate of liquefaction hazard than use of predominate magnitude described above, because all magnitudes contributing to the estimate are used to weight the probabilistic calculation of peak ground acceleration (Real and others, 2000). Thus, large distant earthquakes that occur less frequently but contribute *more* to the liquefaction hazard are appropriately accounted for.

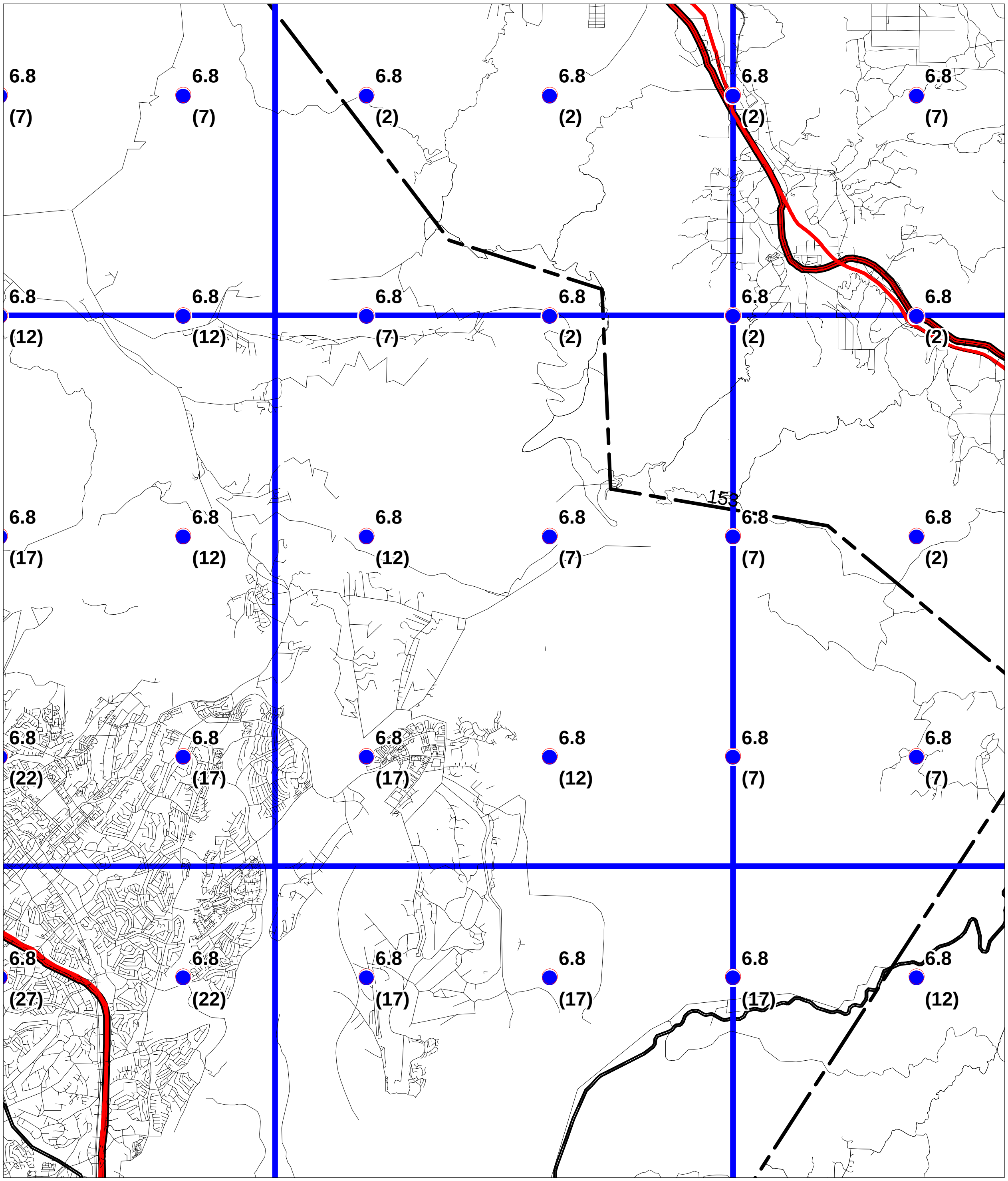
Figure 3.5 shows the magnitude-weighted alluvial PGA based on Idriss’ weighting function (Youd and Idriss, 1997). It is important to note that the values obtained from this map are pseudo-accelerations and should be used in the formula for factor of safety without any magnitude-scaling (a factor of 1) applied.

SANTIAGO PEAK 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION

1998

PREDOMINANT EARTHQUAKE
Magnitude (Mw)
(Distance (km))



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0 1.5 3
Miles

Department of Conservation
California Geological Survey

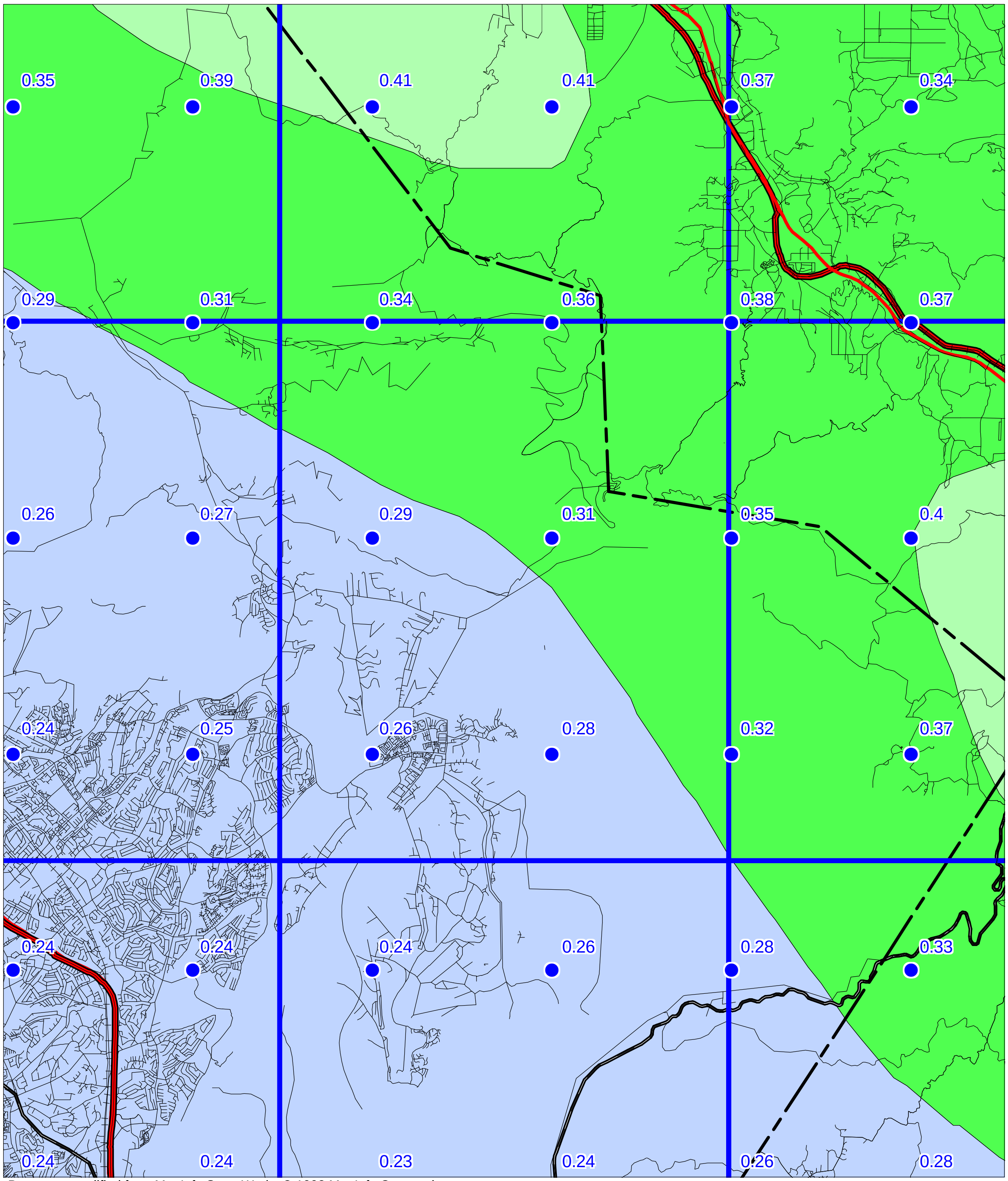
Figure 3.4

SANTIAGO PEAK 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

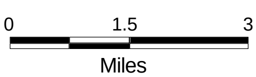
10% EXCEEDANCE IN 50 YEARS MAGNITUDE-WEIGHTED PSEUDO-PEAK ACCELERATION (g) FOR ALLUVIUM

1998

LIQUEFACTION OPPORTUNITY



Base map modified from MapInfo StreetWorks © 1998 MapInfo Corporation



Department of Conservation
California Geological Survey

Figure 3.5

USE AND LIMITATIONS

The statewide map of seismic hazard has been developed using regional information and is ***not appropriate for site specific structural design applications***. Use of the ground motion maps prepared at larger scale is limited to estimating earthquake loading conditions for preliminary assessment of ground failure at a specific location. We recommend consideration of site-specific analyses before deciding on the sole use of these maps for several reasons.

1. The seismogenic sources used to generate the peak ground accelerations were digitized from the 1:750,000-scale fault activity map of Jennings (1994). Uncertainties in fault location are estimated to be about 1 to 2 kilometers (Petersen and others, 1996). Therefore, differences in the location of calculated hazard values may also differ by a similar amount. At a specific location, however, the log-linear attenuation of ground motion with distance renders hazard estimates less sensitive to uncertainties in source location.

2. The hazard was calculated on a grid at sites separated by about 5 km (0.05 degrees). Therefore, the calculated hazard may be located a couple kilometers away from the site. We have provided shaded contours on the maps to indicate regional trends of the hazard model. However, the contours only show regional trends that may not be apparent from points on a single map. Differences of up to 2 km have been observed between contours and individual ground acceleration values. *We recommend that the user interpolate PGA between the grid point values rather than simply using the shaded contours*.

3. Uncertainties in the hazard values have been estimated to be about +/- 50% of the ground motion value at two standard deviations (Cramer and others, 1996).

4. Not all active faults in California are included in this model. For example, faults that do not have documented slip rates are not included in the source model. Scientific research may identify active faults that have not been previously recognized. Therefore, future versions of the hazard model may include other faults and omit faults that are currently considered.

5. A map of the predominant earthquake magnitude and distance is provided from the deaggregation of the probabilistic seismic hazard model. However, it is important to recognize that a site may have more than one earthquake that contributes significantly to the hazard. Therefore, in some cases earthquakes other than the predominant earthquake should also be considered.

Because of its simplicity, it is likely that the SPPV method (DOC, 1997) will be widely used to estimate earthquake shaking loading conditions for the evaluation of ground failure hazards. It should be kept in mind that ground motions at a given distance from an earthquake will vary depending on site-specific characteristics such as geology, soil properties, and topography, which may not have been adequately accounted for in the regional hazard analysis. Although this variance is represented to some degree by the recorded ground motions that form the basis of the hazard model used to produce Figures 3.1, 3.2, and 3.3, extreme deviations can occur. More sophisticated methods that take into account other factors that may be present at the site (site amplification, basin effects, near source effects, etc.) should be employed as warranted. The decision to use the SPPV method with ground motions derived from Figures 3.1, 3.2, or 3.3 should be based on careful consideration of the above limitations, the geotechnical and seismological aspects of the project setting, and the "importance" or sensitivity of the proposed building with regard to occupant safety.

REFERENCES

Boore, D.M., Joyner, W.B. and Fumal, T.E., 1997, Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra: Seismological Research Letters, v. 68, p. 154-179.

California Department of Conservation, Division of Mines and Geology, 1997, Guidelines for evaluating and mitigating seismic hazards in California: Special Publication 117, 74 p.

Campbell, K.W., 1997, Attenuation relationships for shallow crustal earthquakes based on California strong motion data: Seismological Research Letters, v. 68, p. 180-189.

Cramer, C.H. and Petersen, M.D., 1996, Predominant seismic source distance and magnitude maps for Los Angeles, Orange and Ventura counties, California: Bulletin of the Seismological Society of America, v. 85, no. 5, p. 1645-1649.

Cramer, C.H., Petersen, M.D. and Reichle, M.S., 1996, A Monte Carlo approach in estimating uncertainty for a seismic hazard assessment of Los Angeles, Ventura, and Orange counties, California: Bulletin of the Seismological Society of America, v. 86, p. 1681-1691.

International Conference of Building Officials (ICBO), 1997, Uniform Building Code: v. 2, Structural engineering and installation standards, 492 p.

Jennings, C.W., *compiler*, 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, California Geologic Data Map Series, map no. 8.

Petersen, M.D., Bryant, W.A., Cramer, C.H., Cao, T., Reichle, M.S., Frankel, A.D., Lienkaemper, J.J., McCrory, P.A. and Schwartz, D.P., 1996, Probabilistic seismic hazard assessment for the State of California: California Department of Conservation, Division of Mines and Geology Open-File Report 96-08; also U.S. Geological Survey Open-File Report 96-706, 33 p.

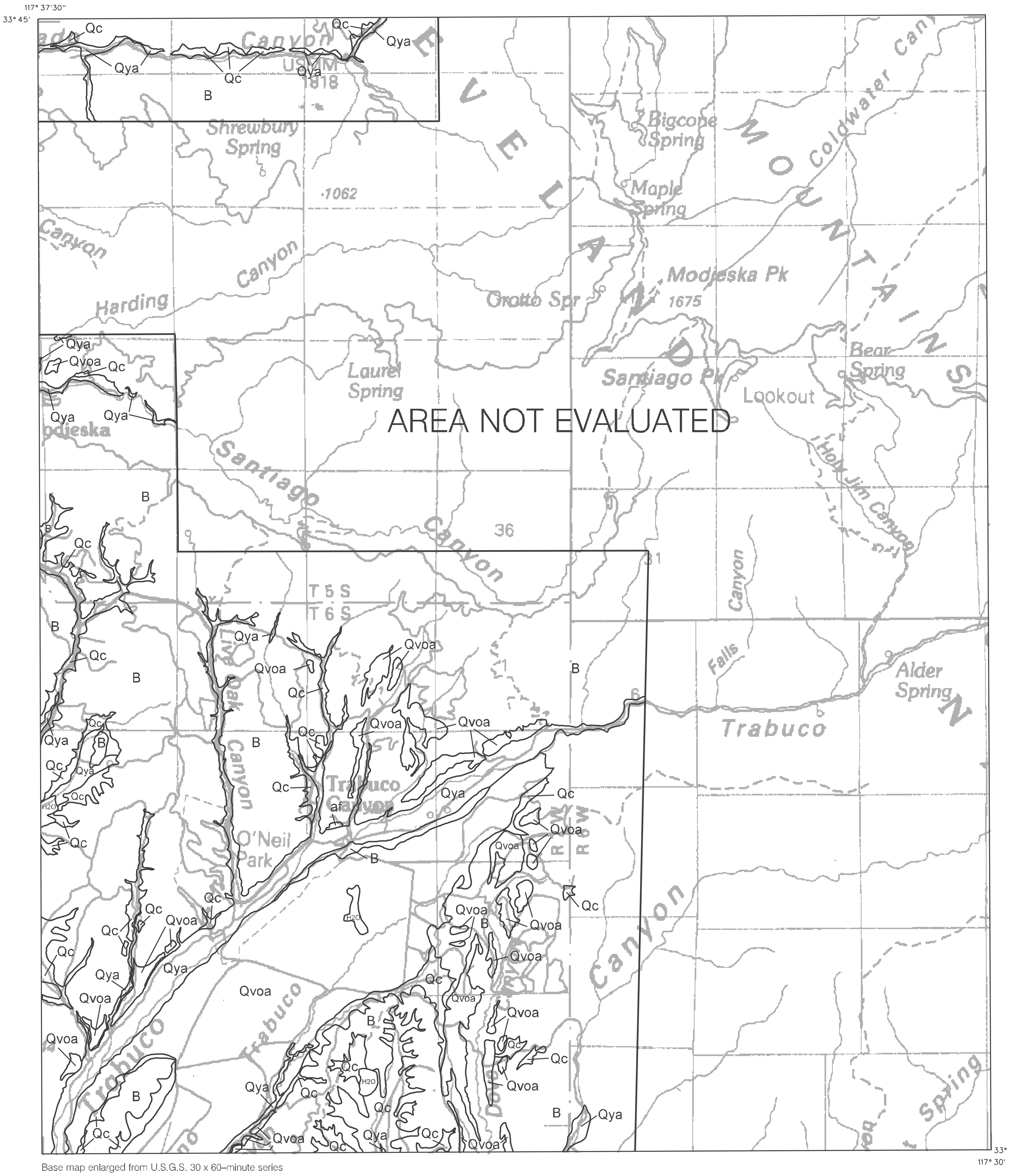
Real, C.R., Petersen, M.D., McCrink, T.P. and Cramer, C.H., 2000, Seismic Hazard Deaggregation in zoning earthquake-induced ground failures in southern California: Proceedings of the Sixth International Conference on Seismic Zonation, November 12-15, Palm Springs, California, EERI, Oakland, CA.

Sadigh, K., Chang, C.-Y., Egan, J.A., Makdisi, F. and Youngs, R.R., 1997, SEA96- A new predictive relation for earthquake ground motions in extensional tectonic regimes: Seismological Research Letters, v. 68, p. 190-198.

Wilson, R.C. and Keefer, D.K., 1983, Dynamic analysis of a slope failure from the 1979 Coyote Lake, California, Earthquake: Bulletin of the Seismological Society of America, v. 73, p. 863-877.

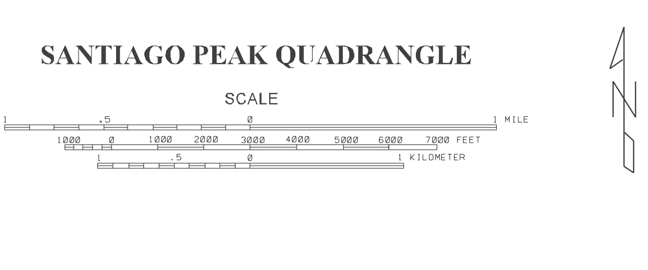
Youd, T.L. and Idriss I.M., 1997, Proceedings of the NCEER workshop on evaluation of liquefaction resistance of soils: Technical Report NCEER-97-0022, 40 p.

Youngs, R.R., Chiou, S.-J., Silva, W.J. and Humphrey, J.R., 1997, Stochastic point-source modeling of ground motions in the Cascadia Region: Seismological Research Letters, v. 68, p. 74-85.



Base map enlarged from U.S.G.S. 30 x 60–minute series

SANTIAGO PEAK QUADRANGLE

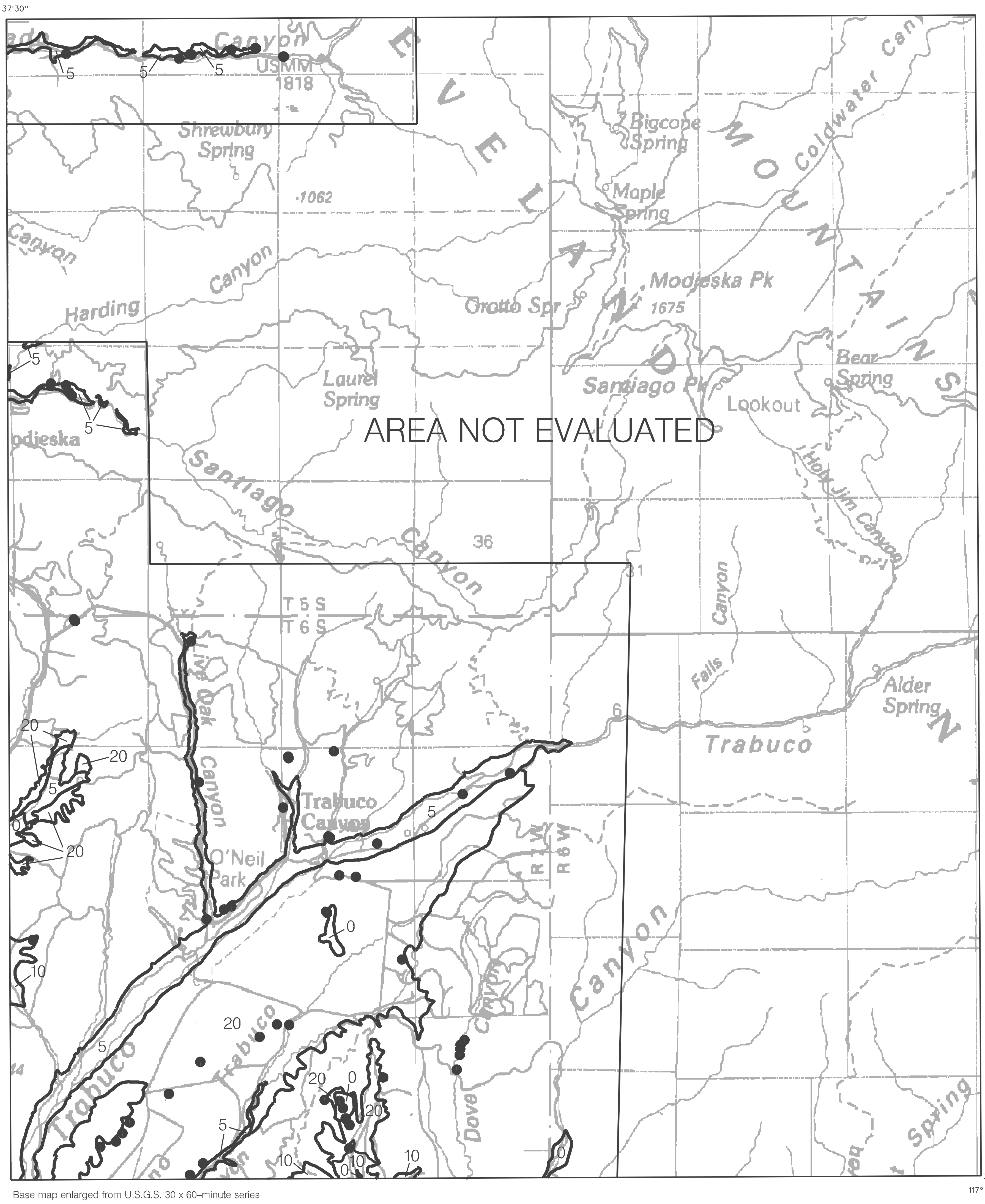


EXPLANATION

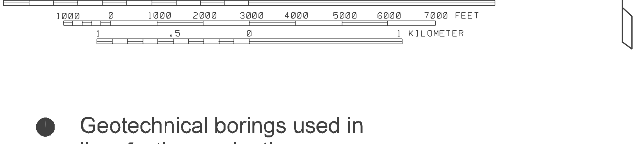
Qc Young Quaternary colluvium/slope wash
Qya Young Quaternary alluvium
Qvoa Very old Quaternary alluvium
B Pre-Quaternary bedrock.

See Section 1 of report for descriptions of Quaternary units.

Plate 1.1 Quaternary Geologic Map of the Santiago Peak 7.5-minute quadrangle (modified from Miller and Morton 1984).



SANTIAGO PEAK QUADRANGLE

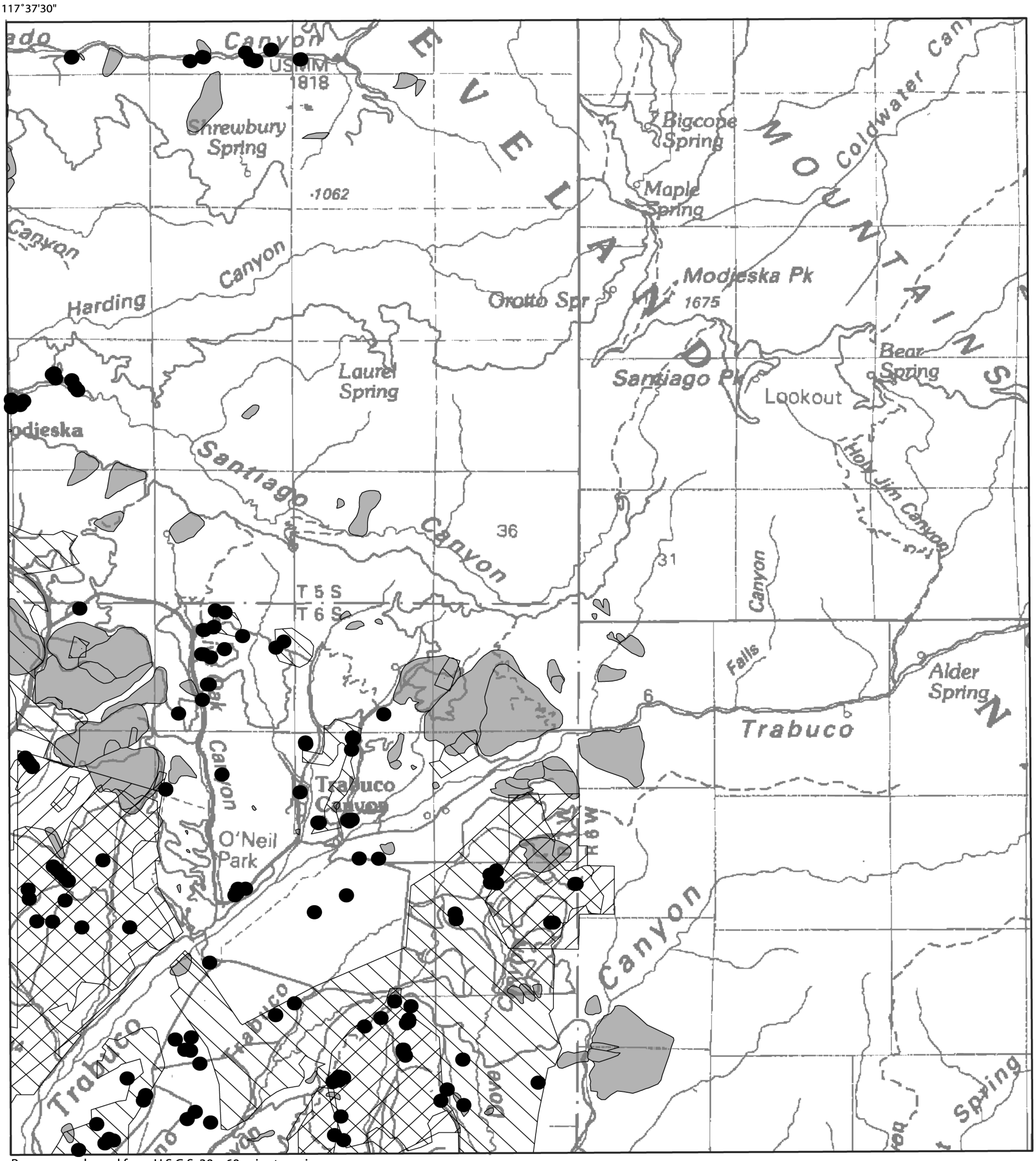


Depth to ground water, in feet

Geotechnical borings used in liquefaction evaluation

Plate 1.2 Depth to historically high ground water and locations of boreholes and trenches, Santiago Peak 7.5-minute Quadrangle, California

117°37'30"
33°45



33°37'30"
117°30

Base map enlarged from U.S.G.S. 30 x 60-minute series

SANTIAGO PEAK QUADRANGLE

SCALE

1 .5 0 1 MILE
1000 0 2000 4000 6000 FEET
1 .5 0 1 KILOMETER

N

● Shear test sample location — Landslide — Area of significant grading — Tract report with multiple shear tests

Plate 2.1 Landslide inventory, shear test sample locations, and areas of significant grading, Santiago Peak 7.5-minute quadrangle.