SEISMIC HAZARD ZONE REPORT 042

SEISMIC HAZARD ZONE REPORT FOR THE THOUSAND OAKS 7.5-MINUTE QUADRANGLE, VENTURA AND LOS ANGELES COUNTIES, CALIFORNIA

2000

DEPARTMENT OF CONSERVATION
Division of Mines and Geology

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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 Thousand Oaks 7.5-minute Quadrangle, Ventura and Los Angeles counties, California. The map displays the boundaries of Zones of Required Investigation for liquefaction and earthquake-induced landslides over an area of approximately 62 square miles at a scale of 1 inch = 2,000 feet.

The Thousand Oaks Quadrangle is located about 35 miles west of the Los Angeles Civic Center and 27 miles east of the Ventura County Civic Center. It includes parts of the cities of Thousand Oaks, Simi Valley, Agoura Hills, and Westlake Village and the unincorporated communities of Oak Park and Lake Sherwood. The northern and central part of the quadrangle is dominated by hilly to mountainous terrain of the Simi Hills, where elevations reach 2403 feet at Simi Peak, and Mountclef Ridge. The southern part of the quadrangle includes Russell Valley and the steep, rugged northern slopes of the Santa Monica Mountains. Commercial development is concentrated in the low-lying areas along the major highways and streets. Residential development has spread from the lowland areas into the hills and mountains where extensive grading is in process. Other current land uses include National parkland (Santa Monica Mountains National Recreation Area) in the Simi Hills and Santa Monica Mountains, regional parkland, golf courses, and several reservoirs. U.S. Highway 101 and State Highway 23 are the major transportation routes through the project area.

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 Thousand Oaks Quadrangle the liquefaction zone is restricted to the Conejo Creek stream valley, a small area along Cheeseboro Creek at the eastern boundary and several north-trending canyons and stream valleys at the northern boundary of the quadrangle. The combination of dissected hills and weak rocks has produced widespread and abundant landslides, especially in the Simi Hills and the Santa Monica Mountains. These conditions contribute to an earthquake-induced landslide zone that covers about 18 percent 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 Division of Mines and Geology's Internet page: http://www.conservation.ca.gov/CGS/index.htm

Paper copies of Official Seismic Hazard Zone Maps, released by DMG, 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 DMG 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) 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 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).

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 DMG 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 Thousand Oaks 7.5-minute Quadrangle.

SECTION 1
LIQUEFACTION EVALUATION REPORT

Liquefaction Zones in the Thousand Oaks 7.5-Minute Quadrangle, Ventura and Los Angeles Counties, California

By
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California Department of Conservation
Division of Mines and Geology

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) 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 DMG 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; also available on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf).

This section of the evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils in the Thousand Oaks 7.5-minute Quadrangle. This section, along with Section 2 (addressing earthquake-induced landslides), and Section 3 (addressing potential ground shaking), form a report that 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 DMG'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 Thousand Oaks 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 DMG 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 Thousand Oaks Quadrangle consist mainly of alluviated valleys, floodplains, and canyons. DMG'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 Thousand Oaks Quadrangle covers approximately 62 square miles in southeastern Ventura and western Los Angeles counties. The project area is located about 35 miles west of the Los Angeles Civic Center and 27 miles east of the Ventura County Civic Center and includes parts of the cities of Thousand Oaks, Simi Valley, Agoura Hills, and Westlake Village and the unincorporated communities of Oak Park and Lake Sherwood. The northern and central part of the quadrangle is dominated by hilly to mountainous terrain of the Simi Hills and Mountclef Ridge. Within and surrounding the Simi Hills are areas where erosion has produced gently sloping mountain valleys and dissected lowlands containing small hills and knobs of bedrock. Narrow canyons cut the steeper mountainous areas. The southernmost part of the quadrangle includes the gently sloping to flat-lying terrain of Russell Valley and the steep, rugged northern slopes of the Santa Monica Mountains, which form the southern boundary of the project area. Elevations range from 500 feet at the northwestern corner of the quadrangle to 2403 feet at Simi Peak. Major drainages in the area include Arroyo Conejo/Conejo Creek, which drains west into Conejo Valley, and Medea Creek and Triunfo Canyon, which drain south and southeast through the Santa Mountains into Malibu Creek.

U.S. Highway 101 and State Highway 23 are the major transportation routes through the project area. Primary access roads within the area include Thousand Oaks and Westlake boulevards, and Moorpark, Lindero Canyon, Kanan, and Olsen roads. Fire roads provide access to remote areas. Commercial development is concentrated in the low-lying areas along the major highways and streets. Residential development has spread from the lowland areas into the hills and mountains where extensive grading is in process. Other current land uses include National parkland (Santa Monica Mountains National Recreation Area) in the Simi Hills and Santa Monica Mountains, regional parkland, golf courses, and several reservoirs.

GEOLOGY

Surficial Geology

Geologic units that generally are susceptible to liquefaction include late Quaternary alluvial and fluvial sedimentary deposits and artificial fill. A recently compiled U.S. Geological Survey (USGS) geologic map (Yerkes and Showalter, 1991) was obtained in digital form (Yerkes and Campbell, 1995) for the Thousand Oaks Quadrangle. In addition, William Lettis and Associates (1999) provided new Quaternary geologic mapping in digital form for use in this study. This map was merged with the digital bedrock map compiled by Yerkes and Campbell (1995) to provide a common geologic map for zoning liquefaction and earthquake-induced landslides. The combined map was further modified based on work by Dibblee (1993) and Weber (1984), along with aerial photo interpretation by project staff. Nomenclature for labeling Quaternary geologic units followed that used by the Southern California Areal Mapping Project (Morton and Kennedy, 1989). Quaternary geologic mapping of the Thousand Oaks Quadrangle is presented as Plate 1.1.

As illustrated on Plate 1.1, Quaternary sedimentary deposits mapped within the Thousand Oaks Quadrangle are restricted to canyons, narrow stream courses, small valleys, and dissected lowlands all of which occupy less than 20 percent of the local terrain. The Quaternary surficial alluvial units are divided into older alluvium (Pleistocene), younger alluvium (latest Pleistocene to Holocene), and modern deposits. They are then further subdivided on the basis of their depositional environment and relative ages (Table 1.1).

Quaternary Map Units	Environment of Deposition	Age
Qw	Wash	Historic time
Qf	Alluvial Fan	Historic time
Qc	Colluvium	Historic – Holocene
Qya1, Qya2	Alluvium	Holocene
Qyf1, Qyf2	Alluvial Fan	Holocene
Qoa	Alluvium	Pleistocene
Qof	Alluvial Fan	Pleistocene
Qoc	Colluvium	Pleistocene

Table 1.1. Quaternary Geologic Nomenclature of the Southern California Areal Mapping Project (SCAMP) Applied in the Thousand Oaks Quadrangle.

ENGINEERING GEOLOGY

Information on subsurface geology and engineering characteristics of flatland deposits was obtained from borehole logs collected from reports on geotechnical projects. For this investigation, more than 175 borehole logs were collected from the City of Thousand Oaks, the County of Ventura, Los Angeles County Public Works, California Department of Transportation (CalTrans), and the Southern California Regional Water Quality Control Board. Data from the borehole logs were entered into a DMG geotechnical GIS database. Locations of all exploratory boreholes considered in this investigation are shown on Plate 1.2.

Standard Penetration Test (SPT) data provide a standardized measure of the penetration resistance of a geologic deposit and commonly are used as an index of density. Many geotechnical investigations record SPT data, including the number of blows by a 140-pound drop weight required to drive a sampler of specific dimensions one foot into the soil. 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), were converted to SPT-equivalent blow count values and entered into the DMG GIS. The actual and converted SPT blow counts were 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 $(N_1)_{60}$.

Evaluation of the borehole logs indicates that the thickness of young Quaternary deposits throughout the Thousand Oaks Quadrangle is not great, usually ranging from a few feet to no more than 20 feet. These young deposits normally overlie Pleistocene deposits that range in thickness from a few feet in canyon areas to about 40 feet. Lithologic descriptions provided in the logs indicate that most of the young Quaternary deposits in the quadrangle are dominated by high plasticity clay, clayey silt and clayey sand. The abundant clay within these deposits is derived mainly from the surrounding exposures of Tertiary clay-rich shale of the Modelo Formation and as weathering products of the Conejo Volcanics. A notable exception is the presence of young Quaternary sand and silty sand beds deposited in the northeast-trending Conejo Creek stream valley north of U.S. Highway 101. The alluvial sand beds in this basin are derived in part from erosion of sandstone and sand-rich beds of the Cretaceous Chatsworth Formation and the Miocene Topanga Formation, which are exposed in the drainage basin of Conejo Creek.

GROUND-WATER CONDITIONS

Liquefaction hazard may exist in areas where depth to ground water is 40 feet or less. DMG uses the highest known ground-water levels because water levels during an earthquake cannot be anticipated because of the unpredictable fluctuations caused by natural processes and human activities. A historical-high ground-water map differs from most ground-water maps, which show the actual water table at a particular time. Plate 1.2 depicts a hypothetical ground-water table within alluviated areas.

Ground-water conditions were investigated in the Thousand Oaks Quadrangle to evaluate the depth to saturated materials. Saturated conditions reduce the effective normal stress, thereby increasing the likelihood of earthquake-induced liquefaction (Youd, 1973). The evaluation was based on first-encountered water levels penetrated by boreholes and selected water wells. The depths to first-encountered unconfined ground water were plotted onto a map of the project area to constrain the estimate of historically shallowest ground water. Water depths from boreholes known to penetrate confined aquifers were not utilized.

Historical ground-water levels in the alluviated stream valley and lowland areas of the Thousand Oaks Quadrangle are generally shallow, commonly at or near a depth of 10 feet. Shallow ground-water conditions commonly exist in these types of depositional environments because they tend to receive and accumulate heavy runoff and near-surface ground water derived from surrounding highlands.

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. This 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.

DMG'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. DMG's qualitative susceptible soil inventory is summarized on Table 1.2.

Geologic Map Unit	Sediment Type	Environment of Deposition	Consistency	Susceptible to Liquefaction?*
Qw	Clayey sand, silty sand, and sand	Active stream channels	Loose	Yes**
Qf,	Clay, clayey silt, and clayey sand	Alluvial fans	Loose	Yes**
Qyf1-2, Qya1-2,	Clay, clayey silt and clayey sand	Alluvium	Loose to moderately dense	Yes**
Qc	Clay, silt, and cobbles	Colluvium	Soft to firm	Low likelihood
Qoa, Qof, Qoc	Clay, silt, sand, gravel	Older alluvium, alluvial fan, and colluvium deposits	Dense to very dense	Not likely

* When saturated.
** Depending on clay content

Table 1.2. General Geotechnical Characteristics and Liquefaction Susceptibility of Quaternary Sedimentary Units in the Thousand Oaks Quadrangle.

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 DMG's analysis is the magnitude that contributes most to the calculated PGA for an area.

For the Thousand Oaks Quadrangle, PGAs ranging between 0.43 and 0.48 g, resulting from an earthquake of magnitude 7.3, 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 section (3) of this report for further details.

Quantitative Liquefaction Analysis

DMG 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, DMG'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. DMG 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 DMG liquefaction analysis program calculates an FS for each geotechnical sample for which blow counts were collected. Typically, multiple samples are collected for each borehole. The lowest FS in each borehole is used for that location. FS values vary in reliability according to the quality of the geotechnical data used in their calculation. 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 175 geotechnical borehole logs reviewed in this study (Plate 1.2), 102 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.

The Seed-Idriss Simplified Procedure for liquefaction evaluation was developed primarily for clean sand and silty sand. As described above, results depend greatly on accurate evaluation of in-situ soil density as measured by the number of soil penetration blow counts using an SPT sampler. However, many of the Holocene alluvial deposits in the study area 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 were made with boreholes in the same unit where the N values do not appear to have been affected by gravel content.

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 Thousand Oaks Quadrangle is summarized below.

Areas of Past Liquefaction

No areas of documented historic liquefaction are known to have occurred in the Thousand Oaks Quadrangle. Neither have areas showing evidence of paleoseismic liquefaction been reported.

Artificial Fills

In the Thousand Oaks Quadrangle, artificial fill areas large enough to show at the scale of mapping (1:24000) consist of engineered fill for home development, elevated freeways, and reservoir dams. Since these fills are generally considered to be properly engineered, zoning for liquefaction in such areas depends on soil conditions in underlying strata.

Areas with Sufficient Existing Geotechnical Data

Geotechnical data obtained during this study are considered sufficient to zone liquefaction potential in those parts of the Thousand Oaks Quadrangle underlain by young Quaternary sedimentary deposits. These areas consist of Russell Valley (Westlake Village) and the canyons and stream valleys that cut through the Simi Hills and Santa Monica Mountains. Of these, only the stream valley occupied by Conejo Creek is found to contain loose, saturated, sandy beds that are zoned as being potentially liquefiable.

Areas with Insufficient Existing Geotechnical Data

It was necessary to apply SMGB criteria for zoning areas lacking sufficient geotechnical data to the short segment of the Cheeseboro Creek stream valley at the eastern edge of the quadrangle along U.S. Highway 101. The sediments deposited by the Creek are derived in large part from Palo Comado and Cheeseboro Canyons, which were zoned for liquefaction in the adjacent Calabasas Quadrangle. Similarly, Long Canyon and adjacent canyons along the northern margin of the quadrangle are zoned for liquefaction. These canyons extend north into the Simi Valley West Quadrangle where they were zoned for liquefaction.

Summary

Less than 10 percent of the Thousand Oaks Quadrangle is covered by young Quaternary alluvial deposits. Borehole log data indicate that alluvial sediments deposited in lowland basins, canyons, and stream valleys are generally dominated by plastic clay, clayey silt, and clayey sand. The abundant clay within these deposits is derived mainly from weathering products of the surrounding Miocene Conejo Volcanics and shale of the Miocene Modelo Formation. Overall potential for liquefaction in these areas is considered to be low. An exception is the northeast-trending, 500- to 1500-foot-wide stream valley occupied by Conejo Creek where several test borehole logs indicate the widespread occurrence of young loose sand and silty sand beds deposited in the uppermost 10 to 20 feet. Historical ground-water depths within the basin are estimated to be about 10 feet. The sand-rich sediments deposited within this stream valley are most likely derived from sandstone of the Cretaceous Chatsworth Formation and the, locally, sand-rich layers of the Topanga Formation exposed in the drainage basin of Conejo Creek. Based on geologic evaluation and analysis of test data, the young Quaternary alluvial deposits of the Conejo Creek stream valley are zoned as being potentially liquefiable.

A small alluviated area along Cheeseboro Creek at the eastern margin of the quadrangle is zoned for liquefacton using SMGB criteria for zoning areas lacking sufficient geotechnical data. The extension of these deposits in the adjacent Calabasas Quadrangle was similarly zoned by California Department of Conservation, Division of Mines and Geology. Likewise, several north-trending canyons and stream valleys at the northern boundary of the quadrangle that extend into the adjoining Simi Valley West Quadrangle are zoned for liquefaction. These alluvial deposits are also derived in part from sandstone of the Cretaceous Chatsworth Formation.

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SECTION 2
EARTHQUAKE-INDUCED LANDSLIDE EVALUATION REPORT

Earthquake-Induced Landslide Zones in the Thousand Oaks 7.5-Minute Quadrangle, Ventura and Los Angeles Counties, California

By
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California Department of Conservation
Division of Mines and Geology

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) 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 DMG 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 seismic hazard zone mapping for earthquake-induced landslides in the Thousand Oaks 7.5-minute Quadrangle. This section, along with Section 1 (addressing liquefaction), and Section 3 (addressing earthquake shaking), form a report that 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 DMG'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 Thousand Oaks 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 DMG 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 DMG pilot study (McCrink and Real, 1996) 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 Thousand Oaks 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 Thousand Oaks 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 Thousand Oaks Quadrangle covers approximately 62 square miles in southeastern Ventura and western Los Angeles counties. The project area is located about 35 miles west of the Los Angeles Civic Center and 28 miles east of Ventura and includes parts of the cities of Thousand Oaks, Simi Valley, Agoura Hills, and Westlake Village and the unincorporated communities of Oak Park and Lake Sherwood. The northern and central part of the quadrangle is dominated by hilly to mountainous terrain of the Simi Hills and Mountclef Ridge. Within and surrounding the Simi Hills are areas where erosion has produced gently sloping mountain valleys and dissected lowlands containing small hills and knobs of bedrock. The steeper mountainous areas are cut by narrow canyons. The southernmost part of the quadrangle includes the gently sloping to flat-lying terrain of Russell Valley and the steep, rugged northern slopes of the Santa Monica Mountains, which form the southern boundary of the project area. Elevations range from 500 feet at the northwestern corner of the quadrangle to 2403 feet at Simi Peak. Major drainages in the area include Arroyo Conejo/Conejo Creek, which drains west into Conejo Valley, and Medea Creek and Triunfo Canyon, which drain south and southeast through the Santa Mountains into Malibu Creek.

U.S. Highway 101 and State Highway 23 are the major transportation routes through the project area. Primary access roads within the area include Thousand Oaks and Westlake boulevards, and Moorpark, Lindero Canyon, Kanan, and Olsen roads. Access to remote areas is provided by fire roads. Commercial development is concentrated in the low-lying areas along the major highways and streets. Residential development has spread from the lowland areas into the hills and mountains where extensive grading is on-going. Other current land uses include National parkland (Santa Monica Mountains National Recreation Area) in the Simi Hills and Santa Monica Mountains, regional parkland, golf courses, and several reservoirs.

Digital Terrain Data

The calculation of slope gradient is an essential part of the evaluation of slope stability under earthquake conditions. An accurate slope gradient calculation begins with an up-to-date map representation of the earth's surface. Within the Thousand Oaks 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 that are based on 1947 aerial photography, has a 10-meter horizontal resolution and a 7.5-meter vertical accuracy.

To update the terrain data to reflect areas that have recently undergone large-scale grading, graded areas in the hilly portions of the Thousand Oaks Quadrangle were identified from NAPP 1994 aerial photographs. Terrain data for these areas were obtained from an airborne interferometric radar (TOPSAR) DEM flown and processed in August 1994 by NASA's Jet Propulsion Laboratory (JPL), and processed by Calgis, Inc. (GeoSAR Consortium, 1995; 1996). The terrain data were also smoothed and filtered prior to analysis. Plate 2.2 shows the area where the topography is updated to 1994 grading conditions.

A slope map was made from the DEMs 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.

GEOLOGY

Bedrock and Surficial Geology

A recently compiled U.S. Geological Survey (USGS) geologic map (Yerkes and Showalter, 1991) was obtained in digital form (Yerkes, 1995) for the Thousand Oaks Quadrangle. Landslide deposits were deleted from the digital map so that the distribution of bedrock formations and the landslide inventory would exist on separate layers for the hazard analysis. The bedrock geology was modified to include more detail and reflect more recent mapping. DMG staff then merged the bedrock contacts on this map with a digital Quaternary geologic map prepared by William Lettis and Associates (1999). The contacts between bedrock and Quaternary surficial deposits on the merged map were then modified based on air-photo interpretation and field reconnaissance by DMG. 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 landslides was noted.

The oldest geologic unit mapped in the Thousand Oaks Quadrangle is the Upper Cretaceous Chatsworth Formation (Kc), which forms spectacular tilted outcrops in the northeast quarter of the quadrangle in the Simi Hills. The Chatsworth Formation consists of well-cemented, thick-bedded, arkosic marine sandstone and minor conglomerate interbedded with thin-bedded siltstone and mudstone.

The Chatsworth Formation is overlain by a sequence of lower Tertiary marine and non-marine clastic rocks, which crop out on the northern flank of the Simi Hills. The lower part of this sequence includes the Paleocene Simi Conglomerate (Tsc), a non-marine to marine pebble-cobble conglomerate with discontinuous sandstone lenses, and the Las Virgenes Sandstone (Tlv), a non-marine, weakly to moderately indurated sandstone and mudstone. Overlying these strata are the upper Paleocene to lower Eocene Santa Susana Formation (Tss), which consists of marine sandstone, siltstone, conglomerate, fossiliferous concretionary sandstone, and shell-hash beds, and the lower to middle Eocene Llajas Formation (Tl), composed of marine silty sandstone and siltstone and non-marine to shallow-marine conglomerate. The Llajas Formation is overlain by the upper Eocene to lower Miocene Sespe Formation (Ts) at the northern edge of the map area. The Sespe Formation consists of non-marine pebble-cobble conglomerate, massive to thick-bedded sandstone, and thin-bedded siltstone and claystone.

The north-dipping Upper Cretaceous through lower Miocene strata that form the Simi Hills are overlapped on the west and south by volcanic and marine clastic rocks of the middle Miocene Topanga Group and deep-marine clastic and biogenic rocks of the upper Miocene Modelo Formation. For the purposes of this study, the sedimentary rocks of the Topanga Group were informally divided into a unit that is predominantly conglomerate and sandstone (Ttc1) and a unit that is predominantly siltstone and claystone with minor sandstone (Ttc2). These sedimentary rocks are interlayered with and/or intruded by volcanic rocks of the Conejo Volcanics (Tc, undifferentiated; Tcbb, basalt/andesite flows; Tcab, andesite-dacite breccias; and Ti, basaltic/andesitic/dacitic dikes and sills). Conejo Volcanics form the steep northern flank of the Santa Monica Mountains in the southern part of the quadrangle and the hilly to mountainous terrain of Mountclef Ridge in the northwest corner of the map area. The Modelo Formation (Tm) is exposed as an arcuate band that cuts diagonally across the area from northwest to southeast and is composed of resistant siliceous shale and calcareous shale, clay shale, diatomaceous shale, siltstone, and minor sandstone.

Quaternary surficial deposits cover the floor and margins of small valleys and relatively low-lying areas in the Thousand Oaks Quadrangle and are also present in the larger canyons that drain the Simi Hills and Santa Monica Mountains. These Pleistocene to Holocene sediments consist of older and younger alluvial-fan and valley deposits, older and younger colluvium, active alluvial fans, and active stream deposits (Qoa, Qof, Qyf, Qoc, Qc, Qf, and Qw). Landslides are widespread in the central portion of the Thousand Oaks Quadrangle, primarily in the tightly folded weaker members of the Modelo Formation. Landslides also occur in the other fine-grained Tertiary sedimentary units, especially where bedding planes are inclined in the same direction as the slope (a dip slope). Landslide deposits are not shown on the bedrock/Quaternary geologic map, but are included on a separate landslide inventory map (Plate 2.1). A more detailed discussion of the Quaternary deposits in the Thousand Oaks Quadrangle can be found in Section 1.

Landslide Inventory

The evaluation of earthquake-induced landsliding requires an up-to-date and complete picture of the previous occurrence of landsliding. An inventory of existing landslides in the Thousand Oaks Quadrangle was prepared (Irvine, unpublished) by using previous work done in the area (Irvine, 1990 and Weber, 1984) and by combining field observations, analysis of aerial photos, and interpretation of landforms on current and older topographic maps. The aerial photos that were used for landslide interpretation are listed under Air Photos in References. Also consulted during the mapping process were the following maps and reports that contain geologic and landslide data: Dibblee (1993); Fugro West (2000); Harp and Jibson (1995); Parker (1985); Squires (1983); Stoney Miller Consultants (2000a and b); Weber and Wills (1983); and Weber and others (1973).

Landslides were mapped and digitized 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. All landslides on the digital geologic map (Yerkes, 1995) were verified or re-mapped during preparation of the inventory map. To keep the landslide inventory of consistent quality, all landslides originally depicted on the digitized geologic map were deleted, and only those included in the final DMG inventory were incorporated into the hazard-evaluation process. A version of this landslide inventory is included with Plate 2.1.

ENGINEERING GEOLOGY

Geologic Material Strength

To evaluate the stability of geologic materials under earthquake conditions, the geologic map units described above were ranked and grouped on the basis of their shear strength. Generally, the primary source for rock shear-strength measurements is geotechnical reports prepared by consultants on file with local government permitting departments. Shear-strength data for the rock units identified on the Thousand Oaks Quadrangle geologic map were obtained from the City of Thousand Oaks (see Appendix A). The locations of rock and soil samples taken for shear testing by consultants are shown on Plate 2.1. When available, shear tests from adjacent quadrangles were used to augment data for geologic formations that had little or no shear test information.

Within the Thousand Oaks Quadrangle, no shear tests were available for Tcab, Tcbb, Tcvb, Ti, Tl, Tlv, Tms, Ts, and Tss. Shear test data for Tms from the Calabasas Quadrangle, for Ts from the Moorpark Quadrangle, and Tcvb from the Newbury Park Quadrangle were used to assign these units to existing strength groups. Additional shear tests for Kc from the Calabasas Quadrangle, and for Qoa, Qya1, Tc, Tm, Ttc1 and Ttc2 from the Newbury Park Quadrangle were used. Tcab, Tcbb, Ti, Tl, Tlv, Tsc, and Tss were added to existing groups on the basis of lithologic and stratigraphic similarities.

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.

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 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, which 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 (higher strength) dominates where bedding dips into a slope (favorable bedding) while fine-grained (lower strength) material 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.

Existing Landslides

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.

The results of the grouping of geologic materials in the Thousand Oaks Quadrangle are in Tables 2.1 and 2.2.

THOUSAND OAKS 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	Tm(fbc)	23	40/39	36	433	Tcbb, Ti	36
	Tcvb	13	38/37			Tsc, Tcab	
	Tc	24	35/35				
	Ttc1	23	34/35				
GROUP 2	Kc(fbc)	45	33/35	33	591	Tl(fbc)	33
	Ts(fbc)	13	32/33			Tlv	
	Ttc2	17	33/31			Tss(fbc)	
	Tms	12	32/34				
GROUP 3	Kc(abc)	18	27/30	29	476	af	29
	Qoa	34	30/28			Qoc?	
	Qof	1	31				
	Tm(abc)	34	30				
GROUP 4	Qya1	10	24/25	25	530	Qc, Qc?, Qc/Qya1	25
	Ts(abc)	5	24/25			Qf, Qya2, Qyf2	
						Qw, Tl(abc)	
						Tss(abc)	
GROUP 5	Qls			10		Qls	10

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 Thousand Oaks Quadrangle.

SHEAR STRENGTH GROUPS FOR THE THOUSAND OAKS QUADRANGLE

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5
Tc	Kc(fbc)	af	Qc	Qls
Tc?	Tl(fbc)	Kc(abc)	Qc?	
Tcab	Tlv	Qoa	Qc/Qya1	
Tcbb	Tms	Qoc?	Qf	
Tcvb	Ts(fbc)	Qof	Qya1	
Ti	Tss(fbc)	Tm(abc)	Qya2	
Tm(fbc)	Ttc2		Qyf2	
Tsc			Qw	
Ttc1			Tl(abc)	
			Ts(abc)	
			Tss(abc)	

Table 2.2. Summary of the Shear Strength Groups for the Thousand Oaks 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 Thousand Oaks 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 DMG for a 10% probability of being exceeded in 50 years (Petersen and others, 1996). The parameters used in the record selection are:

Modal Magnitude:	6.9 to 7.3
Modal Distance:	3.3 to 7.5 km
PGA:	0.43 to 0.60 g

The strong-motion record selected for the slope stability analysis in the Thousand Oaks Quadrangle was the Corralitos record from the magnitude 6.9 (M_w) 1989 Loma Prieta earthquake (Shakal and others, 1989). This record had a source to recording site distance of 5.1 km and a peak ground acceleration (PGA) of 0.64 g. 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 were used as criteria for rating levels of earthquake-induced landslide hazard potential based on the work of Youd (1980), Wilson and Keefer (1983), and a DMG pilot study for earthquake-induced landslides (McCrink and Real, 1996). Applied to the curve in Figure 2.1, these displacements correspond to yield accelerations of 0.086, 0.133 and 0.234g. 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 Thousand Oaks Quadrangle.

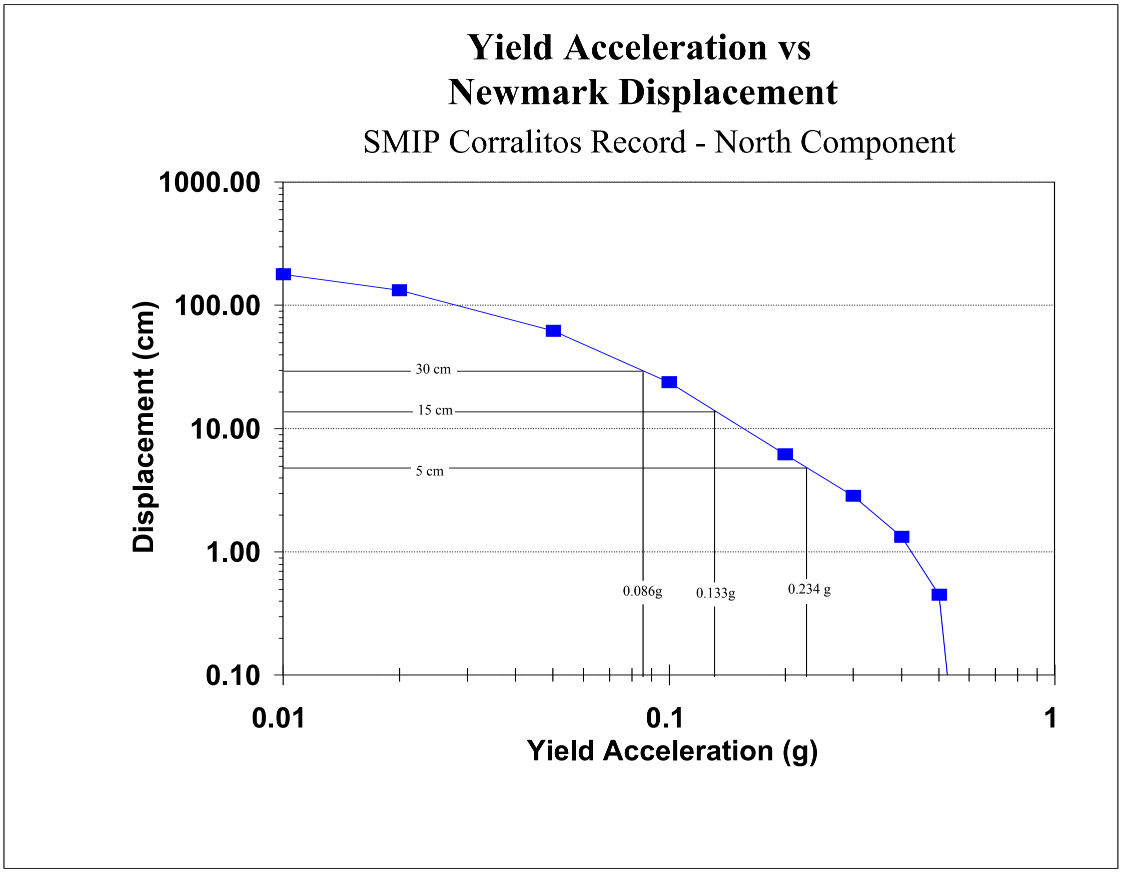

Figure 2.1. Yield Acceleration vs. Newmark Displacement for the 1989 Loma Prieta Earthquake Corralitos Record. Record from California Strong Motion Instrumentation Program (CSMIP) Station 57007.

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 0.086g, 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 0.086g and 0.133g, 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 0.133g and 0.234g, 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 0.234g, 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.

THOUSAND OAKS QUADRANGLE HAZARD POTENTIAL MATRIX

Geologic Material Group	MEAN PHI	SLOPE CATEGORY (% SLOPE) I 0-23	II 23-32	III 32-36	IV 36-40	V 40-46	VI 46-49	VII 49-55	VIII 55-58	IX 58-68	X >68
1	36	VL	VL	VL	VL	VL	VL	L	L	M	H
2	33	VL	VL	VL	VL	L	L	M	H	H	H
3	29	VL	VL	L	L	M	H	H	H	H	H
4	25	VL	L	M	H	H	H	H	H	H	H
5	10	M	H	H	H	H	H	H	H	H	H

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

EARTHQUAKE-INDUCED LANDSLIDE HAZARD ZONE

Criteria for Zoning

Earthquake-induced landslide zones were delineated using criteria adopted by the California State Mining and Geology Board (DOC, 2000). Under these criteria, earthquake-induced landslide hazard zones are defined as areas that meet one or both of the following conditions:

1. Areas that have been identified as having experienced landslide movement in the past, including all mappable landslide deposits and source areas as well as any landslide that is known to have been triggered by historic earthquake activity.

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

These conditions are discussed in further detail in the following sections.

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.

No earthquake-triggered landslides had been identified in the Thousand Oaks Quadrangle prior to the Northridge earthquake. The Northridge earthquake caused a number of relatively small, shallow slope failures in and adjacent to the Thousand Oaks Quadrangle (Harp and Jibson, 1995). Soil falls, debris falls, and debris slides occurred in poorly indurated or highly fractured sedimentary rock on steep slopes and along roadcuts. Seismic shaking also enhanced previously existing headscarps of massive bedrock landslides and created additional cracks on steep slopes and ridge tops. Landslides attributed to the Northridge earthquake covered approximately 20 acres of land in the quadrangle, which is less than ½ of 1 percent of the total area covered by the map. Of the area covered by these Northridge earthquake landslides, 76% falls within the area of the hazard zone based on a computer comparison of the zone map and the Harp and Jibson (1995) inventory.

Geologic and Geotechnical Analysis

Based on the conclusions of a pilot study performed by DMG (McCrink and Real, 1996), 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 23 percent.

3. Geologic Strength Group 3 is included for all slopes steeper than 32 percent.

4. Geologic Strength Group 2 is included for all slopes steeper than 40 percent.

5. Geologic Strength Group 1 is included for all slopes greater than 49 percent.

This results in approximately 18 percent of the quadrangle lying within the earthquake-induced landslide hazard zone for the Thousand Oaks 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. Geologic material strength data were collected at the City of Thousand Oaks Public Works Department with the assistance of Antoinette Mann and Jon Levin. Randy Jibson of the U.S. Geological Survey provided digital terrain data. At DMG, special thanks to Bob Moskovitz, Teri McGuire, Scott Shepherd and Barbara Wanish for their GIS operations support, and to Barbara Wanish for designing and plotting the graphic displays associated with the hazard zone map and this report. Rick Wilson provided DEM assistance in the application of the radar.

Additional information about specific landslides in the area was provided by James P. Quinn (Gorian and Associates Inc.), Thomas F Blake (Fugro West, Inc.), Rudy Ruberti (GeoSoils, Inc.), Jeffrey T. Moerer (Law Office of Jeffrey T. Moerer), and Michael K. Kamino (City of Agoura Hills).

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PACWAS (Pacific Western Aerial Surveys); Flight PW VEN2; May 16, 1978; Frames 113-118 and 140-146; Color; Vertical; scale 1:24,000.

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APPENDIX A
SOURCE OF ROCK STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
City of Thousand Oaks	**192**
Ventura County	**18**
Calabasas Quadrangle	**62**
Total Number of Shear Tests	**272**

SECTION 3
GROUND SHAKING EVALUATION REPORT

Potential Ground Shaking in the Thousand Oaks 7.5-Minute Quadrangle, Ventura and Los Angeles Counties, California

By

Mark D. Petersen*, Chris H. Cramer*, Geoffrey A. Faneros, Charles R. Real, and Michael S. Reichle

California Department of Conservation
Division of Mines and Geology
***Formerly with DMG, 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) 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 DMG’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, 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.

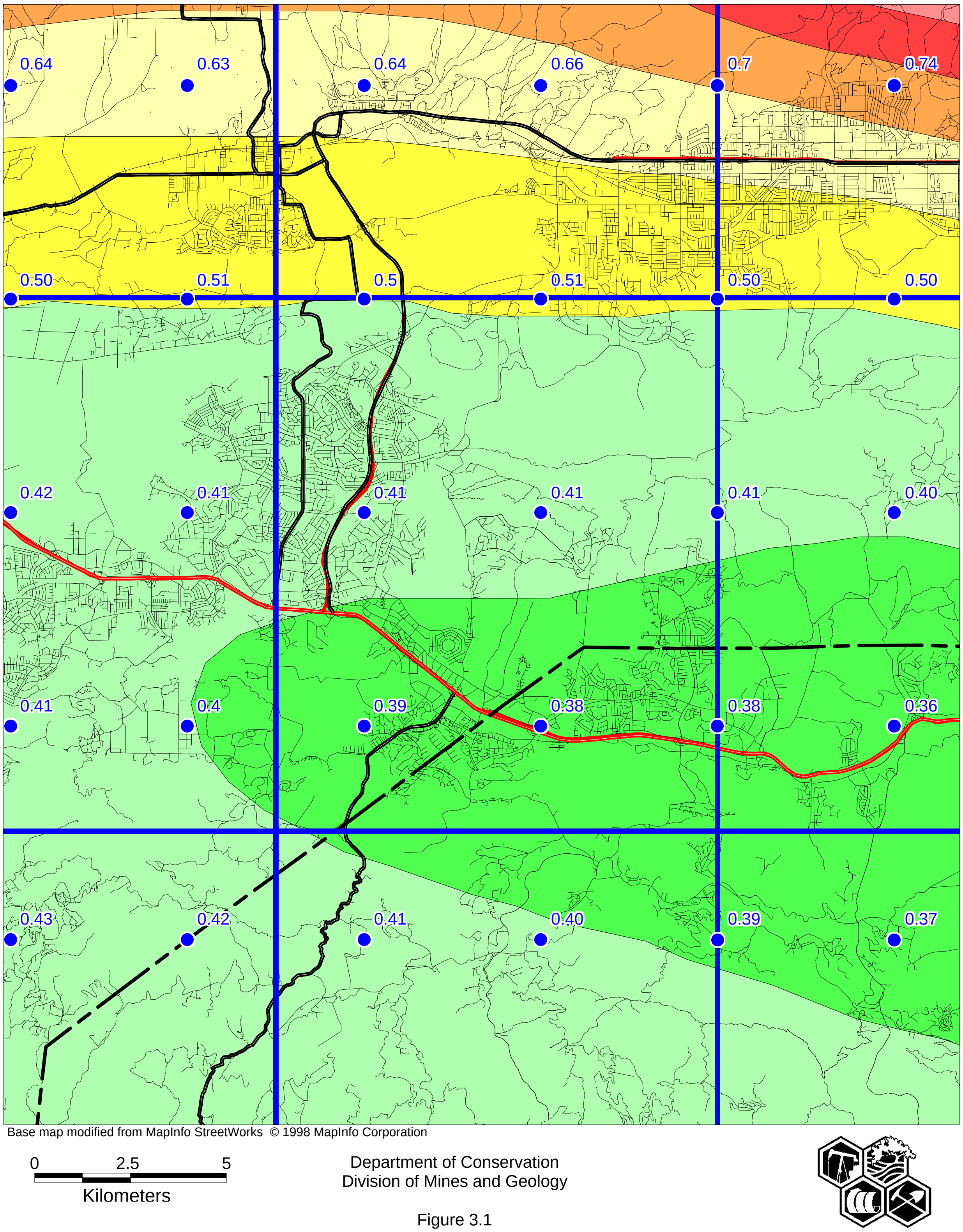
The seismic hazard maps for ground shaking are produced by calculating the hazard at sites separated by about 5 km. Figures 3.1 through 3.3 show the hazard for PGA at 10% probability of exceedance in 50 years assuming the entire map area is firm rock, soft rock, or alluvial site conditions respectively. 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

THOUSAND OAKS 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

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

1998

FIRM ROCK CONDITIONS



Department of Conservation
Division of Mines and Geology

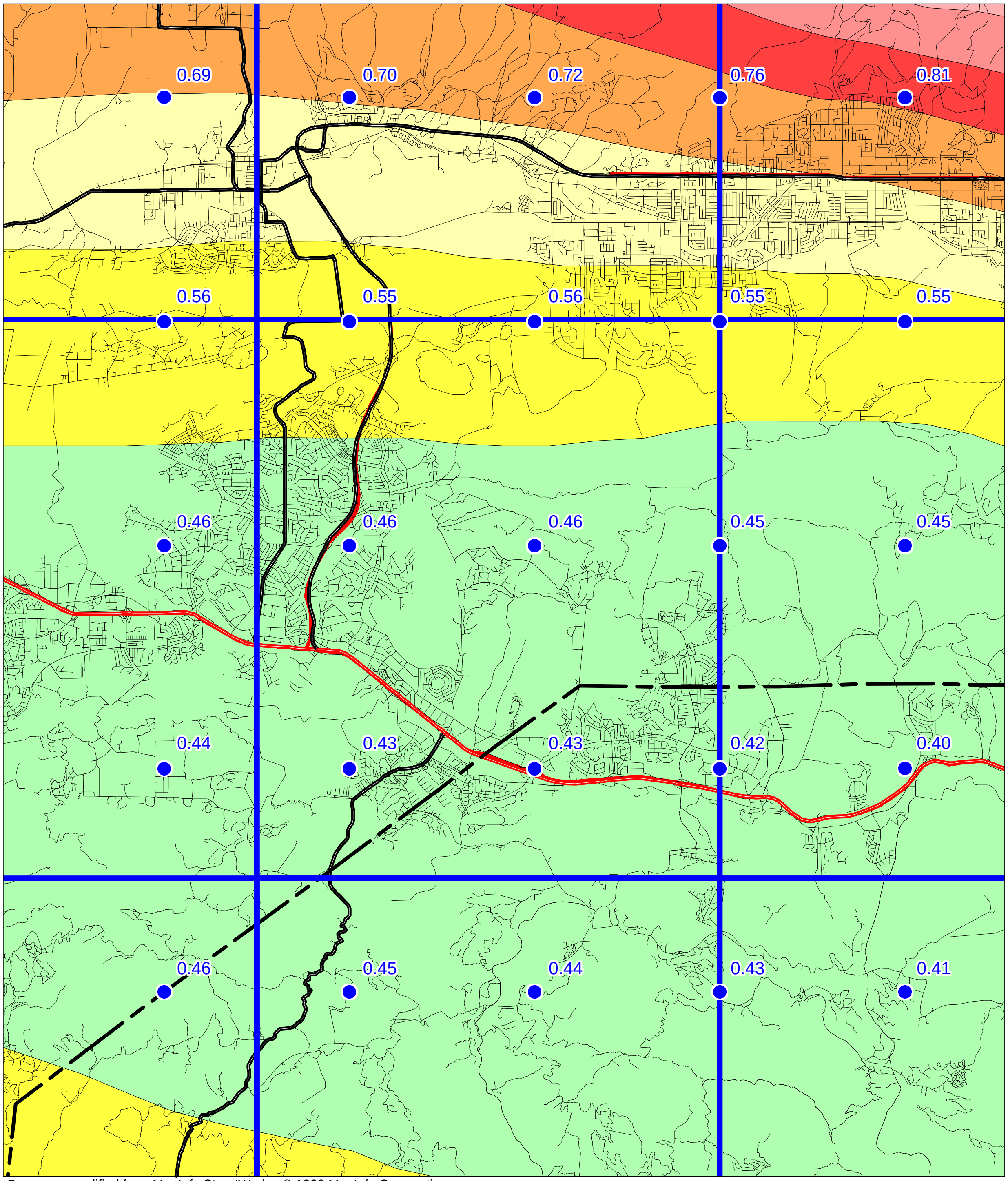
Figure 3.1

THOUSAND OAKS 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

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

1998

SOFT ROCK CONDITIONS



Base map modified from MapInfo StreetWorks © 1998 MapInfo Corporation

0 2.5 5
Kilometers

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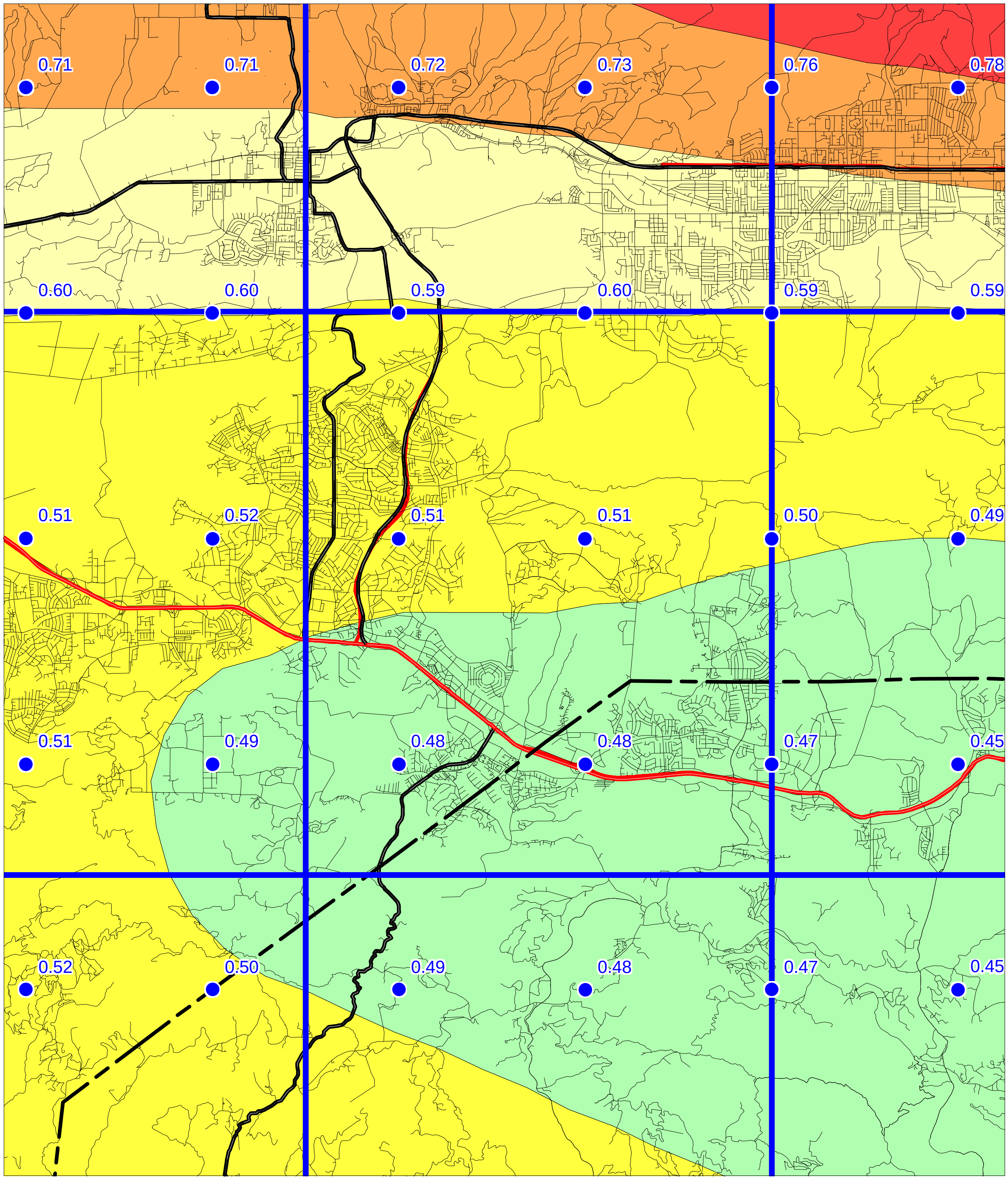
Figure 3.2

THOUSAND OAKS 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

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

1998

ALLUVIUM CONDITIONS



0 2.5 5
Kilometers

Department of Conservation
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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.

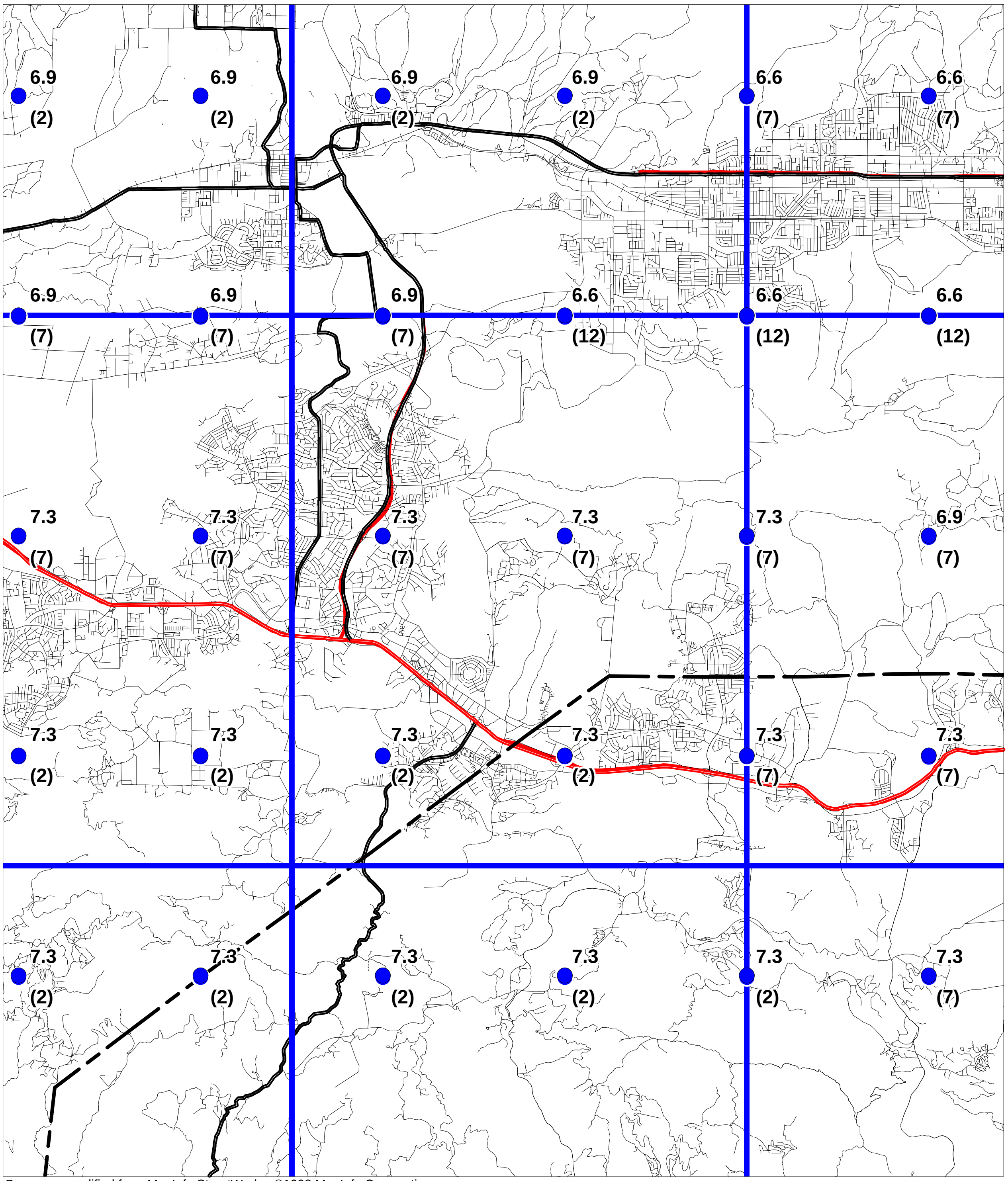
Figure 3.5 shows the magnitude-weighted alluvial PGA based on Idriss’ weighting function (Youd and Idriss, 1997). It is important to note that the values obtained from this map are pseudo-accelerations and should be used in the formula for factor of safety without any magnitude-scaling (a factor of 1)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

THOUSAND OAKS 7.5 MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

10% EXCEEDANCE IN 50 YEARS PEAK GROUND ACCELERATION

1998

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



Base map modified from MapInfo StreetWorks ©1998 MapInfo Corporation

0 2.5 5
Kilometers

Department of Conservation
Division of Mines and Geology

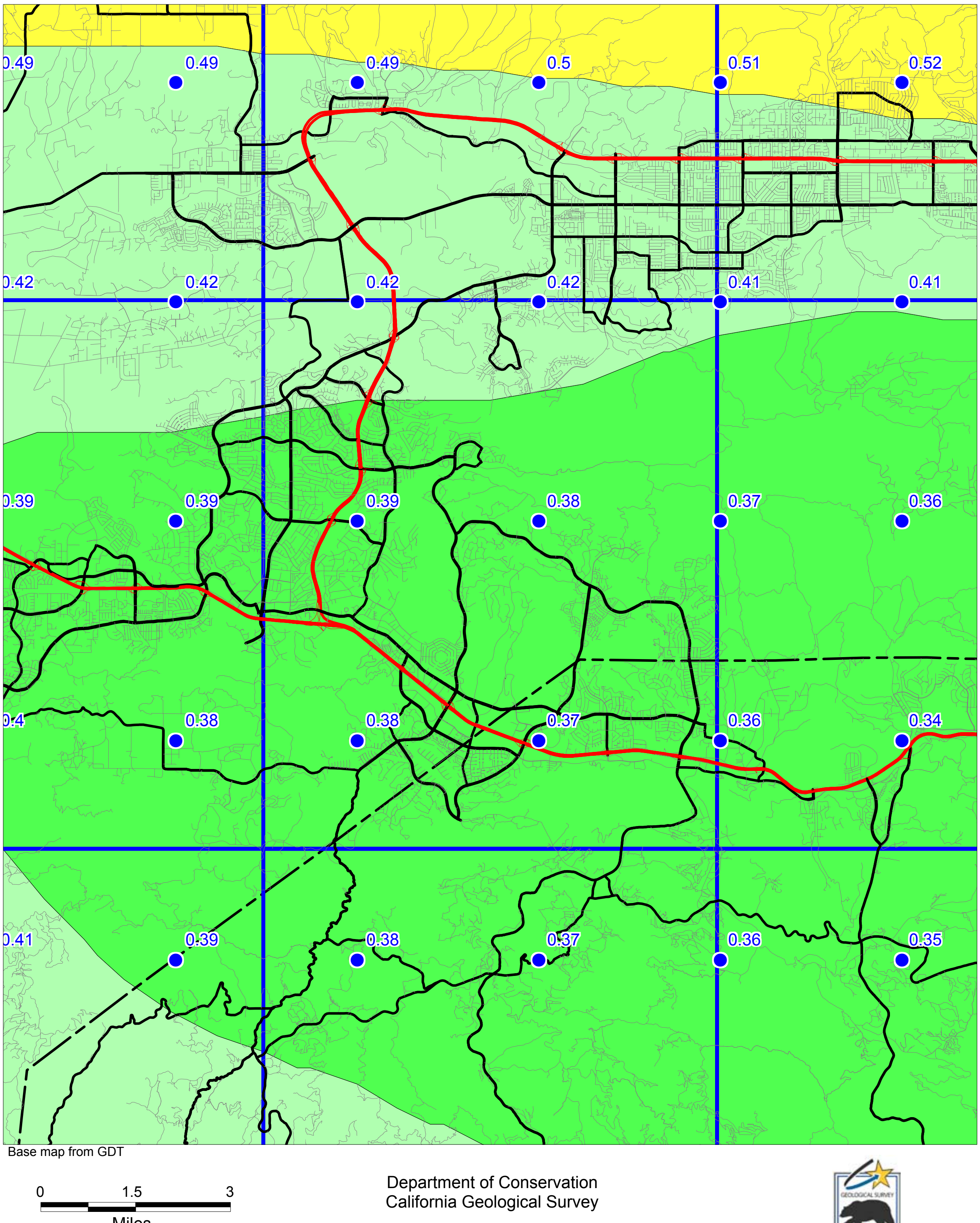
Figure 3.4

THOUSAND OAKS 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



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.

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

Geologic mapping modified from William Lettis & Associates, 1999

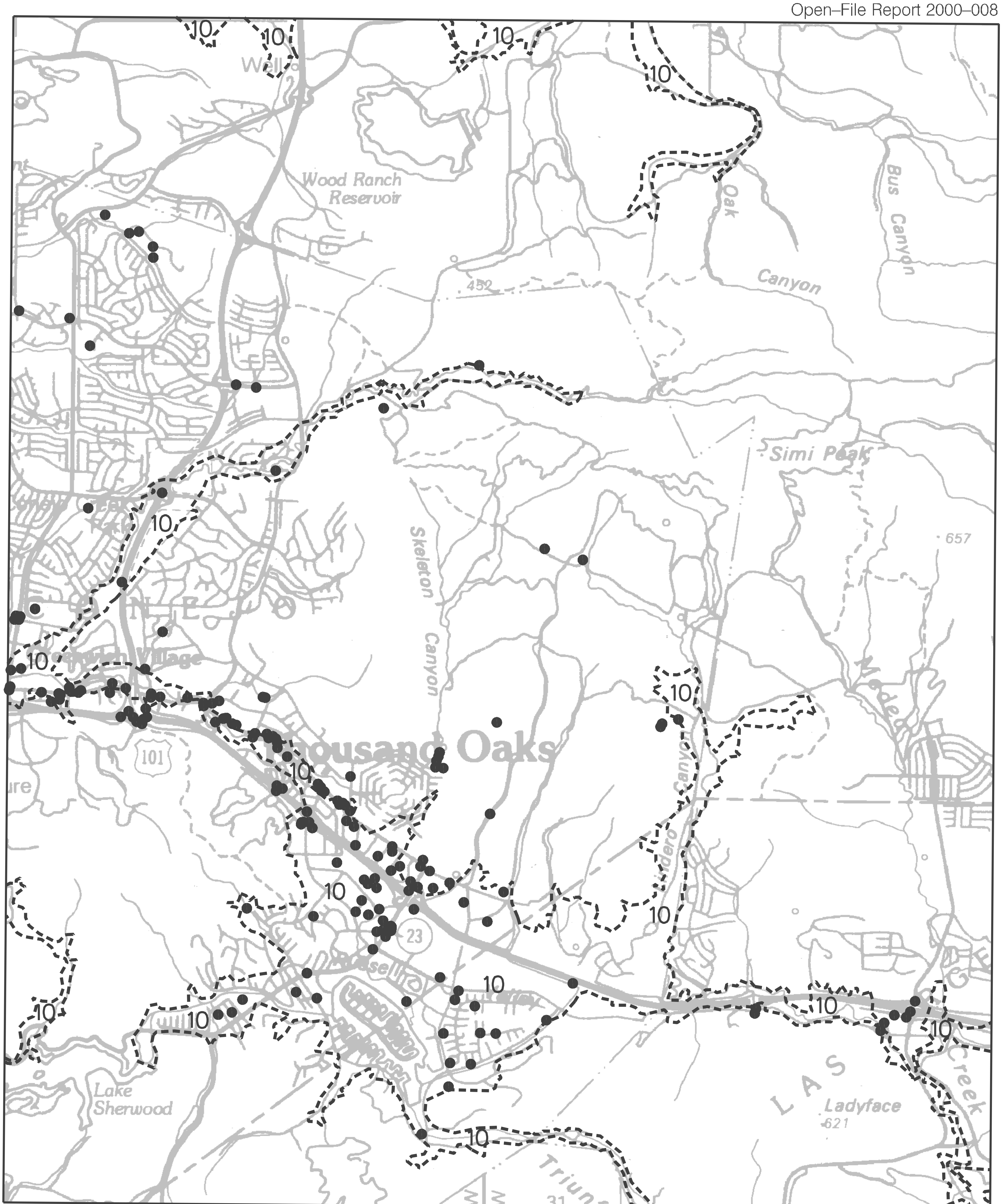
Plate 1.1 Quaternary Geologic Map of the Thousand Oaks Quadrangle.

See Geologic Conditions section in report for descriptions of the units.

B = Pre–Quaternary bedrock.

ONE MILE

Scale



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

Plate 1.2 Historically shallow ground–water depths and borehole data points in alluviated valley areas of the Thousand Oaks Quadrangle.

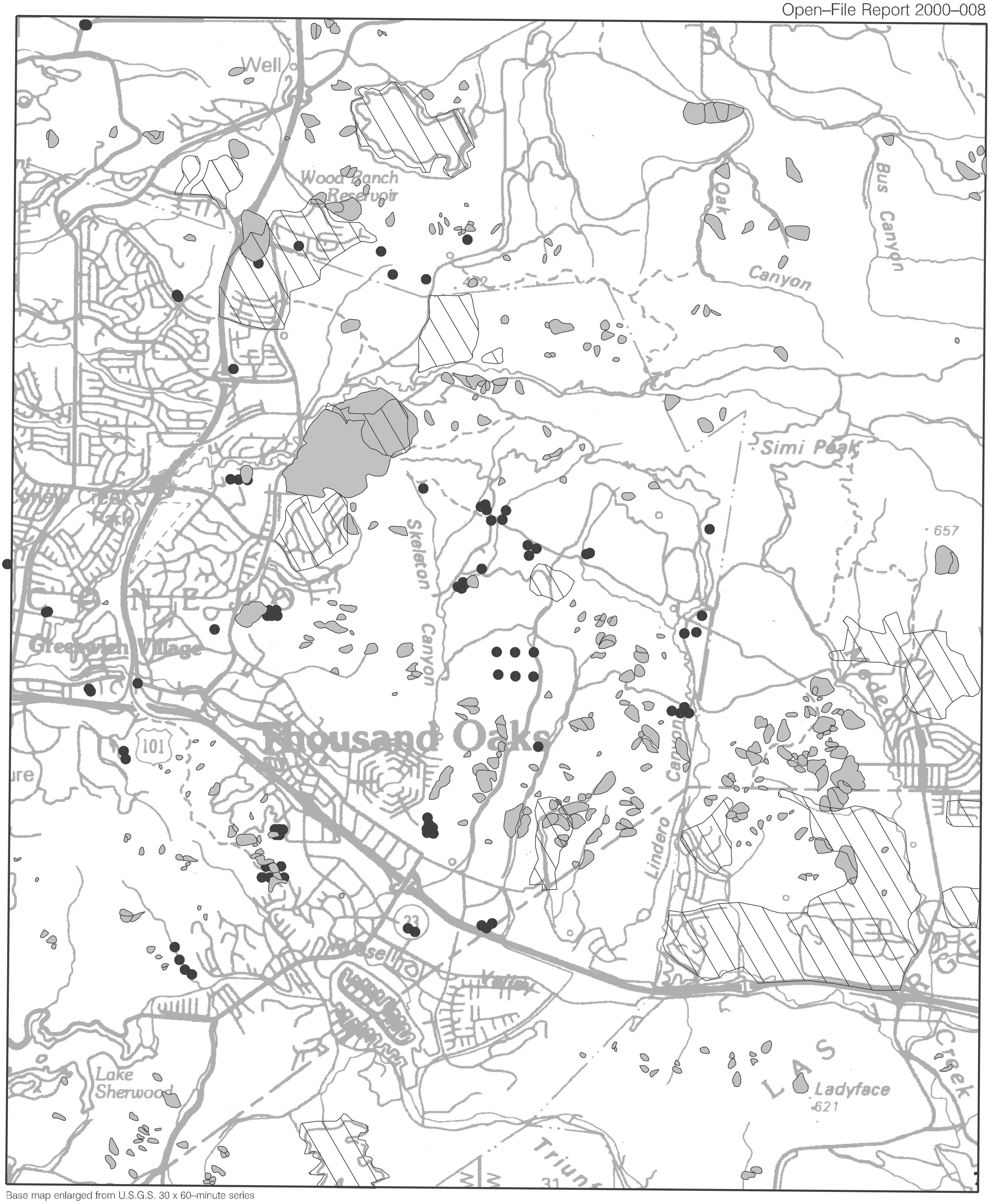
Alluviated Valley

10 Historically shallow ground–water depth where same value occurs over a broad area (in feet)

● Borehole Site

ONE MILE

Scale



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

Plate 2.1 Landslide inventory, Shear Test Sample Locations, and Areas of Significant Grading Thousand Oaks Quadrangle.

● shear test sample location — landslide — areas of significant grading

ONE MILE

SCALE