SEISMIC HAZARD ZONE REPORT FOR THE LIVERMORE 7.5-MINUTE QUADRANGLE, ALAMEDA COUNTY, CALIFORNIA

2008

DEPARTMENT OF CONSERVATION
California Geological Survey

STATE OF CALIFORNIA
ARNOLD SCHWARZENEGGER
GOVERNOR

THE RESOURCES AGENCY
MIKE CHRISMAN
SECRETARY FOR RESOURCES

DEPARTMENT OF CONSERVATION
BRIDGETT LUTHER
DIRECTOR

CALIFORNIA GEOLOGICAL SURVEY
JOHN G. PARRISH, PH.D.
STATE GEOLOGIST

How to view or obtain Seismic Hazard Zone maps

Seismic Hazard Zone Maps, Seismic Hazard Zone Reports, and related information are available on the California Geological Survey's (CGS) Internet page: http://www.consrv.ca.gov/cgs/shzp/Pages/Index.aspx.

The maps and reports are also available for reference at CGS offices in Sacramento, Menlo Park, and Los Angeles at the addresses presented below.

Paper copies of Official Seismic Hazard Zone Maps are available for purchase from:

BPS Reprographic Services
945 Bryant Street
San Francisco, CA 94103
(415) 495-8700

The *Seismic Hazard Zone Report* documents the methods and data used to construct the *Seismic Hazard Zone Map* for each 7.5-minute quadrangle evaluated by CGS. The information should be particularly helpful to site investigators and local government reviewers of geotechnical reports. **NOTE:** *Seismic Hazard Zone Reports* are **not** available through BPS Reprographic Services.

CALIFORNIA GEOLOGICAL SURVEY'S PUBLICATION SALES OFFICES:

Publications and Information Office
801 K Street, MS 14-34
Sacramento, CA 95814-3531
(916) 445-5716

Bay Area Regional Office
345 Middlefield Road, MS-520
Menlo Park, CA 94025
(650) 688-6327

Reports and maps can be viewed at the CGS Southern California Regional Office at the following address:

888 S. Figueroa Street, Suite 475
Los Angeles, CA 90017
(213) 239-0878

TABLE OF CONTENTS

FIGURES

TABLES

PLATES

Release and Revision History: Seismic Hazard Zone Map and Evaluation Report of the Livermore Quadrangle, SHZR 114	
February 27, 2008	Release of Preliminary Seismic Hazard Zone Map
May 8, 2008	Posting of evaluation report on CGS website
August 27, 2008	Posting of official evaluation report on CGS website

EXECUTIVE SUMMARY

This report summarizes the methods and sources of information used to prepare the Seismic Hazard Zone Map for the Livermore 7.5-Minute Quadrangle, Alameda County, California. The quadrangle covers approximately 60 square miles in eastern Alameda and Contra Costa Counties at a scale of 1 inch = 2,000 feet and displays the boundaries of preliminary *Zones of Required Investigation* for liquefaction and earthquake-induced landslides. The area subject to seismic hazard mapping includes parts of the cities of Livermore, Pleasanton, and Dublin. Approximately 1 square mile in the northwest corner of the quadrangle falls within Contra Costa County, which will be evaluated later.

About 19 square miles of land within the Alameda County part of the quadrangle are designated as *Zones of Required Investigation* for liquefaction hazard. These zones encompass about two-thirds of Livermore and Amador Valleys and most of the stream valleys and canyons leading into the surrounding hills. Borehole logs of test holes in alluviated areas indicate the widespread presence of near-surface soil layers composed of saturated, loose sandy and silty sediments. Geotechnical tests conducted downhole and in soil labs indicate that these soils generally have a moderate to high likelihood of liquefying, given the level of strong ground motions expected for this region.

The combined total area within the Livermore Quadrangle designated as *Zones of Required Investigation* for earthquake-induced landsliding is roughly 12 square miles. Most of these zones are concentrated in two separate hilly areas to the north and south of Livermore and Amador Valleys.

Seismic hazard maps are prepared by the California Geological Survey (CGS) using geographic information system (GIS) technology, which allows the manipulation of three-dimensional data. Information analyzed in these studies includes topography, surface and subsurface geology, borehole log data, recorded groundwater levels, existing landslide features, slope gradient, rock-strength measurements, geologic structure, and probabilistic earthquake shaking estimates. Ground shaking inputs are based upon probabilistic seismic hazard maps that depict peak ground acceleration, mode magnitude, and mode distance with a 10 percent probability of exceedance in 50 years.

City, county, and state agencies are required by the California Seismic Hazards Mapping Act to use the seismic hazard zone maps in their land-use planning and permitting processes. They must withhold building permits for sites being developed within *Zones of Required Investigation* 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 of real property within these zones to disclose that fact at the time such property is sold.

THE CALIFORNIA SEISMIC HAZARDS MAPPING PROGRAM

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the State Geologist to prepare maps that delineate seismic hazard zones. The purpose of the Act is to reduce the threat to public safety and to minimize the loss of life and property by identifying and mitigating seismic hazards. City, county, 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 online at: http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf.

The Act 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, the SMGB adopted initial criteria for delineating seismic hazard zones to promote uniform and effective statewide implementation of the Act. These initial criteria, which were published in 1992 as California Geological Survey (CGS) Special Publication 118, were revised in 2004. They provide detailed standards for mapping regional liquefaction and landslide hazards. The Act also directed the State Geologist 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.

In April 2004, significant revisions of liquefaction zone mapping criteria relating to application of historically high groundwater level data in desert regions of the state were adopted by the SMGB. These modifications are reflected in the revised CGS Special Publication 118, which is available on online at: http://gmw.consrv.ca.gov/shmp/webdocs/sp118_revised.pdf.

This Seismic Hazard Zone Report summarizes the development of the *Preliminary Seismic Hazard Zone Map* for the Livermore 7.5-Minute Quadrangle. The process of zonation for liquefaction hazard involves an evaluation of Quaternary geologic maps, groundwater level records, and subsurface geotechnical data. The process of zonation for earthquake-induced landslide hazard incorporates evaluations of earthquake loading, existing landslides, slope gradient, rock strength, and geologic structure. A statewide *Earthquake Shaking Potential Map*, based on probabilistic seismic hazard analysis (PSHA), has been prepared so that uniformly generated ground motion parameters (peak ground acceleration, mode magnitude, mode distance) are applied to all CGS liquefaction and earthquake-induced landslide hazard assessments.

SEISMIC HAZARD ZONE REPORT 114

SEISMIC HAZARD ZONE REPORT FOR THE LIVERMORE 7.5-MINUTE QUADRANGLE, ALAMEDA COUNTY, CALIFORNIA

2008

DEPARTMENT OF CONSERVATION
California Geological Survey

STATE OF CALIFORNIA
ARNOLD SCHWARZENEGGER
GOVERNOR

THE RESOURCES AGENCY
MIKE CHRISMAN
SECRETARY FOR RESOURCES

DEPARTMENT OF CONSERVATION
BRIDGETT LUTHER
DIRECTOR

CALIFORNIA GEOLOGICAL SURVEY
JOHN G. PARRISH, PH.D.
STATE GEOLOGIST

SECTION 1: EVALUATION REPORT FOR LIQUEFACTION HAZARD

in the

LIVERMORE 7.5-MINUTE QUADRANGLE, ALAMEDA COUNTY, CALIFORNIA

By
Anne M. Rosinski

DEPARTMENT OF CONSERVATION
CALIFORNIA GEOLOGICAL SURVEY

INTRODUCTION

Background

The Seismic Hazards Mapping Act of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California State Geologist to compile maps that identify *Seismic Hazard Zones* consistent with requirements and priorities established by the California State Mining and Geology Board (SMGB; DOC, 1997). The text of the guidelines is available online at: http://www.conservation.ca.gov/cgs/shzp/webdocs/sp117.pdf. The Act requires that site-specific geotechnical investigations be performed for most urban development projects situated within seismic hazard zones before lead agencies can issue the building permit.

Following the release of the SMGB Guidelines, local government agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction hazard. 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 (Southern California Earthquake Center, 2002). This text is also online at: http://www.scec.org/.

This section of the evaluation report summarizes seismic hazard zone mapping for potentially liquefiable soils in the Livermore 7.5-Minute Quadrangle. Section 2 (addressing earthquake-induced landslide hazard) and Section 3 (addressing potential ground shaking) complete the evaluation report, which is one of a series that summarizes seismic hazard zone mapping by CGS in developing areas of the state where there is potential for strong ground motion (Smith, 1996). Additional information on seismic hazards zone mapping in California can be accessed on CGS's web page: http://gmw.consrv.ca.gov/shmp/

Liquefaction-induced ground failure historically has been a major cause of earthquake damage in northern California. During the 1989 Loma Prieta and 1906 San Francisco earthquakes, significant damage to roads, utility pipelines, buildings, and other structures in the San Francisco Bay area was caused by liquefaction-induced ground displacement.

Localities most susceptible to liquefaction-induced damage are underlain by loose, water-saturated, granular sediment within 50 feet of the ground surface. These geological and groundwater conditions are widespread in the San Francisco Bay Area, 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 especially in areas marginal to the bay, including areas in the Livermore Quadrangle.

Methodology

CGS's evaluation of liquefaction potential and preparation of seismic hazard zone maps requires the collection, compilation, and analysis of various geotechnical information and map data. The data are processed into a series of geographic information system (GIS) layers using commercially available software. In brief, project geologists complete the following principal tasks to generate a seismic hazard zone map for liquefaction potential:

- Compile digital geologic maps to delineate the spatial distribution of Quaternary sedimentary deposits

- Collect geotechnical borehole log data from public agencies and engineering geologic consultants.

- Enter boring log data into the GIS.

- Generate digital cross sections to evaluate the vertical and lateral extent of Quaternary deposits and their lithologic and engineering properties.

- Evaluate and digitize historically highest groundwater levels in areas containing Quaternary deposits.

- Characterize expected earthquake ground motion, also referred to as ground-shaking opportunity (see Section 3 of this report).

- Perform quantitative analyses of geotechnical and ground motion data to assess the liquefaction potential of Quaternary deposits.

- Synthesize, analyze, and interpret above data to create maps delineating *Zones of Required Investigation* according to criteria adopted by the SMGB (DOC, 2004).

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 Livermore Quadrangle consist mainly of alluviated valleys, floodplains, and canyons. CGS's liquefaction hazard evaluations are based on information on earthquake ground shaking, surface and subsurface lithology, geotechnical soil properties, and groundwater 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 groundwater, 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.

This section of the report is presented in two parts. Part I addresses the geographic and geologic setting of the study area while Part II documents the data and parameters used to evaluate liquefaction hazard and to delineate *Zones of Required Investigation* in the Livermore 7.5-Minute Quadrangle.

PART I: GEOGRAPHIC AND GEOLOGIC SETTING

PHYSIOGRAPHY

Location

The Livermore 7.5-Minute Quadrangle covers approximately 60 square miles of land surface in Alameda and Contra Costa Counties in the eastern San Francisco Bay Area. Approximately one square mile in the northwest portion of the quadrangle is within Contra Costa County, which will be evaluated for seismic hazard mapping at a later date. The remaining map area lies in Alameda County and includes the cities of Livermore, Pleasanton and Dublin.

Most of Livermore and Amador Valley floors fall within the Livermore Quadrangle, with only a small portion of the valley west of Tassajara Road extending into the adjacent Dublin Quadrangle and that portion of the valley lying east of the City of Livermore's civic center falling into the adjoining Altamont Quadrangle.

Major transportation routes in the map area include west-trending Interstate Highway 580. Additional access is provided by a network of city, county, and private roads in developed areas and by fire roads and trails in undeveloped areas.

Land Use

Land use in the Livermore-Pleasanton region historically was dominated by viticulture in valley areas and cattle grazing in the surrounding hills. However, in the last several decades competition for land use, particularly in valley lands, has increased substantially as urban development has continued to expand beyond the original city boundaries. At the same time, the Livermore and Amador Valleys have long been an economically important source of aggregate to the Bay Area, in large part because of the number and size of multiple water courses that over the last several million years have been eroding surrounding highlands and depositing large amounts of sediments, including sand and gravel, into the basin. Several gravel quarries near the west-central portion of the map area are still in production. Some gravel quarries that are no longer in use have been converted to recreational use. In addition, a chain-of-lakes system has been developed using a series of former gravel quarries linked to adjacent arroyos to catch and store winter runoff. Water that is collected in these lakes is allowed to slowly seep into the ground and recharge the underlying basin (Figures and Ehman, 2004).

Topography

Most of the northern third and southern third of the map are occupied by foothills of the Diablo Range, which is part of the Coast Range Geomorphic province. Numerous named and un-named creeks and streams flow through the map area. From the confluence of Dry Creek and Arroyo Valle at the southeast corner of the quadrangle, Arroyo Valle flows northwest until just south of the intersection of the Southern Pacific and Western Pacific Rail lines, at which point Arroyo Valle changes direction and flows due west. Arroyo Mocho and Arroyo Las Positas both originate in the hills at the eastern edge of the map area and flow roughly east through the center of the quadrangle. Cayetano, Cottonwood and Tassajara Creeks all flow south out of the foothills in the northern half of the map area and into Arroyo Las Positas. Elevations within the map area range from 1264 at the Vern vertically authenticated benchmark in the southwest corner of the quadrangle, to less than 350 feet at the western end of the valley floor.

GEOLOGY

Geologic units that generally are susceptible to liquefaction are late Quaternary alluvial and fluvial sedimentary deposits and artificial fill. To evaluate the areal and vertical distribution of Quaternary deposits in the Livermore Quadrangle, recently completed geologic maps of the nine-county San Francisco Bay Area showing Quaternary deposits (Sowers, unpublished) and bedrock units (Graymer and others, 1996) were obtained from the U.S. Geological Survey in digital form. The GIS maps and layers covering the Livermore quadrangle were combined, with minor modifications along the bedrock/Quaternary contact, to form a single, 1:24,000-scale *geologic materials map* that displays map unit polygons only (*i.e.* no faults, fold axes, or point data). The distribution of Quaternary deposits on this map (summarized on Plate 1.1) was used in combination with other data, discussed below, to evaluate liquefaction susceptibility and develop the Seismic Hazard Zone Map.

Digital data, including Intermap Digital Terrain Model (DTM) at five-meter resolution (2003) and Google Digital Globe Color Imagery at a one-meter resolution (2006) were used extensively to validate minor modifications to bedrock/Quaternary contacts. Limited field reconnaissance was conducted to confirm the location of geologic contacts, map recently modified ground surfaces, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units.

Bedrock Units

Although bedrock units are not generally considered subject to liquefaction, they are briefly described in this section because the composition and texture of sediments that accumulate in lowland basins such as the Livermore and Amador Valleys are governed in large part by the lithology of older rocks exposed in surrounding highlands. Most of the bedrock exposed in the hilly areas within the Livermore Quadrangle consists of marine sediments of Miocene and Pliocene age that have been divided into several mappable units, including the Cierbo Sandstone; siltstone, sandstone, conglomerate, and shell breccia of the Briones Formation; and sandstone, siltstone, and conglomerate beds of the Green Valley and Tassajara Formation. Unconformably overlying these rocks is the Plio-Pleistocene Livermore Gravels deposit, the most widely exposed bedrock unit in the basin. It crops out around the northern and southern margins of the Livermore and Amador Valleys and consists mainly of cobble conglomeratic sandstone, coarse-grained sandstone, siltstone, and claystone beds that have been anticlinally folded (Dibblee, 1980). For more detail on bedrock exposed in the Livermore Quadrangle, see Section 2 of this report, *Evaluation Report for Earthquake-Induced Landslide Hazard*.

Quaternary Sedimentary Deposits

Witter and others (2006) mapped 16 distinct Quaternary units covering roughly two-thirds of the area encompassed by the Livermore Quadrangle. The deposits are exposed mainly on the floor of Livermore and Amador Valleys as well as in small, alluviated, upland valleys and canyons (Plate 1.1). The Quaternary geologic mapping methods described by Witter and others (2006) consist of interpretation of topographic maps, aerial photographs, and soil surveys, as well as compiled published and unpublished geologic maps. The authors estimate the ages of deposits using: landform shape, relative geomorphic position, cross cutting relationships, superposition, depth and degree of surface dissection, and relative degree of soil profile development. Table 1.1 compares stratigraphic nomenclature used in Knudsen and others (2000) and the CGS GIS database, with that of several previous studies performed in northern California.

Older Quaternary Units

Large deposits of early to middle Pleistocene alluvium, mapped as undifferentiated (Qoa) are exposed almost exclusively along base of the hills at the southern end of the map area. Late Pleistocene alluvial fan deposits (Qpf) pro-grade from the distal end of Qoa deposits in the southern half of the map area. In addition, Qpf deposits are found at the base of many of the hills in the northeastern corner of the quadrangle. Remnants of late Pleistocene stream terrace deposits (Qpt) are found at the outside edges of the flood plain adjacent to the upstream end of Arroyo Valle.

Young Quaternary Units

Latest Pleistocene to Holocene alluvium, undifferentiated (Qa) is mapped in narrow upland valleys in the hills in the northern and southern parts of the quadrangle. Late Pleistocene to Holocene stream terrace deposits (Qt) are mapped in small quantities adjacent to Arroyo Valle along the south margin of the Livermore Valley, and adjacent to Arroyo Las Positas along the northern margin of the Livermore Valley. Isolated quantities of late Pleistocene to Holocene alluvial fan deposits (Qf) are mapped at the base of the hills in the northern half of the quadrangle and in the vicinity of the south side of the upstream end of Arroyo Mocho at the eastern edge of the map area.

Holocene alluvium, undifferentiated (Qha) is mapped in long, narrow bands in upland canyons and along the banks of several creeks, including Tassajara, Cottonwood, Cayatano, Arroyo Mocho, and Dry Creeks. Holocene alluvial fan (Qhf) deposits cover the floor of the Livermore Valley, and in the northwest portion of the valley, grade into Holocene alluvial fan deposits, fine facies (Qhff). Long, narrow deposits of Latest Holocene alluvial deposits, undifferentiated (Qhay) are mapped along the upstream portion of Cayatano Creek in the northeast corner of the map area. Latest Holocene stream terrace deposits (Qhty) are mapped in large quantities adjacent to the entire length of Arroyo Valle along the southern margin of the Livermore Valley, and in smaller quantities along Arroyo Mocho and Arroyo Las Positas. Latest Holocene alluvial fan deposits (Qhfy) are mapped primarily at the down-stream end of Arroyo Mocho near the center of the Livermore Valley where their natural distribution is truncated by gravel quarry operations.

Modern stream channel deposits (Qhc) “fluvial deposits within active, natural stream channels” (Witter and others, 2006) are mapped along all major creeks and streams in the Livermore Valley. To accommodate larger flows in the winter months, the down stream end of Arroyo Mocho, Arroyo Las Positas, and Cayatano Creeks have been engineered within concrete-lined structures and are mapped as artificial channel (ac). Finally, artificial fill (af), is commonly mapped in association with infrastructure such as highways and rail lines, as well as small-scale construction projects.

Structure

The Livermore Quadrangle lies within the San Andreas Fault system, which constitutes one of Earth’s major crustal plate boundaries, separating the North American and Pacific tectonic plates. The two plates are moving past each other in a right lateral sense at the rate of about 4.8

GEOLOGIC UNIT	Knudsen and others (2000)	Graymer and others, unpublished Stockton 100k	Sowers, unpublished	CGS GIS DATABASE
Artificial fill	af	af	af	af
Artificial fill, levee	alf	alf	alf	alf
Gravel quarries and percolation ponds	gq	GP	gq	gq
Artificial stream channel	ac	Qhasc	ac	ac
Modern stream channel deposits	Qhc	Qhsc	Qhc	Qhc
Latest Holocene alluvial fan deposits	Qhfy		Qhfy	Qhfy
Latest Holocene stream terrace deposits	Qhty	Qhfp1/Qhfp2	Qhty	Qhty
Latest Holocene alluvial deposits, undifferentiated	Qhay		Qhay/Qhi	Qhay
Holocene alluvial fan deposits	Qhf		Qhfy	Qhf
Holocene alluvial fan deposits, fine grained facies	Qhff		Qhff	Qhff
Holocene alluvial fan levee deposits	Qhl			Qhl
Holocene stream terrace deposits	Qht	Qhfp	Qht/Qht1/Qht2	Qht
Holocene alluvium, undifferentiated	Qha	Qhaf	Qha	Qha
Late Pleistocene to Holocene alluvial fan deposits	Qf		Qf	Qf
Late Pleistocene to Holocene stream terrace deposits	Qt		Qt	Qt
Late Pleistocene to Holocene alluvium, undifferentiated	Qa		Qa	Qa
Late Pleistocene alluvial fan deposits	Qpf	Qpaf	Qpf	Qpf
Late Pleistocene stream terrace deposits fan deposits	Qpt		Qpt	Qpt
Early to middle Pleistocene undifferentiated alluvial deposits	Qoa	Qpaf/Qpoaf	Qoa	Qoa
bedrock	br			br

Table 1.1. Correlation chart of Quaternary stratigraphic nomenclatures used in previous studies.

Note: For this study, CGS has adopted the nomenclature of Knudsen and others (2000).

centimeters per year (Petersen and others, 1996). At the latitude of the San Francisco Bay area, about three-fourths of this relative movement is accommodated by shearing distributed across a broad, complex belt of major northwest-trending faults that include the San Andreas, Hayward, and Calaveras, as well as many parallel secondary faults such as the Greenville, Green Valley, and San Ramon-Concord. Furthermore, differential strike-slip movement among these faults locally generates additional thrust faulting, folding, and related structures throughout the belt, including the area covered by the Livermore Quadrangle. From the Livermore and Amador Valley region north through the Diablo Range, this intense zone of deformation is referred to by Unruh and Sawyer (1997) as the Mt. Diablo fold and thrust belt.

The Livermore and Amador Valleys are a synclinal basin bounded on the east by the Greenville Fault and on the west by the Calaveras Fault. The basin is also bounded on the southeast by the Las Positas Fault and on the southwest by hills lying above the northeast-dipping Verona Thrust Fault. The northern edge of the basin is bounded by the Mocho Fault (Unruh and Sawyer, 1997). In addition, previous investigators (DWR, 1974) and Carpenter and others, 1984) show evidence of a buried, northwest-striking fault, referred to as the Livermore Fault, which bisects central Livermore Valley (Sawyer, 1999). The existence of this and other concealed faults in the Livermore and Amador Valleys is based largely on differences in depth to groundwater on either side of their inferred traces as recorded from water well measurements.

ENGINEERING GEOLOGY

Groundwater

Saturated soil conditions are required for liquefaction to occur, and the susceptibility of a soil to liquefaction varies with the depth to groundwater. Saturation reduces the effective normal stress of near-surface sediment, thereby increasing the likelihood of earthquake-induced liquefaction (Youd, 1973). CGS compiles and interprets current and historical groundwater data to identify areas presently or potentially characterized by near-surface, saturated soils. For purposes of seismic hazard zonation, "near-surface" means groundwater level at a depth less than 40 feet.

During the course of this study, groundwater conditions were investigated for alluvial basins within the Livermore Quadrangle. The evaluation was based on first-encountered, unconfined water noted in geotechnical borehole logs acquired from the City of Livermore, Alameda County, and the California Department of Transportation (CalTrans). Additional data were also collected from the State Water Resources Control Board (SWRCB), and the Alameda County Flood Control and Water Conservation District Zone 7 Water Agency (Zone 7 Water Agency). Natural hydrologic processes and human activities can cause groundwater levels to fluctuate over time. Therefore, it is impossible to predict depths to saturated soils when future earthquakes strike. One method of addressing time-variable depth to saturated soils is to establish an anticipated high groundwater level based on historical groundwater data. CGS thus develops contour maps to depict depths to groundwater that are either currently near-surface or could return to near-surface levels within a land-use planning interval of 50 years. Therefore, it is important to note that the contour lines on Plate 1.2 do not generally represent present-day conditions as usually presented on typical groundwater contour maps. Also, keep in mind that large-scale, artificial recharge programs, such as the ones already established in Livermore

Valley, could significantly affect future groundwater levels. In such cases, CGS will periodically evaluate their impact relative to liquefaction potential and revise official seismic hazard zone maps if necessary.

According to a recent study of sequence stratigraphy in the Livermore basin prepared by Figures and Ehman (2004) for the Zone 7 Water Agency, "The current subsurface geologic model of the Livermore basin was developed by the California Department of Water Resources (DWR) in the early 1970's (DWR 1966, 1974, 2003). A large amount of surface and subsurface data has been collected since the DWR basin groundwater model was developed, but there has been no re-evaluation or modification of the basin geologic model." The Zone 7 Water Agency, which is responsible for managing both surface and groundwater supplies in the Livermore Valley basin, has been monitoring groundwater levels for over 30 years. Well data cover the period from 1900 through 2005 and show significant fluctuation in overall water depth during that period. It is the practice of the Zone 7 Water Agency to use water levels measured in 1983-1984 as the historical maximum groundwater depth for basin management purposes (Jones & Stokes, 2006).

CGS digitized the groundwater elevation map prepared by Zone 7 Water Agency and by converting it and a digital elevation map (DEM) to grid maps, produced a third grid map showing depth to historically high groundwater throughout the basin. These values were then compared to the water-depth measurements recorded on geotechnical boring logs collected from the above agencies. For the most part, water depths from individual boring/well logs correlate well with historically highest groundwater elevations shown on the 1983-1984 contour map prepared by the Zone 7 Water Agency.

The boundaries of the Zone 7 Water Agency map of historical high groundwater elevations roughly coincide with the base of the foothills that surround the Livermore Valley. The maps don't describe groundwater conditions in the stream and canyon bottoms in the surrounding hilly terrain or the upland alluviated valleys. Depths to groundwater estimates for these areas are generally based on data from an insufficient number of well logs.

Depth to groundwater near the center of the Livermore 7.5-Minute Quadrangle is strongly influenced by temporary water filled pits associated with gravel mining activities. The continuous relocation of the pits over the years has resulted in localized changes to permeability that affect the ability of water to seep into and flow through the soil, resulting in groundwater contours that are not reliable and/or do not reflect conditions found in nature. For this reason, groundwater contour and grid maps have been simplified to reflect an estimate of groundwater conditions prior to the existence of the gravel pits.

As defined by the Zone 7 Water Agency, historical high groundwater depths in the Livermore Quadrangle range from approximately 0 to 150 feet. Historical high groundwater levels are generally deepest toward the center of the basin, ranging in depth between 40 and 90 feet and becoming progressively shallower toward the basin's boundaries. Measured depth to groundwater for many of the borings located in the foothills outside of the groundwater basin are greater than 60 feet.

Soil Testing

A total of 150 borehole logs were collected for this investigation from the files of Alameda County, CalTrans, the Division of the State Architect, and the cities of Livermore, Dublin, and Pleasanton. Data from 144 of these borehole logs were entered into a CGS geotechnical GIS database.

As stated above, soils that are particularly susceptible to liquefaction are late Quaternary alluvial and fluvial sedimentary deposits and non-engineered artificial fill. Deposits that contain saturated loose sandy and silty soils are the most susceptible to liquefaction. Lithologic descriptions and soil test results reported in geotechnical borehole logs provide valuable information regarding subsurface geology, groundwater levels, and the engineering characteristics of sedimentary deposits. Furthermore, the application of GIS technology greatly enhances the ability to synthesize and manipulate large volumes of geotechnical data. For example, Table 1.2 characterizes the various depositional environments present in the Livermore Valley by showing proportions of the different subsurface sediment types penetrated by the boreholes and recorded on logs.

Of particular value in liquefaction evaluations are logs that report the results of downhole standard penetration tests in alluvial materials. The standard penetration test (SPT) provides a standardized measure of the penetration resistance of soil and, therefore, is commonly used as a tool to index soil density. For this reason, SPT results are also a critical component of the Seed-Idriss Simplified Procedure, a method used by CGS and commonly by the geotechnical community to quantitatively analyze liquefaction potential of sandy and silty material (see Quantitative Liquefaction Analysis in Part II of this section). SPT is an *in-situ* test that is based on counting the number of blows required to drive a split-spoon sampler (1.375-inch inside diameter) one foot into the soil. The driving force is provided by dropping a 140-pound hammer weight a distance of 30 inches. The SPT method is formally defined and specified by the American Society for Testing and Materials in test method D1586 (American Society for Testing and Materials, 2004). Recorded blow counts for non-SPT geotechnical sampling where the sampler diameter, hammer weight or drop distance differs from that specified for an SPT (ASTM D1586), are converted to SPT-equivalent blow counts, if reliable conversions can be made. The actual and converted SPT blow counts are normalized to a common reference, effective-overburden pressure of one atmosphere (approximately 1 ton per square foot) and a hammer efficiency of 60 percent using a method described by Seed and Idriss (1982) and Seed and others (1985). This normalized blow count is referred to as $(N_1)_{60}$.

Geotechnical borehole logs provide information on lithologic and engineering characteristics of Quaternary deposits in and around Livermore Valley. The characteristics reported in Table 1.2 summarize conditions in the Livermore 7.5-Minute Quadrangle while the characteristics reported in Table 1.3 summarize conditions in the entire Livermore and Amador Valleys (Dublin, Livermore and Altamont 7.5-Minute Quadrangles).

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 significant amounts of gravel. In the past, gravel and gravelly materials were considered not to be susceptible to

Geologic Unit [1]	Description	Total Layer Thickness (ft)	Composition by Soil Type (Unified Soil Classification System Symbols)
af	Artificial fill	384	GP 4%; Other 94%
alf	Artificial fill, levee	0	n/a [1]
gq	gravel quarries and percolation ponds	37	GC 58%; ML 28%; SM 14%
ac	Artificial stream channel	0	n/a [1]
Qhc	Modern stream channel deposits	219	GW 19%; ML 18%; SP 16%; Ml-CL 14%; SM 12%; Other 21%
Qhfy	Latest Holocene alluvial fan deposits	40	Ml 61%; CL 28%; Other 11%
Qhty	Latest Holocene stream terrace deposits	9	ML 50%; SM-SP 50%
Qhay	Latest Holocene alluvial deposits, undifferentiated	0	n/a [1]
Qhf	Holocene alluvial fan deposits	1415	CL 34%; ML 21%; Other 45%
Qhff	Holocene alluvial fan deposits, fine grained facies	267	CL 49%; ML-CL-16%; ML 12%; CL-ML 11%; Other 12%
Qhl	Holocene alluvial fan levee deposits	0	n/a [1]
Qht	Holocene stream terrace deposits	104	ML 36%; SM 14%; SM-ML 11 %;
Qha	Holocene alluvium, undifferentiated	0	n/a [1]
Qf	Late Pleistocene to Holocene alluvial fan deposits	578	CL 40%; ML 29%; Other 31%
Qt	Latest Pleistocene to Holocene stream terrace deposits	196	ML 24%; CL 14%; SP 13%; SM 10%; GC 10%; GP 10% Other 19%
Qa	Late Pleistocene to Holocene alluvium, undifferentiated	20	SC 55%; GM 25%; CL 20%
Qpf	Late Pleistocene alluvial fan deposits	246	GM 29%; CL 19%; SC 18%; GW-GM 15%; Other 19%
Qpt	Latest Pleistocene stream terrace deposits	0	n/a [1]
Qpa	Late Pleistocene alluvium, undifferentiated	155	CL 20%; GC 20%; SC 18%; SM 13%; Other 29%
Qoa	Early to Late Pleistocene undifferentiated alluvial deposits,	440	CL 36%; SM 14%; ML 11%; Other 39%
B	Bedrock	0	n/a [1]

(1) n/a = not applicable

Table 1.2. Summary of lithology types for Quaternary map units in the Livermore 7.5-Minute Quadrangle.

GEOLOGIC MAP UNIT		DRY DENSITY (pounds per cubic foot)						STANDARD PENETRATION RESISTANCE (blows per foot, $(N_1)_{60}$)					
Unit [(1)]	Texture[(2)]	Number of Tests	Mean	C[(3)]	Median	Min	Max	Number of Tests	Mean	C[(3)]	Median	Min	Max
af	Fine	3	103.9	0.1	102.0	92.0	114.0	6	26.9	0.3	24.8	16.6	40.8
	Coarse	-	-	-	-	-	-	3	28.4	0.3	24.4	21.1	39.5
alf	Fine	-	-	-	-	-	-	-	-	-	-	-	-
	Coarse	-	-	-	-	-	-	-	-	-	-	-	-
gq	Fine	4	104.5	0.1	106.0	93.0	113.0	7	37.9	0.8	19.9	13.6	82.8
	Coarse	1	-	-	-	-	-	1	-	-	-	-	-
ac	Fine	-	-	-	-	-	-	-	-	-	-	-	-
	Coarse	-	-	-	-	-	-	-	-	-	-	-	-
Qhc	Fine	6	107.8	0.1	110.5	95.0	117.0	30	21.2	0.7	14.4	4.5	50.9
	Coarse	4	109.4	0.1	106.2	99.0	130.8	22	25.3	0.8	22.4	2.4	58.5
Qhfy	Fine	42	99.5	0.2	104.6	14.4	125.0	55	12.2	0.7	9.4	2.9	40.7
	Coarse	10	110.2	0.2	107.4	91.0	135.7	20	11.2	1.0	6.6	3.3	44.0
Qhly	Fine	17	100.8	0.1	101.0	73.0	119.7	21	13.1	0.6	10.2	4.8	37.4
	Coarse	4	108.7	0.0	110.0	101.3	113.5	5	13.6	0.5	15.3	5.9	20.7
Qhty	Fine	19	103.3	0.1	103.0	93.0	119.0	28	14.9	0.4	13.9	5.3	33.8
	Coarse	-	-	-	-	-	-	6	13.2	0.3	14.6	5.6	16.8
Qhay	Fine	10	109.6	0.1	103.0	93.0	119.0	15	19.0	0.4	17.7	5.0	30.5
	Coarse	-	-	-	-	-	-	-	-	-	-	-	-
Qhb	Fine	39	96.2	0.1	95.0	73.0	134.0	81	14.3	0.5	12.0	3.1	42.1
	Coarse	-	-	-	-	-	-	8	31.7	0.5	27.0	10.6	57.6
Qhf	Fine	361	102.4	0.1	95.0	73.0	134.0	646	17.1	0.7	14.0	1.2	>99
	Coarse	48	108.6	0.1	107.5	88.3	140.0	134	24.3	0.8	17.9	1.9	89.6
Qhff	Fine	96	96.4	0.1	96.9	38.8	121.0	202	15.8	0.6	13.7	4.5	65.0
	Coarse	8	109.0	0.1	107.5	100.0	125.6	30	18.0	0.6	15.7	3.2	56.2
Qht	Fine	23	107.0	0.1	107.0	85.0	119.0	57	15.9	0.5	14.6	4.9	39.8
	Coarse	1	-	-	-	-	-	8	20.0	0.4	20.0	7.6	32.4
Qha	Fine	5	92.6	0.1	92.0	84.0	103.0	13	14.7	0.8	11.8	3.7	40.0
	Coarse	-	-	-	-	-	-	1	-	-	-	-	-
Qf	Fine	266	105.4	0.1	106.7	17.2	124.7	395	28.4	0.8	23.0	3.1	>99
	Coarse	35	105.9	0.1	103.0	90.0	139.0	74	29.7	0.8	22.9	6.2	>99
Qt	Fine	10	113.5	0.1	109.5	103.0	136.0	31	52.7	0.6	44.3	9.2	>99
	Coarse	5	121.6	0.1	127.0	102.0	129.0	15	31.2	0.5	30.8	8.8	60.0
Qa	Fine	2	109.5	0.0	109.5	106.0	113.0	3	12.2	0.7	7.1	6.9	22.6
	Coarse	-	-	-	-	-	-	-	-	-	-	-	-
Qpf	Fine	26	110.3	0.1	109.1	98.0	131.0	89	37.7	0.6	33.9	2.6	>99
	Coarse	8	117.3	0.1	115.0	98.0	146.0	42	68.4	0.8	61.3	8.2	>99
Qpt	Fine	-	-	-	-	-	-	-	-	-	-	-	-
	Coarse	-	-	-	-	-	-	-	-	-	-	-	-
Qpa	Fine	15	109.1	0.1	110.0	82.0	132.5	40	40.6	0.6	36.7	2.6	>99
	Coarse	-	-	-	-	-	-	22	43.3	0.5	44.4	6.3	80.5
Qoa	Fine	61	112.9	0.1	114.0	95.0	135.1	74	40.2	0.6	34.7	2.4	98.4
	Coarse	13	116.1	0.1	117.0	103.0	134.9	31	76.7	0.9	51.1	3.9	>99

Notes:
(1) See Table 1.2 for names of the units listed here.
(2) Fine soils (silt and clay) contain a greater percentage passing the #200 sieve (<.074 mm); coarse soils (sand and gravel) contain a greater percentage not passing the #200 sieve.
(3) C = coefficient of variation (standard deviation divided by the mean)

Table 1.3. Summary of geotechnical characteristics for Quaternary units in the entire Livermore Valley.

liquefaction because the high permeability of these soils presumably would allow the dissipation of pore pressures before liquefaction could occur. However, liquefaction in gravel has, in fact, been reported during earthquakes and recent laboratory studies have confirmed the phenomena (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 artificially high. They are likely to lead to over-estimation of the density of the soil and, therefore, result in an underestimation of the liquefaction susceptibility. To identify potentially liquefiable units where blow counts appear to have been affected by gravel content, correlations are made with boreholes in the same unit where the tests do not appear to have been affected by gravel content.

Of the 144 geotechnical borehole logs analyzed in this study (Plate 1.2), most include blow-count data from SPTs or penetration tests that allow reasonable blow count conversions to SPT-equivalent values. Few of the borehole logs collected, however, include all of the information (e.g. soil density, moisture content, sieve analysis, etc.) required for an ideal analysis using the Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed using recorded density, moisture, and sieve test values or averaged test values of similar materials.

PART II: LIQUEFACTION HAZARD ASSESSMENT

MAPPING TECHNIQUES

Liquefaction may occur in water-saturated sediment during moderate to great earthquakes. When this occurs, 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, whereas liquefaction opportunity is a function of potential seismic ground shaking intensity.

The method applied in this study to evaluate liquefaction potential is similar to that Tinsley and others (1985) used to map liquefaction hazards in the Los Angeles region. These investigators, in turn, applied a combination of the techniques developed by Seed and others (1983) and Youd and Perkins (1978). CGS’s method combines geotechnical analyses, geologic and hydrologic mapping, and probabilistic earthquake shaking estimates employing criteria adopted by the SMGB (Department of Conservation, 2004).

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 from the surface 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 specifically addressed in this investigation.

Soil characteristics that result in higher measured penetration resistances generally indicate lower liquefaction susceptibility. In summary, soils that lack resistance (susceptible soils) typically are saturated, loose, and granular. Soils resistant to liquefaction include all soil types that are dry, cohesive, or sufficiently dense.

CGS's inventory of areas containing soils susceptible to liquefaction begins with evaluation of geologic maps and historical occurrences, cross-sections, geotechnical test data, geomorphology, and groundwater hydrology. Soil properties and soil conditions such as type, age, texture, color, and consistency, along with historical depths to groundwater are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on observable similarities between soil units, liquefaction susceptibility maps typically are often similar to Quaternary geologic maps, depending on local groundwater levels.

Much of the surface area of the Livermore and Amador Valley floor is covered by an indeterminate thickness of Holocene sediment and groundwater is within 40 feet of the ground surface throughout the part of the Livermore Valley within the quadrangle. Holocene sediment in the Livermore Valley is composed primarily of clays and silts with interbedded layers of loose sands and gravels. Locally, the general composition of some geologic units differs from average basin-wide composition for the same unit. For example, of the samples collected for modern stream channel (Qhc), Holocene alluvial fan (Qhf), Holocene stream terrace (Qht) and late Pleistocene alluvial, undifferentiated (Qpf) deposits, they appear to be somewhat less clay rich than the basin-wide average. On the other hand o the sample collected for latest Holocene alluvial fan (Qhfy), Holocene alluvial fan (Qhf), Holocene stream terrace (Qht), and late Pleistocene to Holocene alluvial fan (Qf) deposits, they appear to be somewhat more silt rich than the basin-wide average. It should be noted that the apparent change in the relative abundance of the various lithologic materials might simply reflect an increase or decrease in the frequency that the material was sampled rather than a change in the actual abundance of the material.

GROUND SHAKING OPPORTUNITY

Ground shaking opportunity is a calculated measure of the intensity and duration of strong ground motion normally expressed in terms of *peak horizontal ground acceleration* (PGA). Ground motion calculations used by CGS exclusively for regional liquefaction zonation assessments are currently based on the *2002 California Probabilistic Seismic Hazard Assessment (PSHA) Model* developed jointly by the CGS and USGS (Frankel and others, 2002; Cao and others, 2003). The model is set to calculate ground motion hazard at a 10 percent in 50 years exceedance level. CGS calculations of probabilistic peak ground acceleration deviate slightly from the model by incorporating additional programming that weights each earthquake's estimated ground shaking contribution by a scaling factor derived as a function of its magnitude. The function is simply the inverse of the liquefaction threshold-scaling factor used in the Seed-Idriss Simplified Procedure, the quantitative analysis method used by CGS to generate seismic hazard zone maps for liquefaction (see Liquefaction Analysis). The result is a magnitude-weighted, pseudo-PGA that CGS refers to as *Liquefaction Opportunity* (LOP). LOP is then used to calculate cyclic stress ratio (CSR), the seismic load imposed on a soil column at a particular site. This approach provides an improved estimate of liquefaction hazard in a probabilistic sense, ensuring that large, infrequent, distant earthquakes, as well as smaller, more frequent, nearby events are appropriately accounted for (Real and others, 2000).

Calculated LOP for alluviated areas in the Livermore Quadrangle range from 0.35 to 0.50 g (see Section 3, Figure 3.3). These values were obtained by applying the NEHRP corrections (FEMA, 1994; Table 3.1) to the firm-rock LOP values derived from the CGS liquefaction application of the 2002 probabilistic ground motion model. The calculations are based on an earthquake of Moment Magnitude range of 6.6 to 7.0 with a Modal Distance of 3 to 15 kilometers.

LIQUEFACTION ANALYSIS

CGS performs quantitative analysis of geotechnical data to evaluate liquefaction potential using an in-house developed computer program based on 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; Youd and others, 2001). The procedure first calculates the resistance to liquefaction of each soil layer penetrated at a test-drilling site, expressed in terms of cyclic resistance ratio (CRR). The calculations are based on standard penetration test (SPT) results, groundwater level, soil density, grain-size analysis, moisture content, soil type, and sample depth. The procedure then estimates the factor of safety relative to liquefaction hazard for each of the soil layers logged at the site by dividing their calculated CRR by the pseudo PGA-derived CSR described in the previous section.

CGS uses a factor of safety (FS) of 1.0 or less, where CSR equals or exceeds CRR, to indicate the presence of potentially liquefiable soil layers. The 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 $(N_1)_{60}$ 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. In addition to FS, consideration is given to the proximity to stream channels, which accounts in a general way for factors such as sloping ground or free face that contribute to severity of liquefaction-related ground deformation.

ZONATION CRITERIA: LIQUEFACTION

Areas underlain by materials susceptible to liquefaction during an earthquake are included in liquefaction zones using criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (DOC, 2004). 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 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 subsurface data are not sufficient for quantitative evaluation of liquefaction hazard. Within such areas, zones may be delineated 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 percent probability of being exceeded in 50 years is greater than or equal to 0.10 g and the anticipated depth to saturated soil is less than 40 feet; 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 percent probability of being exceeded in 50 years is greater than or equal to 0.20 g and the anticipated depth to saturated soil is less than 30 feet; 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 percent probability of being exceeded in 50 years is greater than or equal to 0.30 g and the anticipated depth to saturated soil is less than 20 feet.

Application of the above criteria allows compilation of *Zones of Required Investigation* for liquefaction hazard, which are useful for preliminary evaluations, general land-use planning and delineation of special studies zones (Youd, 1991).

DELINEATION OF SEISMIC HAZARD ZONES: LIQUEFACTION

Upon completion of a liquefaction hazard evaluation within a project quadrangle, CGS applies the above criteria to its findings in order to delineate *Zones of Required Investigation*. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone map for the Livermore Quadrangle.

Areas of Past Liquefaction

There is no documentation of historical surface liquefaction or paleoseismic liquefaction in the Livermore Quadrangle.

Artificial Fills

Non-engineered fill placements are often composed of uncompacted, silty or sandy material and, therefore, are generally considered to have a high potential for liquefaction when saturated. No significant placements of non-engineered artificial fill, other than aggregate extraction waste piles, were identified in the study area. Conversely, significant amounts of engineered artificial fill, which by definition are designed to resist liquefaction, have been used in the construction of river levees and elevated freeways in Livermore and Amador Valleys. In these areas, seismic hazard zonation for liquefaction does not depend on the fill, but on soil properties and groundwater levels in underlying strata.

Areas with Sufficient Existing Geotechnical Data

Most of the 140 plus logs evaluated for this study represent boreholes drilled into the floor of Livermore and Amador Valleys. Collectively, the logs provide the level of subsurface information needed to conduct a regional assessment of liquefaction susceptibility with a reasonable level of certainty. Analysis of blow count values and other soil property measurements reported in the logs indicate that most of the boreholes penetrated one or more layers of liquefiable material where seismic stress ratio (CSR) is greater than the soils' seismic resistance ratio (CRR). Accordingly, all areas covered by Holocene alluvium that is saturated within 40 feet of the surface are designated *Zones of Required Investigation*.

The majority of the boundary for the *Zones of Required Investigation* is defined by the contact between Holocene and late Pleistocene deposits and/or bedrock, and extends along base of the foothills that surrounds the Livermore Valley. Although the groundwater conditions in the center of the Livermore Valley have been complicated by the ongoing gravel mining operations, groundwater increases toward the center of the valley. Analysis of blow count values and other soil property measurements reported in the logs inside the zone boundary indicate that most of the boreholes penetrated one or more layers of liquefiable material where seismic stress ratio (CSR) is greater than the soils' seismic resistance ratio (CRR). Accordingly, all areas covered by Holocene alluvium that is saturated within 40 feet of the surface are designated *Zones of Required Investigation*.

Areas with Insufficient Existing Geotechnical Data

Adequate geotechnical borehole information is lacking for most parts of canyons in the hilly to mountainous terrain surrounding Livermore and Amador Valleys and immediately adjacent to Arroyo Valle. These, along with other isolated deposits of Holocene and undifferentiated Holocene alluvium (Qha), Holocene alluvial fan (Qhf) in upland areas, as well as the narrow bands of Holocene deposits in the Livermore Quadrangle associated with active stream channels (ac, Qhty, Qhc, Qha, Qhf) are young, loose, granular and saturated. Those conditions, along with the strong ground motions expected for the region, combine to form a sufficient basis for designating areas underlain by these types of deposits as *Zones of Required Investigation* for liquefaction.

ACKNOWLEDGMENTS

The author wishes to thank Matt Katen and Tom Rooze at Alameda County Flood Control and Water Conservation District Zone 7 Water Agency, planning and building department staff at the cities of Livermore and Pleasanton. The author also appreciates the assistance and support provided by CGS staff. Particularly, Keith Knudsen, Teri Mcguire, Barbara Wanish, Candace Hill, Bob Moscovitz, Rick Wilson, Marvin Woods, Elise Mattison, Tully Simoni, and Jackie Bott of CGS.

REFERENCES

American Society for Testing and Materials, 2004, 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: California Division of Mines and Geology Special Publication 117, 74 p.

California Department of Conservation, Division of Mines and Geology, 2004, Recommended criteria for delineating seismic hazard zones in California: California Division of Mines and Geology Special Publication 118, 12 p.

California Department of Water Resources, 2003, California's Groundwater, Bulletin 118, http://www.groundwater.water.ca.gov/bulletin118/update2003

California Department of Water Resources, 1974, Evaluation of Groundwater Resources: Livermore and Sunol Valleys; DWR Bulletin 118-2, 153 p.

California Department of Water Resources, 1966, Livermore and Sunol Valleys, Evaluation of Groundwater Resources; DWR Bulletin118-2, Appendix A, Geology, 79 p.

Cao, T., Bryant, W.A., Rowshandel, B., Branum, D., and Wills, C.J., 2003, The Revised 2002 California Probabilistic Seismic Hazard Maps; California Geological Survey, Online Report, 12 p. http://www.consrv.ca.gov/cgs/rghm/psha/fault_parameters/pdf/2002_CA_Hazard_Maps.pdf

Carpenter, D. W., Sweeney, J.J., Kasameyer, P.W., Purkland, N. R., Knauss, K.G., and Shlemon, R.J., 1984, Geology of the Lawrence Livermore national laboratory site and adjacent area: Springfield, Virginia, National Technical Information Service, 94 p.

Dibblee, T.W., 1980, Preliminary geologic map of the Livermore quadrangle, Alameda and Contra Costa Counties, California: U.S. Geological Survey Open-File Report OF-80-533-B, scale 1:24,000.

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

FEMA, 1994, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures: Washington, D.C., FEMA 222A.

Figures, S., and Ehman, K.D., 2004, Preliminary Stratigraphic Evaluation West Side of the Main Basin Livermore-Amador Groundwater Basin; prepared by Norfleet Consultants and Skyline Ridge, Inc. for Alameda County Flood Control and Water Conservation District Zone 7 Water Agency.

Frankel, A.D., Petersen, M.D., Muller, C.S., Haller, K.M., Wheeler, R.L., Layendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps: U.S. Geological Survey, Open-File Report 02-420, 33 p.

Graymer, R.W., Jones, D.L., and Brabb, E. E., 1996, Preliminary geologic map emphasizing bedrock formations in Alameda County, California: A digital database: U.S. Geological Survey Open-File Report 96-252, scale 1:100,000 (1:750,000 digital version).

Graymer, R.W., 2000, Geologic map and map database of the Oakland metropolitan area, Alameda, Contra Costa, and San Francisco counties, California, U.S. Geological Survey Miscellaneous Field Studies MF-2342, scale 1:24,000, Version 1.0.

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.

Jones & Stokes, 2006, Annual report for the groundwater management plan, 2005 Water Year; prepared for the Alameda County Flood Control and Water Conservation District Zone 7 Water Agency, 52 p.

Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., and Helley, E.J., 2000, Description of mapping of quaternary deposits and liquefaction susceptibility, nine-county San Francisco Bay region, California: U.S. Geological Survey Open-File Report 00-444.

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, 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.

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.

Sowers, J.M., unpublished geologic map of the Livermore quadrangle, Alameda and Contra Costa counties, California: USGS, map scale 1:24,000.

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.

Unruh, J.R., and Sawyer, T.L., 1997, Assessment of blind seismogenic sources, Livermore Valley, eastern San Francisco Bay region: Final Technical Report submitted to the U.S. Geological Survey National Earthquake Hazards Reduction Program, 88 p.

Witter, R.C., Knudsen, K.L, Sowers, J.M., Wentworth, C.M., Koehler, R.D., Randolph, C.E., Brooks, S.K., and Gans, K.D., 2006, Maps of Quaternary deposits and liquefaction susceptibility in the central San Francisco Bay region, California: U.S. Geological Survey Open-File Report 2006-1037 [available on the World Wide Web at URL http://pubs.usgs.gov/of/2006/1037/].

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., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D.L., Harder, L.F. Jr., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcusson, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe, K.H., 2001, Liquefaction resistance of soils; Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils: Journal of Geotechnical and Geoenvironmental Engineering, October 2001, p. 817-833.

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: EVALUATION REPORT FOR EARTHQUAKE-INDUCED LANDSLIDE HAZARD

in the

LIVERMORE 7.5-MINUTE QUADRANGLE, ALAMEDA COUNTY, CALIFORNIA

By

Florante G. Perez

Department of Conservation
California Geological Survey

INTRODUCTION

Purpose

The Seismic Hazards Mapping Act of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California State Geologist to compile maps that identify *seismic hazard zones* consistent with requirements and priorities established by the California State Mining and Geology Board (SMGB; DOC, 1997). The text of the guidelines is available online at http://www.conservation.ca.gov/cgs/shzp/webdocs/sp117.pdf. The Act requires that site-specific geotechnical investigations be performed for most urban development projects situated within seismic hazard zones before lead agencies can issue the building permit and that sellers.

Following the release of the SMGB Guidelines, local government agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction hazard. 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 (Southern California Earthquake Center, 2002). This text is also online at: http://www.scec.org/

This report is one of a series that summarizes the preparation of seismic hazard zone maps within the state (Smith, 1996). This particular part of the report, Section II, summarizes seismic hazard zone mapping for earthquake-induced landslides in the Livermore 7.5-minute Quadrangle. Section 1, which addresses liquefaction hazard, and Section 3, which addresses earthquake-shaking hazard, complete the report. Additional information on seismic hazard zone mapping in California can be accessed online at: http://www.conservation.ca.gov/cgs/shzp/.

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 lifeline infrastructure. Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks, sloped 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 mountainous and hilly areas within the Livermore Quadrangle.

Methodology

The delineation 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 collected or generated to provide an up-to-date representation of slope gradient and slope aspect in the study area.

- Geologic mapping was compiled to provide an accurate representation of the spatial distribution of geologic materials in the study area. In addition, a map of existing landslides, whether or not triggered by earthquakes, 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 compiled and 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 (Newmark, 1965), in order to generate a map showing 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 subsequently adopted by the State Mining and Geology Board (California Department of Conservation, 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 run out areas 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.

This section of the report is presented in two parts. Part I addresses the natural setting of the area covered by the Livermore Quadrangle, namely the physiographic, geologic and engineering geology conditions. Part II covers the preparation of landslide hazard potential and landslide zone maps.

PART I: GEOGRAPHIC AND GEOLOGIC SETTING

PHYSIOGRAPHY

Location

The Livermore 7.5-Minute Quadrangle, situated about 20 miles southeast of Oakland, covers approximately 60 square miles of land surface in Alameda and Contra Costa Counties in the eastern San Francisco Bay area. Approximately one square mile in the northwest portion of the quadrangle is within Contra Costa County, which will be evaluated for seismic hazard mapping later. The remaining map area lies in Alameda County and includes the cities of Livermore, Pleasanton and Dublin.

Most of Livermore Valley falls within the Livermore Quadrangle, with only a small portion of the valley west of Tassajara Road extending into the adjacent Dublin Quadrangle and that portion of the valley lying east of the City of Livermore's Civic Center falling into the adjoining Altamont Quadrangle.

Major transportation routes in the map area include west-trending Interstate Highway 580. Additional access is provided by a network of city, county and private roads in developed areas and by fire roads and trails in undeveloped areas.

Land Use

Land use in the Livermore-Pleasanton region historically was dominated by viticulture in valley areas and cattle grazing in the surrounding hills. However, in the last several decades competition for land use, particularly in valley lands, has increased substantially as urban development has continued to expand beyond the original city boundaries. At the same time, the Livermore and Amador Valleys have long been an economically important source of aggregate to the Bay Area, in large part because of the number and size of multiple water courses that over the last several million years have eroding surrounding highlands and depositing large amounts of sediments, including of sand and gravel, into the basin. Several gravel quarries near the western central portion of the map area are still in production. Some gravel quarries that are no longer in use have been converted for recreational use. In addition, a chain-of-lakes system has been developed using a series of former gravel quarries linked to adjacent arroyos to catch and store winter runoff. Water that is collected in these lakes is allowed to slowly seep into the ground and recharge the underlying basin (Figures and Ehman, 2004).

Topography

The northern half and the southwestern corner of the map are occupied by foothills of the Diablo Range, which is part of the Coast Range Geomorphic Province. Numerous named and un-named creeks and streams flow through the map area. From the confluence of Dry Creek and Arroyo Valle at the southeast corner of the quadrangle, Arroyo Valle flows northwest until just south of the intersection of the Southern Pacific and Western Pacific Rail lines, at which point Arroyo Valle changes direction and flows due west. Arroyo Mocho and Arroyo Las Positas both originate in the hills at the western edge of the map area and flow roughly east through the center of the quadrangle. Cayetano, Cottonwood and Tassajara Creeks all flow south out of the foothills in the northern half of the map area and into Arroyo Las Positas. Elevations within the map area range from 1264 at the Vern vertically authenticated benchmark in the southwest corner of the quadrangle, to less than 350 feet at the western end of the valley floor.

Digital Topography

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 in the form of a digital topographic map. Within the Livermore Quadrangle, a Digital Terrain Model (DTM) was obtained from Intermap's Interferometric Synthetic Aperture Radar (IFSAR) system. This DTM was derived from the original radar data, the Digital Surface Model (DSM). Vegetation, buildings, and other cultural features were digitally removed using the company's proprietary software called TerrainFit (Intermap, 2003). This terrain data, which was acquired in 2003, presents elevations at five-meter postings with two meters RSME horizontal positional accuracy and one-meter vertical positional accuracy. Furthermore, the DTM was resampled using bilinear method to minimize the presence of false geometric artifacts in the radar data. Slope gradient map was generated from the DTM using a third-order, finite-difference, center-weighted algorithm (Horn, 1981).

GEOLOGY

The primary sources of bedrock geologic mapping used in this slope stability evaluation were obtained from U.S. Geological Survey Open File Report, OFR 96-252 (Graymer and others, 1996) and the unpublished 1:24,000-scale geologic map recently completed by J.M. Sowers (2006). Geologic mapping by Dibblee (1980) was also reviewed. The nomenclature of the Quaternary geologic units was based on U.S. Geological Survey Open File Report, OFR 00-444 (Knudsen and others, 2000). Bedrock units are described in detail in this section. Quaternary geologic units are briefly described here and are discussed in more detail in Section 1, *Evaluation Report for Liquefaction Hazard*.

CGS geologists modified the digital geologic map in the following ways: landslide deposits were deleted from the map so that bedrock formations and the newly created landslide inventory would exist on separate layers for the hazard analysis. Air-photo interpretation, digital ortho-photo quarter quadrangle review, satellite imagery review, and field reconnaissance were performed to assist in the adjustment of contacts between bedrock and surficial geologic units. Contacts and distribution of alluvial deposits, as well as active gravel quarries, were modified to conform to 2006 topography as depicted on DigitalGlobe imagery (Google Earth, 2006) and Intermap’s Ortho-rectified Radar Imagery (Intermap, 2003). In addition, the relation of the various geologic units to the development and abundance of landslides was noted.

Bedrock Units

The following bedrock geologic units from oldest to youngest are exposed in the Livermore Quadrangle: Cierbo Sandstone (Tc), Briones Formation (Tbr), Green Valley and Tassajara Formation of Conduit (Tgvt), Green Valley and Tassajara Formation-tuff layer (Tgvtt), and Livermore Gravels (QTl).

The Miocene Cierbo Sandstone (Tc) is exposed only in the extreme southwestern corner of the quadrangle where it consists of thick-bedded, fine- to coarse-grained, moderately consolidated, light gray to white sandstone with marine fossils. In the southeastern corner of the quadrangle (southeast), small outcrops of the late to middle Miocene Briones Formation (Tbr) are exposed. This unit is comprised of interbedded sandstone, siltstone, conglomerate, and shell breccia. Conglomerate clasts include black and red chert, quartzite, andesite, argillite, siltstone, basalt, felsic tuff, and quartz.

The Green Valley and Tassajara Formation of Conduit (Tgvt) is exposed only in the northern portion of the Livermore Quadrangle. It consists of steep, southwesterly dipping non-marine sandstone, siltstone, and conglomerate of Pliocene and Miocene age. Wagner (1978) and subsequent investigators have referred to this sedimentary unit as Sycamore Formation (Sawyer, 1999). A tuff marker bed within the Green Valley and Tassjara Formation (Tgvtt) crops out as a northwest-trending narrow bed alongside the upper reaches of the western tributary of Cayetano Creek.

Quaternary Sedimentary Deposits

Unconformably overlying the Green Valley and Tassajara Formation is the Plio-Pleistocene Livermore Gravels (QTl) deposits, the most extensive bedrock unit in the area. It is exposed around the northern and southern margins of the Livermore-Amador Valley and has been anticlinally folded (Dibblee, 1980). It is composed of gray, poorly- to moderately-consolidated, indistinctly bedded, cobble conglomeratic sandstone, and gray coarse-grained sandstone as well as siltstone and claystone. Clasts primarily consist of graywacke, chert, and metamorphic rocks. These gravel deposits are inferred by Anderson et al (1955) to have been derived from the Franciscan rock complex (Sawyer, 1999).

Approximately two-thirds of the Livermore Quadrangle is covered by Quaternary alluvial sediments. Alluvial deposits (Qhay, Qha, Qa, Qoa, Qoa1, Qoa2) cover the upstream portions and banks of several creeks as well as the narrow bands in upland canyons and along base of hills. Alluvial fan deposits (Qhfy, Qhf, Qhff, Qf, Qpf) occur within the floor of Livermore Valley and downstream portions of Arroyo Mocho and at the base of the hills in the northern half of the quadrangle. Stream terrace deposits (Qhty, Qht, Qht1, Qht2, Qt, Qpt) are mapped at the outside edges of the flood plain and adjacent to the channels of major streams. Modern stream channel deposits (Qhc) are found along all active creeks and streams in the Livermore Valley. Artificial channel (ac) is mapped within concrete-lined drainages; artificial fill (af) are associated with infrastructure such as highway and rail lines. Gravel exposed in quarries (gq) is mapped in the central portion of the valley.

Structure

The Livermore basin within the study area is defined by an east-west trending syncline or synclinorium (Unruh and Sawyer, 1997) with a series of low amplitude northwest-trending folds (Springtown anticlines) in the central-eastern portion of the quadrangle. This part of the basin is bounded by the Las Positas Fault on the southeast and by the northeast-dipping Verona Thrust Fault on the southwest. The northern edge of the basin is bounded by blind and emergent thrust faults that are inferred to be the continuation of the Mt. Diablo Thrust Fault (Unruh and Sawyer, 1997). Another fault running parallel to it was also mapped by Ford (1970) as Mocho Fault. Previous investigators have also indicated the presence of buried northwest-striking faults (Livermore Fault) bisecting the central Livermore Valley (Sawyer, 1999).

The Springtown anticlines are a pair of low-amplitude, south-plunging folds that are expressed as a series of low hills (Sawyer, 1999) near the confluence of Arroyo Las Positas and Cayetano Creek. These folds have been locally manifested by bedding altitudes in the Livermore Gravels (Dibblee, 1980) with the western limbs dipping as steeply as 25° to 37°. The length of the Springtown anticlines is approximately eight kilometers. The northeast trending Las Positas Fault transects the southeastern portion of the quadrangle. Herd (1977) and Wagner et al (1990) established the length of the fault to be approximately 15 kilometers. The sense of slip is primarily left lateral and the trace of the fault is marked by discontinuous northwest facing scarp in the Livermore Gravels and younger alluvial deposits (Unruh and Sawyer, 1997). The Verona Fault is a northwest-striking thrust fault along the southwestern margin of Livermore basin. It is manifested by a west-facing escarpment in the Livermore Gravels. The northeast-dipping beds, west-facing scarp, and range of low hills to the north of the fault are consistent with northeast-side-up thrust or reverse motion on the Verona Thrust Fault (Unruh and Sawyer, 1997). CGS officially designated the segment of this fault within Livermore Quadrangles as a Special Fault Studies Zone in 1982 (DOC, 1982; 1997b).

The northern edge of the Livermore basin is bounded by a blind thrust that is depicted as a potential candidate for an emerging trace of the Mt. Diablo Thrust Fault (Unruh and Sawyer, 1997). Hart (1981) mapped the western half of this fault as a south facing erosional scarp with parallel and steeply dipping beds on the north side of the scarp. Ford (1970) delineated a fault parallel and to the north of this fault and termed it Mocho Fault. He based the existence of the Mocho Fault on a line of depressed ridge tops (Hart, 1981).

The Livermore Fault was mapped by Ford (1970) and Carpenter and others (1984) as a northwest-striking zone of concealed faults bisecting the central Livermore basin (Sawyer, 1999). The presence of the fault zone is based largely on differences in the depth of groundwater encountered in water wells on either side of the faults.

Landslide Inventory

As a part of the geologic data compilation, an inventory of existing landslides in the Livermore Quadrangle was prepared by field reconnaissance, analysis of stereo-paired aerial photographs and satellite imagery, and a review of previously published landslide mapping. 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 recency of activity, thickness, associated geologic unit(s), and the confidence of interpretation (definite, probable and questionable). Landslides rated as definite and probable were incorporated into the landslide zoning as described later in this report. Landslides rated as questionable were not carried into the landslide zoning due to the uncertainty of their existence. The completed landslide map was digitized, and the attributes were compiled in a database. A small-scale version of the landslide inventory map is shown on Plate 2.1.

In the Livermore Quadrangle, most of the landslides occur in the Green Valley and Tassajara formations and the Livermore Gravels in the form of debris slides and debris flows. Minor rock slides are also mapped in the Livermore Gravels. A noteworthy example is a large debris slide in the upper reach of Cottonwood Creek along Doolan Canyon that was mapped using aerial photos and satellite imagery. This debris slide has blocked the drainage and formed a natural lake upstream, creating a potential source of flooding.

Minor debris slides were noted along steep canyon walls in drainages, especially in the steeply dipping sedimentary rocks in the northern portion of the quadrangle. However, these deposits are too small to be shown at the scale of this map. A number of debris flows and slides mapped in 1975 by T.H. Nilsen (Roberts and others, 1999) and Majmundar (1991) were not included in the inventory because they were either too small or their existence could not be verified. 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 surface expression currently exists, are included in the landslide inventory.

ENGINEERING GEOLOGY

Geologic Material Strength

To evaluate the stability of geologic materials under earthquake conditions, the geologic map units described above are ranked and grouped relative to 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 Livermore Quadrangle geologic map were obtained from the cities of Livermore, Pleasanton, and Dublin, from the County of Alameda, and from CalTrans (see Appendix A). The locations of rock and soil samples taken for shear testing within the Livermore Quadrangle are shown on Plate 2.1. Shear tests from the adjoining quadrangle (Dublin) were used to augment data for several geologic formations for which little or no shear-test information was available within the Livermore Quadrangle.

Shear-strength data gathered from the above sources were compiled for each geologic map unit. Geologic units were grouped according to average angle of internal friction (average phi) and lithologic character. Average (mean or median) phi values for each geologic map unit and corresponding strength groups are summarized in Table 2.1. For each geologic strength group (Table 2.2) in the map area, the average shear strength value was assigned and used in our slope stability analysis. A geologic material strength map that provides spatial representation of material strength for use in slope stability analysis was developed based on groupings presented 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 (Qyls) 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. We collect and compile 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 included in our compilation. For the Livermore Quadrangle, strength parameters applicable to existing landslide planes were not available.

LIVERMORE 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	Tbr	5*	32/32	32/32	533/305	Tc	32
GROUP 2	QTl Qoa2 Qoa1 Qf Qoa	36 6 14 27* 23*	27/26 27/26 24/27 25/26 26/23	26/26	811/740	Tgvt, Tgvtt, ac, af, Qa, Qt, Qpt, Qpf, gq	26
GROUP 3	Qhf Qha Qhff Qht	25 15 3 5*	24/24 24/21 23/23 23/25	23/23	739/652	Qhc, Qhay, Qhty, Qht1, Qht2, Qhfy	23
*Shear Strength Data from Dublin Quadrangle							

Table 2.1. Summary of the shear strength statistics for the Livermore Quadrangle.

SHEAR STRENGTH GROUPS FOR THE LIVERMORE 7.5-MINUTE QUADRANGLE		
GROUP 1	GROUP 2	GROUP 3
Tbr, Tc	QTl, Qoa2, Qoa1, Qf, Qoa, Tgvt, Tgvtt, ac, af, Qa, Qt, Qpt, Qpf, gq	Qhf, Qha, Qhff, Qht, Qhc, Qhay, Qhty, Qht1, Qht2, Qhfy

Table 2.2. Summary of shear strength groups for the Livermore Quadrangle.

PART II: EARTHQUAKE-INDUCED LANDSLIDE HAZARD ASSESSMENT

GROUND SHAKING OPPORTUNITY

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 Livermore 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 Cao and others, 2003. The parameters used in the record selection are:

Modal Magnitude:	6.8
Modal Distance:	3.1 to 12.1 km
PGA:	0.5 to 0.86 g

The strong-motion record selected for the slope stability analysis in the Livermore Quadrangle is the Corralitos record from the 1989 magnitude 6.9 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. The selected strong-motion record was not scaled or otherwise modified prior to its use in the analysis.

LANDSLIDE 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 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 threshold 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 Livermore Quadrangle.

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.

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.

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.

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.

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.

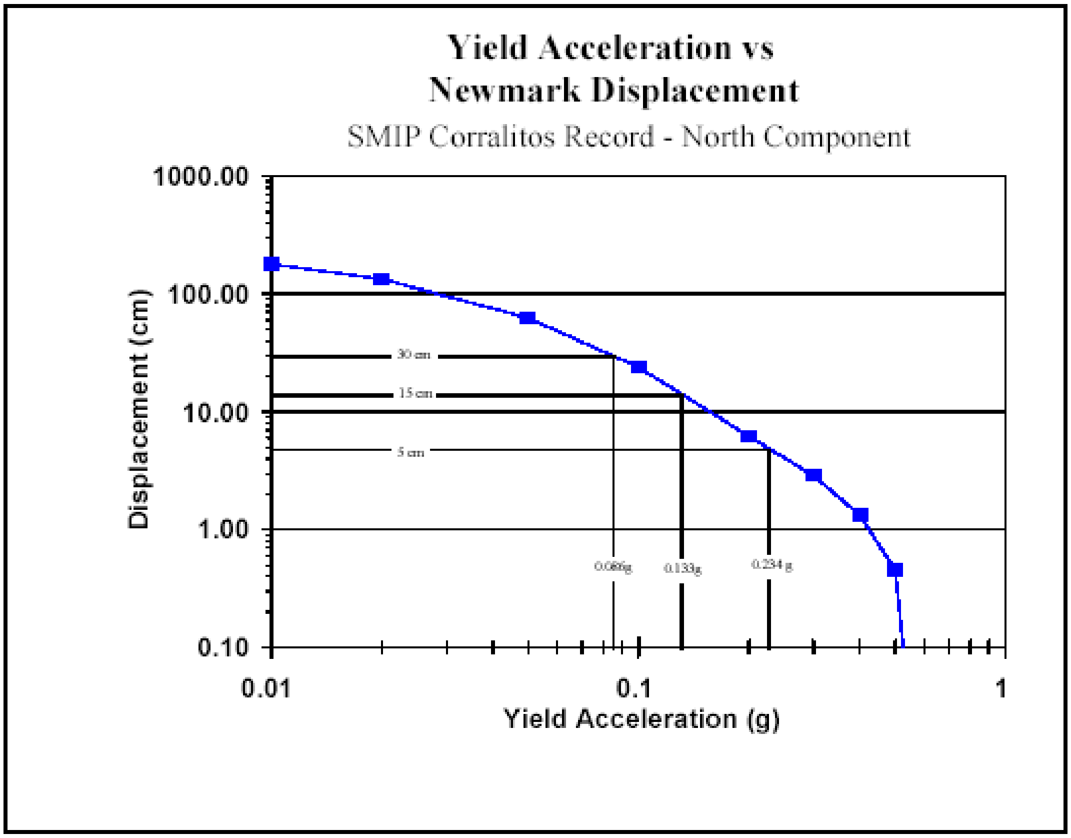


Figure 2.1. Yield acceleration vs. Newmark displacement for the Corralitos record of the 1989 Loma Prieta Earthquake.

Note: Record from California Strong Motion Instrumentation Program (CSMIP) Station 57007.

LIVERMORE QUADRANGLE HAZARD POTENTIAL MATRIX				
Geologic Material Strength Group (Average Phi)	**HAZARD POTENTIAL (Degrees)**			
	Very Low	**Low**	**Moderate**	**High**
1 (32)	0 to 20	21 to 25	26 to 27	>28
2 (26)	0 to 15	16 to 18	19 to 20	>21
3 (23)	0 to 10	11 to 15	16 to 18	>19

Table 2.3. Hazard potential matrix for earthquake-induced landslides in the Livermore Quadrangle.

Note: Values in the table show the range of slope gradient (expressed in degrees) corresponding to calculated Newmark displacement ranges from the design earthquake for each material strength group.

.

ZONATION CRITERIA: EARTHQUAKE-INDUCED LANDSLIDES

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.

DELINEATION OF SEISMIC HAZARD ZONES: EARTHQUAKE-INDUCED LANDSLIDES

Upon completion of an earthquake-induced landslide hazard evaluation within a project quadrangle, CGS applies the above criteria to its findings in order to delineate *Zones of Required Investigation*. Following is a description of the criteria-based factors that governed the construction of the *Seismic Hazard Zone* map for the Livermore Quadrangle.

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.

Hazard Potential 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 five centimeters or greater. Areas with a Very Low hazard potential, indicating less than five 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 3 is included in the zone for all slopes greater than 11 degrees.

2. Geologic Strength Group 2 is included for all slopes greater than 16 degrees.

3. Geologic Strength Group 1 is included for all slopes greater than 21 degrees.

This results in 19 percent of the entire quadrangle lying within the earthquake-induced landslide hazard zone for the Livermore Quadrangle.

ACKNOWLEDGMENTS

The authors thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project: Stephan Kiefer and Melinda Sunnarborg of Livermore City, Les Lyons of Pleasanton City, Gary Moore and Mary Anne Hubbard of Alameda County, and Mark Willian and Connie Reyes of the CalTrans Laboratory arranged access and assisted in retrieving geotechnical data from files maintained by their respective offices. At CGS, Keith Knudsen, Mark Wiegers, and Wayne Haydon provided valuable insights on the geology and landslide of the area during the field reconnaissance survey. Bill Bryant provided hard to find reference materials for structural geology. Mike Silva assisted in the grid overlaying. Diane Vaughan, Terilee McGuire, Lee Wallinder, and Bob Moscovitz provided GIS support. Barbara Wanish prepared the final landslide hazard zone maps and the graphic displays for this report. Candace Hill provided editorial assistance.

REFERENCES

Anderson, D.W., Isaacson, K.A., Barlock, V. E., 1995, Neogene evolution of the Livermore basin within the California Coast ranges: *in* Fritsche, A.E., ed., Cenozoic paleogeography of the western united States-II, Pacific Section, SEPM, book 75, p. 151-161.

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

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

California Department of Conservation, Division of Mines and Geology, 1997b, fault rupture hazard zones in California: California Division of Mines and Geology, Special Publication 42, 38 p.

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

California Department of Conservation, Division of Mines and Geology, 1982, Special Studies Zones (Alquist-Priolo) map of Livermore Quadrangle, scale 1:24,000.

Cao, T., Bryant, W.A., Rowshandel, B., Branum, D., and Wills, C.J., 2003, The Revised 2002 California Probabilistic Seismic Hazard Maps; California Geological Survey, Online Report, 12 p. http://www.consrv.ca.gov/cgs/rghm/psha/fault_parameters/pdf/2002_CA_Hazard_Maps.pdf

Carpenter, D. W., Sweeney, J.J., Kasameyer, P.W., Purkland, N. R., Knauss, K.G., and Shlemon, R.J., 1984, Geology of the Lawrence Livermore national laboratory site and adjacent area: Springfield, Virginia, National Technical Information Service, 94 p.

Dibblee, T.W., Jr., 1980, Preliminary geologic map of the Livermore quadrangle, Alameda and Contra Costa counties, California: U.S. Geological Survey Open-File Report 80-533-B, scale 1:24,000.

Figures, S., and Ehman, K.D., 2004, Preliminary Stratigraphic Evaluation West Side of the Main Basin Livermore-Amador Groundwater Basin; prepared by Norfleet Consultants and Skyline Ridge, Inc. for Alameda County Flood Control and Water Conservation District Zone 7 Water Agency.

Ford, R.S., and Hills, E.E., 1974, Evaluation of groundwater resources: Livermore and Sunol Valleys: CA DWR Bulletin No. 118-2, 153 p.

Ford, R.S., 1970, Livermore and Sunol Valleys, evaluation of groundwater resources: California Department of Water Resources, Memorandum Report.

Graymer, R.W., Jones, D.L., and Brabb, E. E., 1996, Preliminary geologic map emphasizing bedrock formations in Alameda County, California: A digital database: U.S. Geological Survey Open-File Report 96-252, scale 1:100,000 (1:750,000 digital version).

Hart, E.W., 1981, Fault Evaluation Report FER-109, Pleasanton and related faults: California Division of Mines and Geology, 38 p., map scale 1:24,000, *in* Fault Evaluation Reports Prepared Under the Alquist-Priolo Earthquake Fault Zoning Act, Region 1 -Northern California: California Geological Survey CGS CD 2002-01 (2002).

Herd, D.H., 1977, Geologic map of the Las Positas, Greenville and Verona faults, eastern Alameda County, California: U.S. Geological Survey Open-File Report OFR 77-689, 25 p.

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

Intermap Technologies, Inc., 2003, Intermap product handbook and quick start guide: Intermap NEXTmap document, 112 p.

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.

Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., and Helley, E.J., 2000, Description of mapping of quaternary deposits and liquefaction susceptibility, nine-county San Francisco Bay region, California: U.S. Geological Survey Open-File Report 00-444.

Majmundar, H.H., 1991, Landslide hazards in Livermore valley and vicinity, Alameda and Contra Costa Counties, California: California Division of Mines and Geology Open-File Report 91-02, scale 1:24,000.

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.

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

Roberts, S., Roberts, M.A., and Brennan, E.M., 1999, Landslides in Alameda County, California, a digital database extracted from preliminary photo interpretation maps of surficial deposits by T.H. Nilsen in USGS Open File report 75-277: U.S. Geological Survey Open-File Report 99-504, scale 1:62,500 digital ver.1.0.

Sawyer, T.L., 1999, Assessment of contractual deformation rates of the Mt. Diablo fold and thrust belts, eastern San Francisco Bay region, northern California: Final Technical Report submitted to the U.S. Geological Survey National Earthquake Hazards Reduction Program, 45 p.

Shakal, A., Huang, M., Reichle, M., Ventura, C., Cao, T., Sherburne, R., Savage, M., Darragh, R., and Petersen, C., 1989, CSMIP strong-motion records from the Santa Cruz Mountains (Loma Prieta), California earthquake of 17 October 1989: California Division of Mines and Geology, Office of Strong Motion Studies Report OSMS 89-06, 196 p.

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.

Sowers, J.M., Unpublished geologic map of the Livermore quadrangle, Alameda and Contra Costa counties, California: USGS, scale 1:24,000.

Southern California Earthquake Center, 2002, Recommended procedures for implementation of DMG Special Publication 117 guidelines for analyzing and mitigating landslide hazards in California: T.F. Blake, R.A. Hollingsworth, and J.P. Stewart, *editors*, Southern California Earthquake Center, University of Southern California, 108 p.

Unruh, J.R., and Sawyer, T.L., 1997, Assessment of blind seismogenic sources, Livermore Valley, eastern San Francisco Bay region: Final Technical Report submitted to the U.S. Geological Survey National Earthquake Hazards Reduction Program, 88 p.

Unruh, J.R., 2000, Characterization of blind seismic sources, in the Mt. Diablo-Livermore region, San Francisco Bay area, California: Final Technical Report submitted to the U.S. Geological Survey National Earthquake Hazards Reduction Program, 34 p.

Wagner, D. L., Bortugno, E. J., and McJunkin, R.D., 1990, Geologic Map of the San Francisco-San Jose Quadrangle: California Division of mines and geology, scale 1:250,000.

Wagner, J. R., 1978, Cenozoic history of the Coast Ranges east of San Francisco Bay: Ph.D. dissertation, University of California, Berkeley, 161 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 and Imagery

Google Earth Pro DigitalGlobe, 1-m resolution, 2006, covering Livermore Quadrangle.

Intermap IfSAR DTM, 5-m resolution, 2003, 7.5-minute Livermore Quadrangle.

National Archives BUU Aerial Photographs, June 6, 1939, flight 268, frames 1-4, black and white, vertical, approximate scale 1:20000.

National Archives BUT Aerial Photographs, July 26, 1939, flight 281, frames 1-7, black and white, vertical, approximate scale 1:20000.

National Archives BUU Aerial Photographs, August 2, 1939, flight 288, frames 52-57, black and white, vertical, approximate scale 1:20000.

National Archives BUT Aerial Photographs, May 8, 1940, flight 341, frames 51-55, black and white, vertical, approximate scale 1:20000.

National Archives BUT Aerial Photographs, June 8, 1940, flight 341, frames 35-45, black and white, vertical, approximate scale 1:20000.

USGS DOQQ, 1-m resolution, June 12, 1993, black and white, Livermore Quadrangle. (information concerning DOQQ can be obtained at http://www-wmc.wr.usgs.gov/doq/).

USGS LP DAAC ASTER VNIR imagery, 15-m resolution, 2006, http://LPDAAC.usgs.gov

W.A.C. Corp. Aerial Photographs, March 28, 1984, flight 3, frames 8-15, flight 12, frames 48-55, black and white, vertical, approximate scale 1:24000.

W.A.C. Corp. 2002 Aerial Photographs, flight 4, frames 54-62, 79-87, 106-113, flight 5, 29-36, color, vertical, approximate scale 1:24000.

APPENDIX A: SOURCES OF ROCK STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
City of Pleasanton	64
City of Dublin	51
County of Alameda	5
CalTrans Laboratory	4
City of Livermore	3
Dublin Quadrangle	60
Total Number of Shear Tests	**187 (159)***

* Actual number of shear tests used in the analysis

SECTION 3: GROUND SHAKING ASSESSMENT

for the

LIVERMORE 7.5-MINUTE QUADRANGLE, ALAMEDA COUNTY, CALIFORNIA

using the

2002 Probabilistic Seismic Hazard Assessment Model

By
Charles R. Real and Marvin Woods

Department of Conservation
California Geological Survey

INTRODUCTION

The Seismic Hazards Mapping Act (the Act) of 1990 (Public Resources Code, Chapter 7.8, Division 2) directs the California Department of Conservation, 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 located within the hazard zones. Evaluation and mitigation of seismic hazards are to be conducted under guidelines adopted by the California State Mining and Geology Board (CGS, 1997). The guidelines are available on the Internet at http://gmw.consrv.ca.gov/shmp/webdocs/sp117.pdf

This section of the evaluation report summarizes the calculations of ground motions used to evaluate liquefaction and earthquake-induced landslide potential for zoning purposes. Included are ground motion maps, a brief overview on how these maps were prepared, precautionary notes concerning their use, and related references. The maps presented herein are 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 (CGS,

1997). Alternatively, they can be used as a basis for comparing levels of ground motion determined by other methods with the statewide standard. Site ground motion levels from the 2002 seismic hazard model are also available interactively online:
http://eqint.cr.usgs.gov/deaggint/2002 or
http://www.consrv.ca.gov/cgs/rghm/pshamap/pshamain.html.

This section and Sections 1 and 2, which address 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 the California Geological Survey's Internet page: http://conservation.ca.gov/CGS/shzp.

2002 PROBABILISTIC SEISMIC HAZARD ANALYSIS MODEL

The estimated ground shaking is derived from the revised statewide Probabilistic Seismic Hazard Analysis (PSHA) model released cooperatively by the California Geological Survey and the U.S. Geological Survey (Cao and others, 2003; Frankel and others, 2002). This model replaces the previous ground-motion model of Petersen and others (1996) used in previous Official Seismic Hazard Zone Maps. Like the previous model, the 2002 model is the product of an extensive effort to obtain consensus within the scientific and engineering communities 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 2002 model improves the way energy is partitioned among fault types and source areas. The model also significantly narrows the gap that has existed between the earlier model and historical recurrence rates of earthquakes in the M6.5 to M7.0 range.

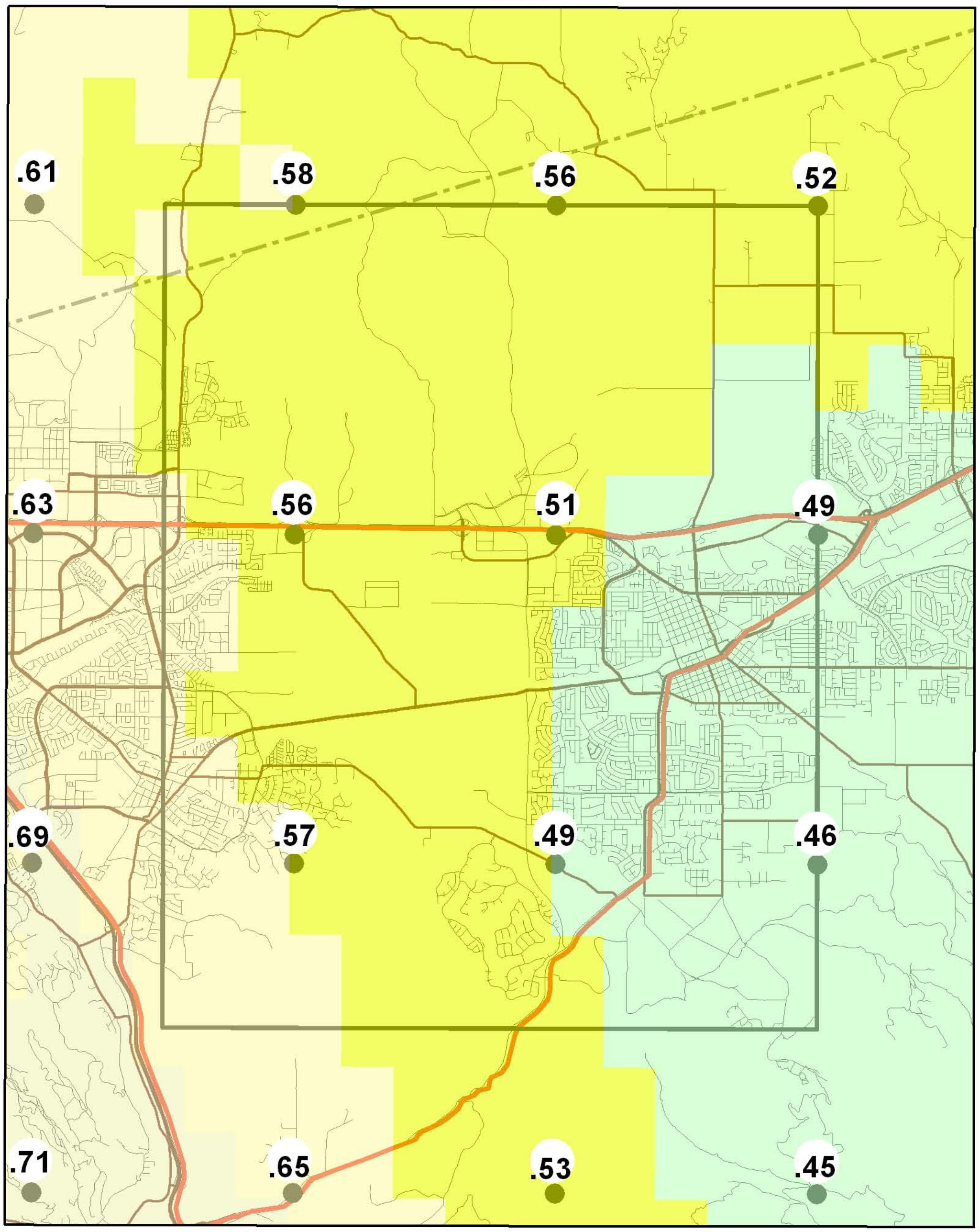
The ground shaking levels are estimated for each of the sources included in the seismic source model using attenuation relations that relate earthquake shaking with magnitude, distance from the earthquake, and type of fault rupture (strike-slip, reverse, normal, or subduction). Unlike the previous model, which used attenuation relations for various soil types, the current model considers only uniform firm-rock site conditions. In a separate post-PSHA step, we apply the NEHRP soil profile type D factor for PGA (FEMA, 1994) to adjust for alluvial soil conditions. For more details on changes in the new PSHA model, see Cao and others (2003) and Frankel and others (2002).

The seismic hazard maps for ground shaking are produced by calculating the hazard at sites separated by about 5 km. Figure 3.1 shows the hazard for PGA at 10 percent probability of exceedance in 50 years assuming the entire map area is firm rock (NEHRP B/C boundary soil condition). 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 quadrangles are also shown so that the trends in the ground motion may be more apparent. We recommend estimating PGA by interpolating ground motion from the calculated values of PGA rather than the contours, since the points are more accurate, and adjusting the value to site conditions using the NEHRP soil factors (Table 3.1).

LIVERMORE 7.5-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

PEAK GROUND ACCELERATION FOR FIRM ROCK NEHRP B/C CONDITIONS (Vs30 = 760 m/sec) AT 10 PERCENT EXCEEDENCE IN 50 YEARS

2002



Basemap from GDT

Department of Conservation
California Geological Survey

0 1 2 3 Miles
0 1 2 3 Kilometers

Figure 3.1

Soil Profile Type	**NEHRP (1994) Correction Factors for Different PGA Values (g)**				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
B	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
C	**1.2**	**1.2**	**1.1**	**1.0**	**1.0**
D	**1.6**	**1.4**	**1.2**	**1.1**	**1.0**
E	**2.5**	**1.7**	**1.2**	**0.9**	**-**

Table 3.1. 1994 NEHRP soil factors for peak ground acceleration

APPLICATION TO LIQUEFACTION AND LANDSLIDE HAZARD ASSESSMENT

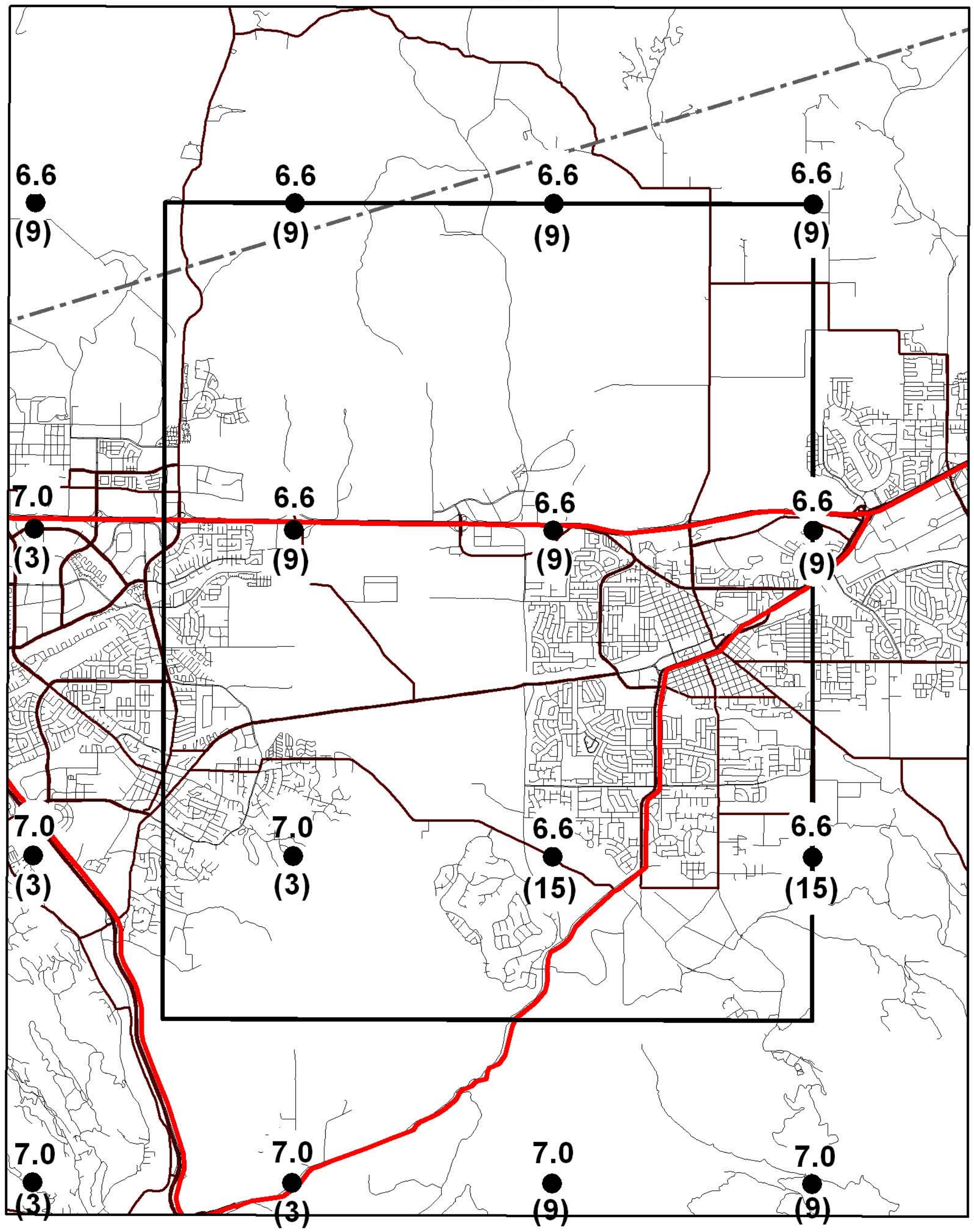
Deaggregation of the seismic hazard identifies the contribution of each earthquake source (various magnitudes and distances) in the model to the ground motion hazard for a particular exposure period (Cramer and Petersen, 1996). The map presented in Figure 3.2 identifies the magnitude and the distance (value in parentheses) of the earthquake that contributes most to the hazard at 10 percent probability of exceedance in 50 years (*predominant earthquake*). This information provides a rationale for selecting seismic records or ground motion level for evaluating ground failure potential. For zoning earthquake-induced landslide hazard, the predominant earthquake distance and magnitude is used to select ground motion recordings that are consistent with the hazard for calculating landslide displacement using the simple rigid sliding-block approach (Wilson and Keefer, 1983) described more fully in Section 2 of this report.

Predominant earthquake information shown in Figure 3.2 can also be used with more complex, fully coupled-compliant models for site-specific estimates of landslide displacement (Rathje and Bray, 2000). It can also be used with the Seed-Idriss simplified procedure (Youd and others, 2001) to estimate seismic demand (cyclic stress ratio) for site-specific assessment of liquefaction hazard. The predominant earthquake is used to identify the causative fault, then an appropriate attenuation relation and predominant magnitude are used to estimate PGA at the site. The predominant magnitude is then used to adjust the liquefaction cyclic stress ratio threshold curves by a scaling factor in the final calculation of factor of safety according to the simplified procedure.

LIVERMORE 7.5-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

MAGNITUDE OF AND DISTANCE TO (VALUE IN PARENTHESES) THE PREDOMINATE EARTHQUAKE AT10 PERCENT EXCEEDENCE IN 50 YEARS

2002



Basemap from GDT

Department of Conservation
California Geological Survey

0 1 2 3 Miles
0 1 2 3 Kilometers

Figure 3.2

When selecting the predominant earthquake magnitude and distance 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. It is advisable to consider the range of values at 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.

When calculating probabilistic peak ground acceleration for purposes of zoning liquefaction hazard, we weight each earthquake's contribution to the hazard estimate by a factor that is a function of its magnitude. The function is simply the inverse of the liquefaction threshold scaling factor mentioned previously. The result is a "magnitude-weighted" ground motion that we then adjust for NEHRP alluvial conditions and use directly in the calculation of the induced cyclic stress ratio demand and thus the estimate of the factor of safety against liquefaction. Unlike the predominant–earthquake approach described previously, this approach provides an improved estimate of liquefaction hazard in a probabilistic sense. All magnitudes contributing to the hazard estimate are used to weight the probabilistic calculation of peak ground acceleration, effectively causing the cyclic stress ratio liquefaction threshold curves to be scaled probabilistically when computing factor of safety. This procedure ensures large, distant earthquakes that occur less frequently, but contribute *more* and smaller, more frequent events that contribute *less* to the liquefaction hazard are appropriately accounted for (Real and others, 2000).

Figure 3.3 shows the magnitude-weighted alluvial PGA based on the Idriss scaling function (Youd and others, 2001). It is important to note that the values obtained from this map are pseudo-accelerations and should be used only in the simplified formulas for computing liquefaction factor of safety without applying any additional magnitude-scaling factor. We refer to this parameter as "liquefaction opportunity."

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 the following reasons.

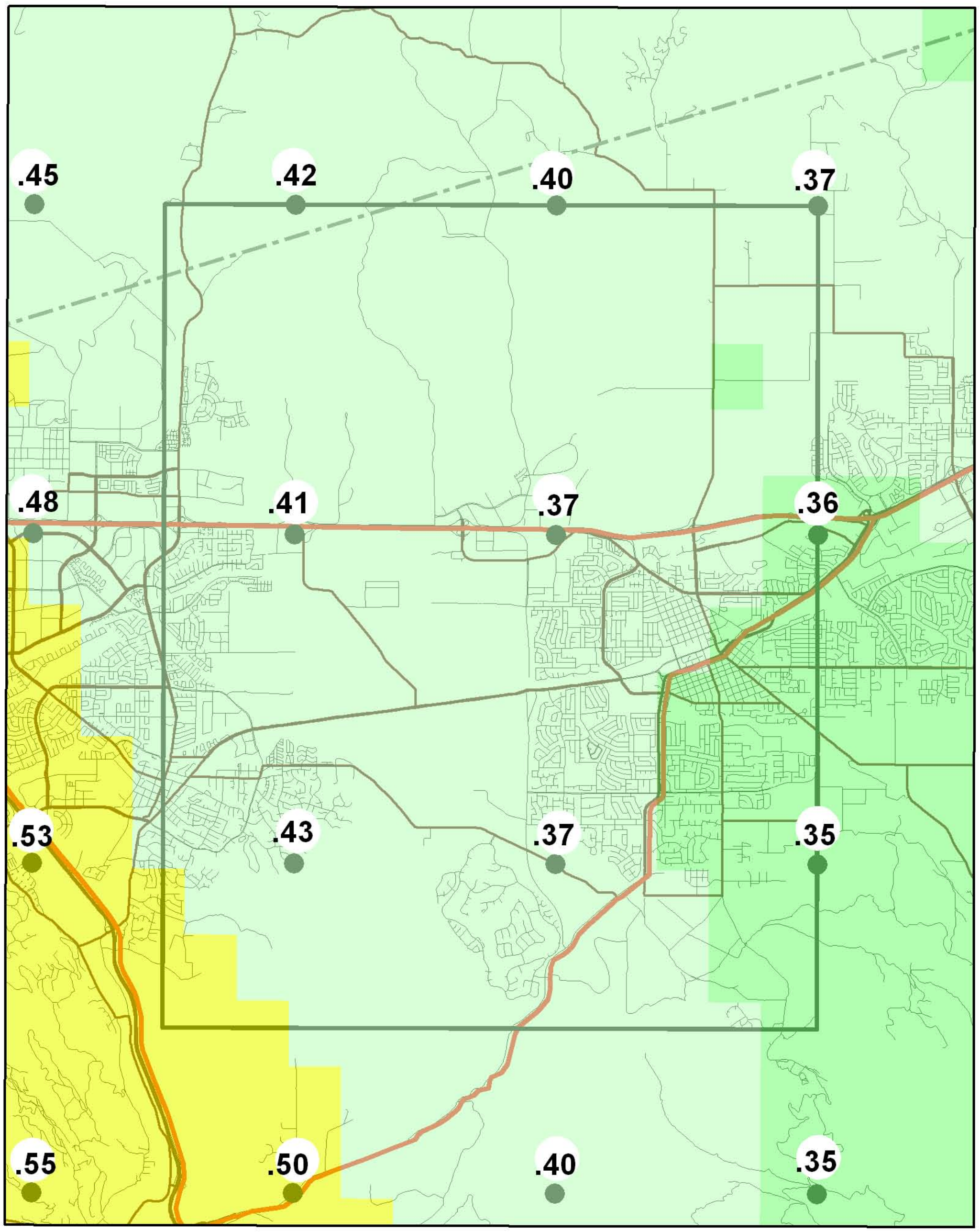
1. The seismogenic sources used to generate the peak ground accelerations were digitized from the 1:750,000-scale fault activity map of Jennings (1994). Uncertainties in fault location are estimated to be about 1 to 2 kilometers (Petersen and others, 1996). Therefore, differences in the location of calculated 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.

LIVERMORE 7.4-MINUTE QUADRANGLE AND PORTIONS OF ADJACENT QUADRANGLES

LIQUEFACTION OPPORTUNITY MAP

VALUES ARE MAGNITUDE-WEIGHTED PSEUDO-PEAK GROUND ACCELERATION FOR ALLUVIAL CONDITIONS AT 10 PERCENT EXCEEDENCE IN 50 YEARS

2002



Basemap from GDT

Department of Conservation
California Geological Survey

0 1 2 3 Miles

0 1 2 3 Kilometers

Figure 3.3

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 range from about +/- 10 to 30 percent of the ground motion value at two standard deviations for most of California (Cao and others, 2005). It may be as high as 50 percent in some locations where the earthquake source parameters have higher uncertainty.

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.

6. Because of its simplicity, it is likely that the SPPV method (CGS, 1997) will be widely used to estimate earthquake shaking for the evaluation of ground failure hazards. Because ground motion models evolve with time it is best to refer to the aforementioned web sites in order to obtain the most current ground shaking information when using this method: http://eqint.cr.usgs.gov/deaggint/2002 or http://www.consrv.ca.gov/cgs/rghm/pshamap/pshamain.html.

As a final caution, 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 variability is represented to some degree by the recorded ground motions that form the basis of the hazard model used to produce Figures 3.1 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 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

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

Cao, T., Petersen, M.D., and Frankel, A. D., 2005, Model uncertainties of the 2002 update of California seismic hazard maps: Bulletin of the Seismological Society of America, vol. 95, p. 2040-2057.

Cao, T., Bryant, W.A., Rowshandel, B., Branum, D., and Wills, C.J., 2003, Revised 2002 California Probabilistic Seismic Hazard Maps, California Geological Survey, Online Report, http://www.consrv.ca.gov/cgs/rghm/psha/fault_parameters/pdf/2002_CA_Hazard_Maps.pdf, 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, vol. 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, vol. 86, p. 1681-1691.

Frankel, A.D., Petersen, M.D., Muller, C.S., Haller, K.M., Wheeler, R.L., Layendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps: U.S. Geological Survey, Open-File Report 02-420, 33 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.

FEMA, 1994, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures: Washington, D.C., FEMA 222A.

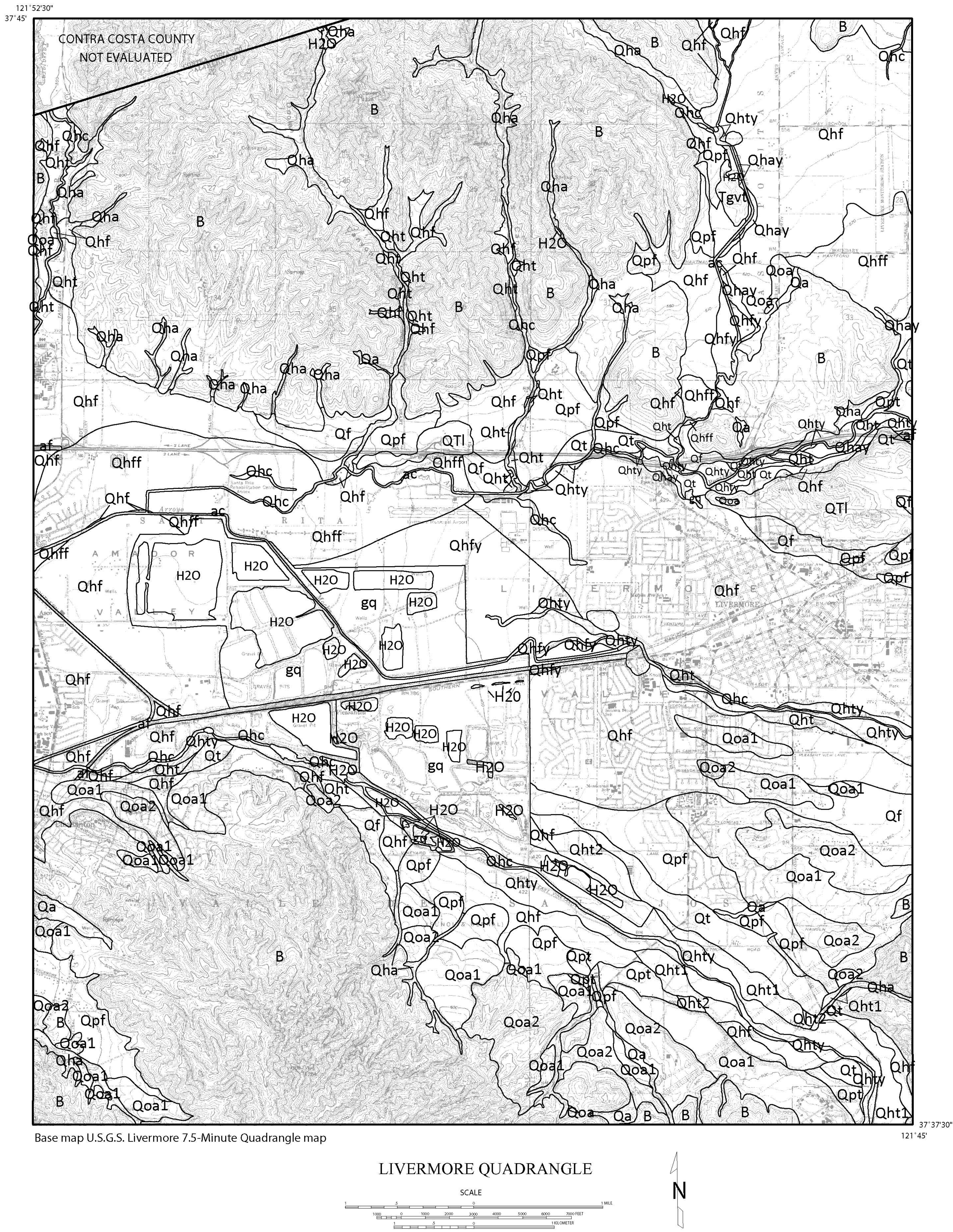
Petersen, M.D., Bryant, W.A., Cramer, C.H., Cao, T., Reichle, M.S., Frankel, A.D., Lienkaemper, J.J., McCrory, P.A., and Schwartz, D.P., 1996, Probabilistic seismic hazard assessment for the State of California: California Department of Conservation, Division of Mines and Geology Open-File Report 96-08;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

Rathje, E.M., and Bray, J.D., 2000, Nonlinear Coupled Seismic Sliding Analysis of Earth Structures: Journal of Geotechnical and Geoenvironmental Engineering, vol. 126, p. 1002-1014.

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.

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, vol. 73, p. 863-877.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D., Harder Jr., L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S., Marcuson III, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe II, K.H., 2001, Liquefaction Resistance of Soils: Summary Report From the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils: Journal of Geotechnical and Geoenvironmental Engineering, vol.127, p. 817-827.



See "Geology" in Section 1 of report for descriptions of units.
B = Pre-Quaternary bedrock.

Plate 1.1 Quaternary Geologic Map of the Livermore 7.5-minute quadrangle.

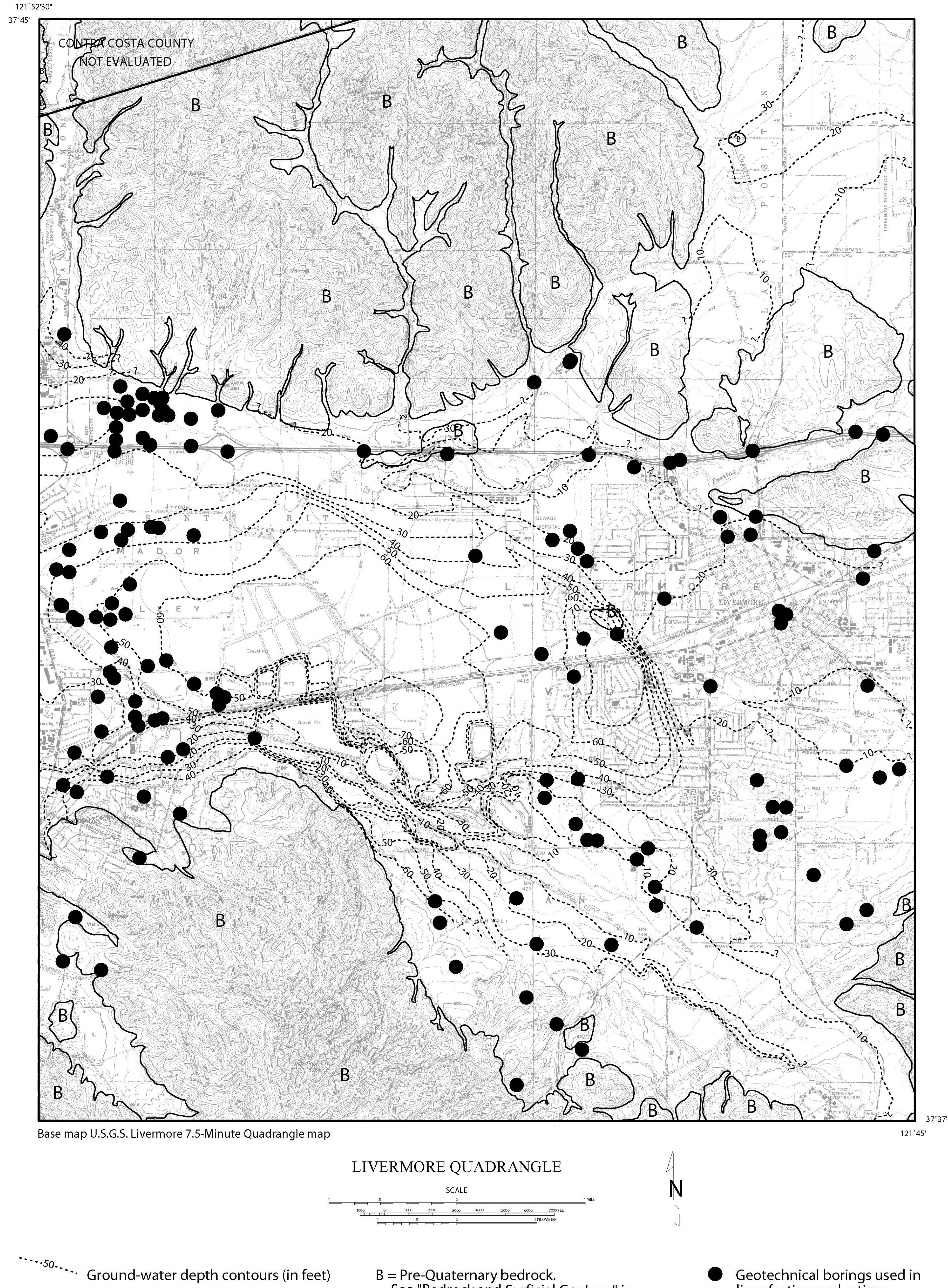


Plate 1.2 Depth to Historically High Ground Water Levels in the Quaternary Alluvial Deposits, and Locations of Boreholes Used in this Study, Livermore 7.5-Minute Quadrangle, California.

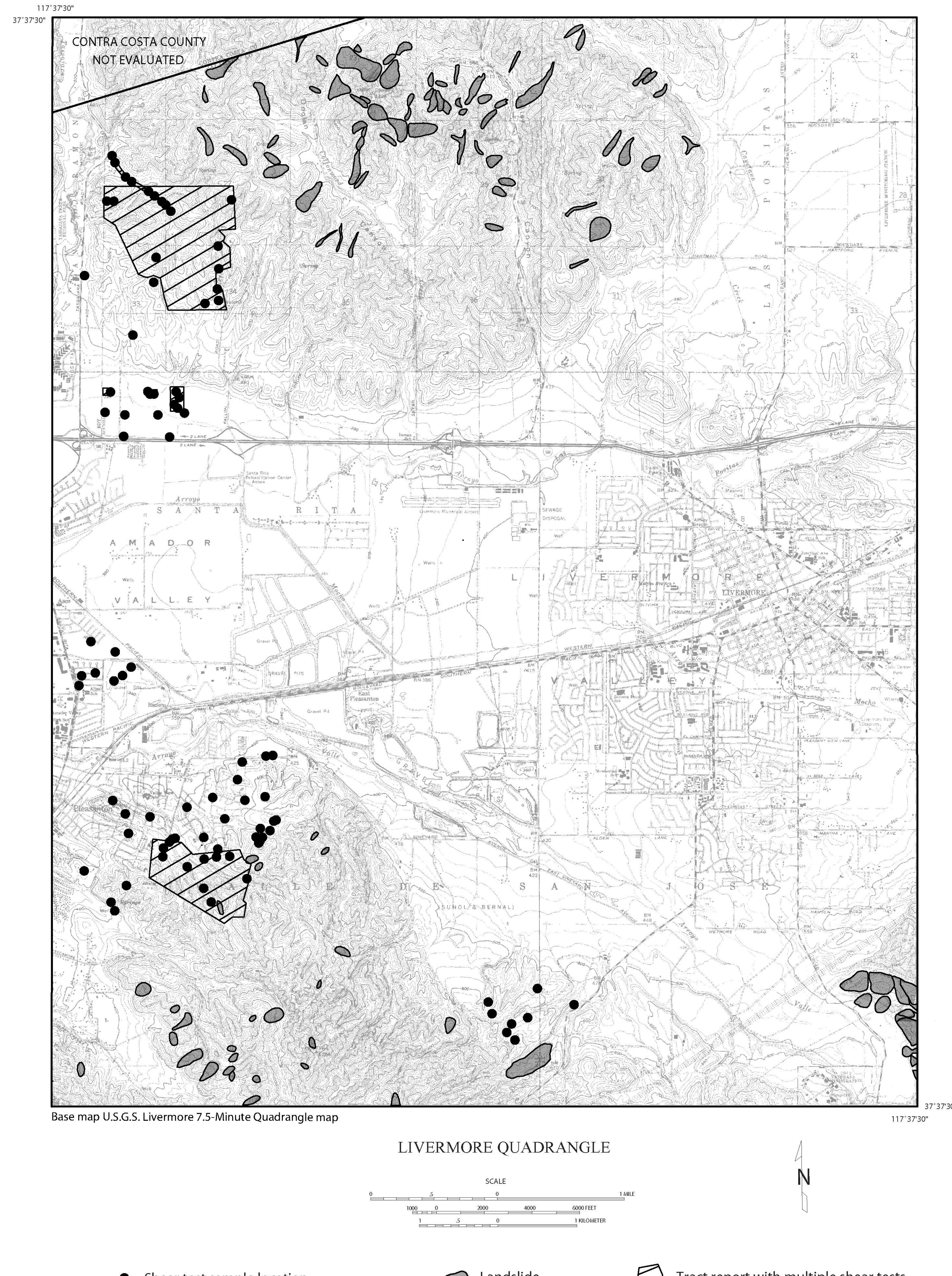


Plate 2.1 Landslide Inventory, and Shear Test Sample Locations, Livermore 7.5-Minute Quadrangle, California.