

SEISMIC HAZARD ZONE REPORT 143

SEISMIC HAZARD ZONE REPORT FOR THE SEBASTOPOL 7.5-MINUTE QUADRANGLE, SONOMA COUNTY, CALIFORNIA

2025



STATE OF CALIFORNIA
GAVIN NEWSOM
GOVERNOR

THE RESOURCES AGENCY
WADE CROWFOOT
SECRETARY FOR RESOURCES

DEPARTMENT OF CONSERVATION
JENNIFER LUCCHESI
DIRECTOR

CALIFORNIA GEOLOGICAL SURVEY
JEREMY LANCASTER
STATE GEOLOGIST



CALIFORNIA GEOLOGICAL SURVEY
JEREMY LANCASTER, STATE GEOLOGIST

Copyright © 2025 by the California Department of Conservation California Geological Survey. All rights reserved. No part of this publication may be reproduced without written consent of the California Geological Survey. The Department of Conservation makes no warranties as to the suitability of this product for any given purpose.

Web Accessibility Statement: If you find any part of this document to be inaccessible with assistive technology, visit our Accessibility web page at [conservation.ca.gov](https://www.conservation.ca.gov) to report the issue and request alternative means of access. To help us respond to your concern, please include the following three items in your request: 1. your contact information. 2. the title of this document. 3. the web address where you obtained the document.

TABLE OF CONTENTS

EXECUTIVE SUMMARY	iv
INTRODUCTION	v
The California Seismic Hazards Mapping Program	v
Methodology and Organization of this Report.....	v
Scope and Limitations.....	vi
Accessing Earthquake Zones of Required Investigation Maps, Reports, and GIS Data	vii
SECTION 1: GEOGRAPHY, GEOLOGY, AND ENGINEERING GEOLOGY	1
Purpose of this Section.....	1
GEOGRAPHY	1
Location.....	1
Land Use	2
Digital Terrain Data	2
GEOLOGY	2
Bedrock Units.....	3
Quaternary Sedimentary Deposits.....	3
Geologic Structure.....	5
Adverse Bedding Conditions	6
Existing Landslides	6
ENGINEERING GEOLOGY.....	7
Historical-High Groundwater Mapping	7
Geologic Material Testing.....	8
REFERENCES	11
Imagery.....	13
APPENDIX A: Sources of Rock Strength Data.....	14
SECTION 2: GROUND MOTION ASSESSMENT	15
Purpose of this Section.....	15
PROBABILISTIC SEISMIC HAZARD ANALYSIS MODEL.....	15
APPLICATION TO LIQUEFACTION AND EARTHQUAKE-INDUCED LANDSLIDE HAZARD ASSESSMENT	17
REFERENCES	18

SECTION 3: EVALUATION OF LIQUEFACTION HAZARD 21

 Purpose of this Section..... 21

ZONING TECHNIQUES 21

 Liquefaction Susceptibility 21

 Ground Motion for Liquefaction Opportunity 23

 Liquefaction Analysis 24

 Liquefaction Zoning Criteria..... 24

 Delineation of Liquefaction Hazard Zones 25

ACKNOWLEDGMENTS..... 26

REFERENCES 26

**SECTION 4: EVALUATION OF EARTHQUAKE-INDUCED LANDSLIDE
HAZARD..... 29**

 Purpose of this Section..... 29

ZONING TECHNIQUES 29

 Earthquake-Induced Landslide Susceptibility..... 29

 Ground Motion for Landslide Hazard Assessment 30

 Earthquake-Induced Landslide Hazard Potential 30

 Earthquake-Induced Landslide Zoning Criteria..... 31

 Delineation of Earthquake-Induced Landslide Hazard Zones 31

ACKNOWLEDGMENTS..... 32

REFERENCES 32

TABLES

Table 1.1	Quaternary units mapped in the Sebastopol Quadrangle (Sonoma County)	5
Table 1.2	Summary of the shear strength statistics for the Sebastopol Quadrangle (Sonoma County)	11
Table 2.1	Summary of ground motion parameters used for liquefaction and earthquake-induced landslide analyses.....	18
Table 3.1	Liquefaction susceptibility of Quaternary units in the Sebastopol Quadrangle (Sonoma County).....	22

PLATES

Plate 1.1	Quaternary geologic materials map and locations of boreholes used in evaluating liquefaction hazard, Sebastopol Quadrangle, Sonoma County, California.
Plate 1.2	Geologic materials and landslide inventory map with locations of shear test samples and Geologic Strength Index (GSI) measurements used in evaluating landslide hazard, Sebastopol Quadrangle, Sonoma County, California.
Plate 1.3	Groundwater basins, depth to historical-high groundwater levels, and groundwater data points, Sebastopol Quadrangle, Sonoma County, California.
Plate 2.1	Map of V_{S30} from Thompson (2018), Sebastopol Quadrangle and surrounding area, California.
Plate 2.2	Pseudo-PGA for liquefaction hazard mapping analysis, Sebastopol Quadrangle and surrounding area, California.
Plate 2.3	Probabilistic peak ground acceleration for landslide hazard mapping analysis, Sebastopol Quadrangle and surrounding area, California.
Plate 2.4	Modal magnitude for landslide hazard mapping analysis, Sebastopol Quadrangle and surrounding area, California.

EXECUTIVE SUMMARY

This report summarizes the sources of information and methods used to prepare the map of *Seismic Hazard Zones* (a subset of *Earthquake Zones of Required Investigation* (EZRI)) for the Sebastopol 7.5-Minute Quadrangle, Sonoma County, California (project area). The topographic quadrangle map, which covers approximately 151.5 square kilometers (58.5 square miles) at a scale of 1:24,000 (41.7 mm = 1,000 meters; 1 inch = 2,000 feet), displays the boundaries of the EZRI for liquefaction and earthquake-induced landslides. The areas subject to seismic hazard mapping include the city of Sebastopol, portions of the cities of Windsor and Santa Rosa, and unincorporated census designated areas of Sonoma County.

This Seismic Hazard Zone Report describes the development of the Seismic Hazard Zones for the Sebastopol 7.5-Minute Quadrangle. The process of zonation for liquefaction hazard involves evaluation of earthquake loading, Quaternary geologic maps, groundwater level records, and subsurface geotechnical data. The process of zonation for earthquake-induced landslide hazard incorporates evaluation of earthquake loading, existing landslides, slope gradient, rock strength, and geologic structure. Ground motion calculations used by CGS exclusively for regional zonation assessments are currently based on the probabilistic seismic hazard analysis (PSHA) model developed by the United States Geological Survey for the 2023 *Update of the United States National Seismic Hazard Maps*.

About 41.9 square kilometers (16.2 square miles) of the land within the project area has been designated as an EZRI for liquefaction hazard, encompassing major drainages such as the Laguna de Santa Rosa, Santa Rosa Creek, Mark West Creek, Atascadero Creek, and associated tributaries. Borehole logs within these areas indicate widespread presence of saturated, loose sandy sediments in the shallow subsurface. These materials generally have a moderate to high likelihood of liquefying during an earthquake event.

About 2.8 square kilometers (1.1 square miles) of the land in the project area has been designated as an EZRI for earthquake-induced landslides. This area encompasses terrain within the western half of the project area, including most of the hill north of River Road near Trenton, the slopes descending from the Vine Hill ridge, and moderate slopes within the low-relief hills surrounding the City of Sebastopol.

The State of California Seismic Hazards Mapping Act (“the Act”) requires city, county, and state agencies to use the Seismic Hazard Zone maps in their land-use planning and permitting processes. The Act requires that building permits for sites being developed within an EZRI cannot be issued 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.

INTRODUCTION

The California Seismic Hazards Mapping Program

The Seismic Hazards Mapping Act of 1990 (the Act) (Public Resources Code, Division 2, Chapter 7.8) directs the State Geologist to prepare maps that delineate Seismic Hazard Zones for liquefaction, earthquake-induced landslides, tsunami inundation, and other ground failures. These are a subset of Earthquake Zones of Required Investigation (EZRI), which also include Earthquake Fault Zones. The California Geological Survey (CGS) prepares EZRIs following guidelines prepared by the California State Mining and Geology Board (SMGB). For liquefaction and landslide hazard zone delineation, the SMGB established the Seismic Hazard Mapping Act Advisory Committee to develop guidelines and criteria for the preparation of seismic hazard zones in the state. The committee's recommendations are published in CGS Special Publication 118, which is available online at:

<https://www.conservation.ca.gov/cgs/publications/sp118>.

The purpose of the Act is to reduce the threat to public health and safety 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. State-of-the-practice evaluation and mitigation of seismic hazards are conducted under guidelines published in CGS Special Publication 117A, which are available online at:

<https://www.conservation.ca.gov/cgs/publications/sp117a>.

Following the initial release of the Special Publication 117 in 1997, local government agencies in the Los Angeles metropolitan region sought more definitive guidance in the review of geotechnical investigations addressing liquefaction and landslide hazards. These agencies convened two independent committees, one for liquefaction and one for landslides, to provide more detailed procedures for implementing Special Publication 117 guidelines. The reports produced by these committees were published under the auspices of the Southern California Earthquake Center (SCEC) and are available online at:

<http://scecinfo.usc.edu/resources/catalog/hazardmitigation.html>. Special Publication 117 was revised in 2008 as Special Publication 117A.

Methodology and Organization of this Report

Delineating liquefaction and landslide hazard zones requires the collection, compilation, and analysis of multiple types of digital data. These data include geologic maps, groundwater measurements, subsurface and laboratory geotechnical tests, elevation (terrain) maps, and probabilistic ground motion estimates. The data are processed into a series of geographic information system (GIS) layers using commercially available and open-source software, which are used as input for the delineation of hazard zones.

Earthquake Zones of Required Investigation (EZRI) for liquefaction and earthquake-induced landslides share many input datasets. Section 1 of this report describes the geographic, geologic, and hydrologic characteristics of the project area and laboratory tests used to categorize geologic materials within the quadrangles according to their susceptibility to liquefaction and/or landslide failure. Section 2 describes the development of the earthquake shaking parameters used in the liquefaction and landslide hazard analyses and summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential in the project area. Sections 3 and 4 summarize the analyses and criteria used to delineate liquefaction and earthquake-induced landslide hazard zones, respectively, in the project area.

Scope and Limitations

Seismic Hazard Zones for liquefaction and earthquake-induced landslides are intended to prompt more detailed, site-specific geotechnical investigations. Due to scale and other limitations inherent in these zones, they should not be used as a substitute for site-specific geologic or geotechnical investigations required under Chapters 7.5 and 7.8 of Division 2 of the California Public Resources Code. Site-specific geologic/geotechnical investigations are the best way to determine if these hazards could affect structures or facilities at a project site.

The zones described in this report identify areas where the potential for ground failure related to liquefaction and earthquake-induced landslides is relatively high. Liquefaction and landslides may occur outside the delineated zones in future earthquakes, but most of the occurrences should be within zoned areas. Conversely, not all the area within a hazard zone will experience damaging ground failure in future earthquakes. The analyses used to delineate liquefaction and earthquake-induced landslide zones cannot predict the amount or direction of liquefaction- or landslide-related ground displacements, or the amount of damage to structures or facilities that may result from such displacements. Because of this limitation, it is possible that run-out areas during future earthquakes could extend beyond zone boundaries.

Other earthquake-induced ground failures that are not specifically addressed in the analyses conducted for the project area include those associated with soft clay deformation, non-liquefaction-related settlement, ridge-top spreading, and shattered ridges.

Although data used in this evaluation was selected using rigorous criteria, 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.

Accessing Earthquake Zones of Required Investigation Maps, Reports, and GIS Data

CGS EZRI, including Seismic Hazard Zones and Earthquake Fault Zones, their related reports and GIS data, are available for download and/or online viewing on the CGS Information Warehouse: <https://maps.conservation.ca.gov/cgs/informationwarehouse/>

Alternatively, EZRI are available as an interactive web map service (WMS) here:

https://gis.conservation.ca.gov/server/rest/services/CGS_Earthquake_Hazard_Zones

EZRI are also available on a statewide parcel base, which can be useful for initial Natural Hazards Disclosure determinations, by using the California Earthquake Hazards Zone Application (EQ Zapp): <https://maps.conservation.ca.gov/cgs/EQZApp/app/>

Information regarding the Seismic Hazard Zonation Program is available on the CGS website: <https://www.conservation.ca.gov/cgs/sh/program/>

SECTION 1: GEOGRAPHY, GEOLOGY, AND ENGINEERING GEOLOGY

for the

SEBASTOPOL 7.5-MINUTE QUADRANGLE, SONOMA COUNTY, CALIFORNIA

by

Alyssa Tunnelle

P.G. 10002

and

Justin LaForge

P.G. 9796

DEPARTMENT OF CONSERVATION
CALIFORNIA GEOLOGICAL SURVEY

Purpose of this Section

Preparing Earthquake Zones of Required Investigation (EZRI) for liquefaction and earthquake-induced landslides requires many input datasets and complex analyses. The purpose of Section 1 of the Seismic Hazard Zone Report is to describe the overall geologic and geographic setting of the Sebastopol Quadrangle in Sonoma County (the project area) and then discuss the collection, processing, and analyses of primary geologic and engineering geologic data that were used to delineate EZRI.

GEOGRAPHY

Location

The project area covers approximately 151.5 square kilometers (58.5 square miles) in Sonoma County, and includes the city of Sebastopol, portions of the cities of Windsor and Santa Rosa, as well as unincorporated areas of Sonoma County.

The project area is situated at the southwestern boundary of the Santa Rosa Plain, a topographically low alluvial valley bound by the Coast Ranges to the west and the Mayacamas Mountains to the east. Bedrock units in the quadrangle consist of Mesozoic Franciscan Complex and serpentinite, and younger Miocene to Pliocene sedimentary and volcanic deposits. Surficial geology includes a thick sequence of Quaternary alluvial and fluvial sediments derived from the upland areas and deposited by stream systems. The project area is characterized by rolling hills and low-lying alluvial valleys with overall low relief. Elevations range from 9 meters (31 feet) above sea level along the Laguna de Santa Rosa and Mark West Creek stream channels to 174 meters (572 feet) above sea level in the foothills to the southwest. Significant valleys include the northwest-southeast trending Santa Rosa Plain, which dominates most of the eastern half of the quadrangle, as well as the narrower Atascadero Creek valley to the west.

Land Use

The region was originally inhabited by First Nations Coast Miwok and Southern Pomo tribes. Settlers from Mexico began arriving to the area in the early 1800s. The fertile, well-drained volcanic soils, particularly the Goldridge Sandy Loam, supported a wide variety of crops, including apples, cherries, and hops. By 1850, the town of Sebastopol had formed, and the surrounding agricultural lands continued to expand during the Gold Rush with the arrival of immigrants from Europe and China. The 1890 expansion of the San Francisco and North Pacific Railroad connected the region to the growing San Francisco Bay Area. Over time, vineyards began to take the place of apple orchards, and today, wine grapes are the dominant crop grown in the region.

Present land use in the Sebastopol area includes ongoing urban development, vineyards, row crops, orchards, pastures, and rural residential areas. The project area includes Ragle Ranch Regional Park, city parks, and protected open space lands. Tribal presence remains important to the area; current tribes include the Federated Indians of Graton Rancheria and the Lytton Band of Pomo Indians. The City of Sebastopol, the primary urban center, has a population of approximately 7,380 people. Major transportation routes include Highways 101, 12, and 116, which connect the region to Santa Rosa and the greater San Francisco Bay Area.

Digital Terrain Data

A digital representation of the earth's surface is a key component in delineating earthquake-induced liquefaction and landslide hazards. Within the project area, digital topography in the form of a bare earth digital elevation model (DEM) was obtained from the Sonoma County Vegetation Mapping & LiDAR Program (<https://sonomavegmap.org/data-downloads/>). These lidar data were collected in 2013 and include ground surface elevations at a point spacing of 1 meter, with 5-cm RMSE vertical accuracy.

For liquefaction hazard analyses, surface elevations derived from the DEM are differenced with historical-high ground water elevations to derive a "depth to water" map. In alluvial areas, the depth value obtained is combined with geologic data from boreholes and used in liquefaction calculations.

For earthquake-induced landslide hazard analyses, slope gradient and slope aspect are calculated using the slope applications built into commercially available GIS software. Both parameters are calculated using a third-order, finite difference, center-weighted algorithm based on Horn (1981), as documented in Burrough and McDonnell (1998). The slope gradient is combined with the geologic material strength map to calculate yield acceleration, a measure of susceptibility to earthquake slope failure as described in Section 4 of this report. Slope aspect, the compass direction that a slope faces, is used to identify potential adverse geologic bedding conditions and refine the geologic material strength map.

GEOLOGY

The primary source of geologic information used in the evaluation of liquefaction and earthquake-induced landslide hazards in the project area is the CGS geologic map digital database of the Napa-Bodega Bay 30' x 60' Quadrangle (Wagner and Gutierrez, 2017) which was compiled from new and existing geologic mapping, including the Preliminary Geologic Map of the Sebastopol 7.5' Quadrangle completed by Delattre and Koehler (2008).

The digital geologic maps covering the project area were combined to form a single 1:24,000-scale geologic materials map. CGS staff used DEMs, aerial photos, online imagery, and field reconnaissance to confirm the location of geologic contacts, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units. Landslide deposits were deleted from the geologic map so that the distribution of bedrock formations and the newly created landslide inventory would exist on separate layers for the hazard analysis. Young alluvial deposits were added or modified by CGS geologists in some areas to refine the map and ensure continuity of geologic mapping with adjacent quadrangles. Linear structural features such as folds, faults, and anticlines that did not form a geologic boundary were removed. The distribution of bedrock units and Quaternary deposits on the final geologic materials map was used, in combination with other data, to evaluate liquefaction and landslide susceptibility and develop the Seismic Hazard Zone Map.

The unit names and descriptions of geologic deposits exposed in the project area are taken from mapping completed by Wagner and Gutierrez (2017). Additional Quaternary unit nomenclature was correlated from Witter and others (2006).

Bedrock Units

Mesozoic Units

Mesozoic bedrock units mapped in the project area consist of Serpentinite derived from the Coast Range Ophiolite (**sp**), Franciscan Complex Central Belt mélange (**KJfm**), and Franciscan Complex Coastal or Central Belt Sandstone (**TKfs**). These units are exposed along the Trenton Thrust Fault, Mt. Jackson Fault Zone, and unnamed faults in the northwestern corner of the project area.

Cenozoic Units

Tertiary bedrock units mapped in the project area consist of a series of conglomerate, sandstone, siltstone, shale, claystone, and volcanic rock that range from late Miocene to late Pliocene in age. These units include the Roblar Tuff (**Mrt**) water-laid pumice lapilli tuff and tuff breccia, the Middle Petaluma Formation (**Mpm**) fluvial sandstone and conglomerate, and the Wilson Grove Formation (**Mwg**) marine and estuarine sandstone and pebbly sandstone. These units are exposed primarily in the low-lying hills in the western portion of the project area.

Quaternary Sedimentary Deposits

Approximately 112 square kilometers (43 square miles) of the quadrangle are underlain by Quaternary-aged sedimentary deposits. Most of these deposits consist of unconsolidated Pleistocene to Holocene-aged alluvium including stream channel, floodplain, terrace, fan, and undifferentiated alluvial deposits. Holocene alluvium deposited along modern drainage networks generally consists of poorly sorted sand, silt, and clay, and is often associated with the shallowest groundwater depths. Older alluvial fan and terrace deposits are found on slightly elevated surfaces and tend to be more consolidated, dissected, and have stronger soil development. The oldest Quaternary-aged unit is the Glen Ellen Formation (**QPge**), a tuffaceous sedimentary rock deposited in the Pliocene-Pleistocene with some exposures uplifted in the central study area by an unnamed fault. The eighteen distinct Quaternary units are classified based on their age and

depositional environment (Table 1.1). The distribution of these deposits informs the liquefaction susceptibility map as younger deposits are more likely to be susceptible to liquefaction (Plate 1.1).

Historical Artificial Fills

Four different types of fills are mapped in the area including artificial fill, artificial dam fill, artificial levee fill, and artificial stream channel deposits. Characteristics of these materials, such as grain size, density, and thickness, is not always known. Therefore, unless more detailed information is known, the liquefaction susceptibility of these units is determined based on the underlying geologic strata and depth to historical high groundwater.

Artificial fill (**af**) is present in various parts of the quadrangle and may be engineered or non-engineered. The northeastern area of the quad includes artificial fill emplaced along the railroad line, River Road, and Highway 101. In the southeastern area of the quadrangle, swaths of artificial fill are located along Highway 12 and underlie the outline of the historical Santa Rosa Air Center.

Artificial dam fill (**adf**) consists of earthen dams and embankments constructed to impound water. Several areas of dam fill are mapped on farmlands, around the perimeters of irrigation ponds, and along roadways.

Artificial levee deposits (**alf**) are limited to a narrow section along the Santa Rosa Flood control channel where it is underlain by Holocene alluvium (**Qha**).

Artificial channel fill (**ac**) consists of materials emplaced in historically active stream channels to re-route water flow and modify existing stream channels. Channel fills are located in straightened channels, flood control channels, and canals, and consist of loose sand, silt, and gravels. These fills are present along sections of the Laguna de Santa Rosa, Atascadero Creek, Santa Rosa Creek, and the Colgan Creek Flood Control Channel. The most extensive channel fill deposits are found along the Santa Rosa Creek, Santa Rosa Flood Control Channel, and their tributaries in the central study area.

Table 1.1. Quaternary units mapped in the Sebastopol Quadrangle (Sonoma County).

Map Unit	Environment of Deposition	Age
af	Artificial fill	Historical
adf	Artificial dam fill	Historical
alf	Artificial levee fill	Historical
ac	Artificial stream channel	Historical
Qhc	Stream channel deposit	Historical to late Holocene
Qhty	Stream terrace deposits	Latest Holocene
Qhay	Alluvial (fluvial)	Latest Holocene
Qha	Alluvial fan, terrace, or basin	Holocene
Qhb	Basin deposits	Holocene
Qht	Stream terrace	Holocene
Qhf	Alluvial fan	Holocene
Qhl	Fan levee	Holocene
Qa	Alluvial fan, terrace, or basin	Holocene to latest Pleistocene
Qf	Alluvial fan	Holocene to latest Pleistocene
Qt	Stream terrace	Holocene to latest Pleistocene
Qls	Landslides	Holocene to Pleistocene
Qoa	Alluvial fan, stream terrace, basin, or channel	Late to early Pleistocene
QPge	Lithified sedimentary deposits (Glen Ellen Formation)	Pleistocene-Pliocene

Geologic Structure

The structural framework of the California Coast Ranges is defined by a broad, complex belt of northwest-trending faults (Graymer and others, 2006; Jennings and others, 2010). In the northern San Francisco Bay region, this zone of deformation has experienced episodes of extensional, contractional, and dextral faulting throughout its evolution (Wagner and Gutierrez, 2017).

The Sebastopol Quadrangle covers an area within the Santa Rosa Plain and extends into the low-lying hills beyond its western margin. The Santa Rosa Plain, a northwest-trending topographic and structural low, is bound by the active right-lateral Rodgers Creek-Healdsburg fault zone to the east and by a system of poorly defined faults including the Sebastopol Fault to the west and southwest (Sweetkind and others, 2010).

Within the Sebastopol Quadrangle, northwest-oriented faults transect the Santa Rosa Plain and western low-lying hill regions. These faults include the Trenton Thrust Fault and several high angle faults, such as the Mt. Jackson Fault Zone (Delattre and Koehler, 2008; Langenheim and others, 2010). Several high-angle faults are considered Quaternary-active, but no Holocene or historically active faults are mapped within the project area (Jennings and Bryant, 2010). Map-scale folds are rare, and dips of Cenozoic strata are generally gentle, with moderate dips

occurring adjacent to faults. The Wilson Grove Formation (**Mwg**), one of the most extensive bedrock units in the quadrangle, predominately has a gentle northeastward dip (Sweetkind and others, 2010).

Adverse Bedding Conditions

Adverse bedding conditions are an important consideration in slope stability analyses. Adverse bedding conditions occur where the dip direction of bedded sedimentary rocks is roughly the same as the slope aspect, and where the dip magnitude is less than the slope gradient. Under these conditions, landslides can slip along bedding surfaces due to a lack of lateral support. To account for adverse bedding in our slope stability evaluation, we used geologic structural data in combination with digital terrain data to identify areas with potentially adverse bedding, using methods similar to those of Brabb (1983). The structural data, strike and dip measurements, and fold axes derived from the geologic map database were used to categorize areas of common bedding dip direction and magnitude. The dip direction was then compared to the slope aspect and, if the same, the dip magnitude and slope gradient categories were compared. The area was marked as a potential adverse bedding area if the dip magnitude category was less than or equal to the slope gradient category, but greater than 25% (4:1 slope).

Existing Landslides

As a part of the geologic data compilation, an inventory of existing landslides in the project area has been prepared (Spangler, in preparation) primarily from geomorphic analyses of lidar-derived elevation data and Google Earth Pro imagery, as well as through field reconnaissance and review of previously published landslide mapping (Delattre and Koehler, 2008; Huffman and Armstrong, 1980). The lidar dataset consists of bare earth DEM-derived hillshade, contour, slope, and other derivative layers. These data were acquired by Sonoma County in 2013 and meet QL1 accuracy achieving a mean pulse density of 11.04 points per square meter (Sonoma County Vegetation Mapping and LiDAR Program, 2013). All landslides in this inventory were digitized in an ArcGIS environment at a resolution of no larger than 1:2,000.

For each mapped landslide, several characteristics (attributes) were compiled. These characteristics include the confidence of interpretation (definite, probable, or questionable), activity, thickness, and associated geologic unit(s). The completed landslide map was digitized, and the attributes were entered into a database. Landslides rated as definite or probable were carried into the landslide zones as described in Section 4. A small-scale version of the landslide inventory is included on Plate 1.2.

A total of 118 landslides were mapped in the project area. There are 95 rock slides, 20 earth flows, and three debris fans. These landslides occur on moderate slopes in the western half of the project area. A notable cluster of landslides is mapped on the slopes that descend from Gold Ridge Road in the southwestern corner of the quadrangle.

The largest amount of land covered by landslides occurs in Wilson Grove Formation (**Mwg**). In terms of area percentage affected by landslides, the bedrock geologic units most susceptible to landsliding are Franciscan Complex Central Belt mélangé (**KJfm**, 15%), Franciscan Complex Coastal or Central Belt Sandstone (**TKfs**, 11%), Middle Petaluma Formation (**Mpm**, 9%), and Wilson Grove Formation (**Mwg**, 7%).

Numerous landslides occurred in Sonoma County during the April 18, 1906, earthquake, including small shallow landslides in the Sebastopol area (Lawson and Reid, 1908). However, mapped locations of these slides were not available, and they were not included in this study.

Because it is not within the scope of the Seismic Hazards Mapping Act to review and monitor grading practices to ensure past slope failures have been properly mitigated, all documented slope failures, whether surface expression currently exists, are included in the landslide inventory.

ENGINEERING GEOLOGY

Historical-High Groundwater Mapping

Liquefaction occurs only in saturated soil conditions, and the susceptibility of a soil to liquefaction varies with the depth to groundwater. Natural hydrologic processes and human activities can cause groundwater levels to fluctuate over time. Therefore, it is impossible to predict depths to saturated soils during future earthquakes. One method of addressing time-variable depth to saturated soils is to establish a high groundwater level based on historical groundwater data. In areas where groundwater is either currently near surface or could return to near-surface levels within a land-use planning interval of 50 years, CGS constructs regional contour maps that depict highest historical depths to groundwater surface. Plate 1.3 depicts groundwater basins and contours reflecting the historical-high depth to groundwater surface within the project area.

Groundwater Basins

The project area is within the North Coast hydrologic region, and the eastern portion of the quadrangle lies within the Santa Rosa Plain groundwater basin (number 1-055.01) as designated by the California Department of Water Resources (CDWR, 2020). This low-lying, northwest-southeast trending basin is bound on the west by the Coast Ranges and on the east by the Sonoma and Mayacamas Mountains. Principal streams in the project area include the Laguna de Santa Rosa, Mark West Creek, Santa Rosa Creek, and Atascadero Creek. Groundwater generally flows westward from the Mayacamas Mountains down a gentle gradient towards the Laguna de Santa Rosa via Mark West Creek, Santa Rosa Creek, and several unnamed channels and tributaries. The Laguna de Santa Rosa flows northwestward along the western basin edge, and while it receives some groundwater inflow from the Wilson Grove Formation, lateral flow appears to be limited by the Sebastopol fault acting as a partial barrier (USGS, 2013). The Laguna de Santa Rosa continues towards a confluence with Mark West and Windsor Creeks, which then flow into the Russian River. Groundwater depths in the alluvium generally range from 5 to 30 feet below the ground surface. Additionally, the western quadrangle area includes a portion of the Wilson Grove Formation-Highlands Basin where Atascadero Creek flows northward in a relatively narrow alluvial valley.

Shallow aquifer materials consist of Quaternary alluvial deposits and include Holocene to Pleistocene-aged stream channel deposits, stream terrace deposits, alluvium, fan deposits, and basin deposits consisting of sand, silt, and clay. Groundwater is rapidly recharged by rainfall and runoff into the groundwater system. The shallow aquifer is generally unconfined and mean annual precipitation in the project area is approximately 36 inches. The region has a

Mediterranean climate with most of the precipitation in the region occurring as rain between December and March.

Groundwater Data

Water level data evaluated in this study include groundwater measurements from 139 locations in the Sebastopol Quadrangle (Plate 1.3). For this study, groundwater conditions were investigated in the alluvial materials within the project area. The evaluation was based on first-encountered, unconfined water noted in geotechnical borehole logs on file with the planning and building departments of Sonoma County and the cities of Sebastopol and Santa Rosa, the State Water Resources Control Board on GeoTracker (CWRCB, 2024), and the California Department of Water Resources Statewide Groundwater Elevation Monitoring and Water Data Library (CDWR, 2024). These datasets reflect singular water levels from 1941 to present. Additional groundwater measurements were collected from the United States Geological Survey groundwater dataset (USGS, 2024). The data collected from this source are generally of higher quality as they consist of monitoring wells with strict measurement protocols that record the evolution of water levels through time on hydrographs.

Groundwater levels from all available records were spatially and temporally evaluated in a GIS database to constrain the estimate of historically shallowest groundwater for the project area. The historical-high groundwater map was modified, where warranted, with input from current ground surface water, such as active creeks, recharge ponds, detention basins, reservoirs, and other water impoundments. The depth to groundwater contours depicted on Plate 1.3 does not represent conditions at a particular point in time, as usually presented on typical groundwater contour maps, but rather the historical-high depth to groundwater anticipated within the project area.

Groundwater Levels

Historical-high groundwater depths in the map area are generally shallow (less than 10 feet below the ground surface) along the active stream channels throughout the study area, reflecting increased surface water infiltration and groundwater inflow in these areas. Higher historical high groundwater depths in the range of 10 to 40 feet occur in the slightly elevated older alluvial fan deposits, where groundwater flow is likely more diffuse causing recharge to occur at longer time scales.

Geologic Material Testing

Liquefaction Hazard Zoning: In-Situ Penetration Resistance

A key component of liquefaction evaluations are measurements of a given deposit's density and consistency. The Standard Penetration Test (SPT) provides a standardized measure of the penetration resistance of geologic deposits and is used as an index of soil density. For this reason, SPT results are a critical component of the Seed-Idriss Simplified Procedure, a method used by CGS and the geotechnical community to quantitatively analyze liquefaction potential of sandy and silty material. The SPT is an in-field test 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 30 inches. The SPT method is formally defined and specified by the American Society for Testing and Materials in test method D1586 (ASTM, 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 1 atmosphere (approximately 1 ton per square foot) and a hammer efficiency of 60% using a method described by Seed and Idriss (1982) and Seed and others (1985). This normalized blow count is referred to as $(N_1)_{60}$. Geotechnical borehole logs provided information on lithologic and engineering characteristics of Quaternary deposits within the project area.

For liquefaction hazard zoning in the project area, we reviewed soils reports on file with the planning departments at Sonoma County and the cities of Sebastopol and Santa Rosa. Additional borehole information was gathered from geotechnical evaluations at school and hospital sites reviewed by CGS under contract with the Division of the State Architect (DSA) and the Department of Health Care Access and Information (HCAI). The data were entered into the CGS geotechnical GIS database. After an initial review process and data quality controls, 405 borehole logs were selected for this study, all located within the Sebastopol Quadrangle, as shown on Plate 1.1.

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

Landslide Hazard Zoning: Laboratory Shear Strength

To evaluate the stability of geologic materials susceptible to landslide failure under earthquake conditions, the geologic map units were assigned values based on their shear strength.

Generally, the primary source for shear-strength data is measurements of angle of internal friction (ϕ) and cohesion (c) from geotechnical reports prepared by consultants, on file with local government permitting departments. A total of 10 shear tests were collected in the project area, all located within the Sebastopol Quadrangle as shown on Plate 1.2. These data were supplemented with shear tests for geologic map units in the project area from adjoining quadrangles (Healdsburg, Jintown, Cotati, Guerneville, Santa Rosa, see Appendix A).

For geologic units where sufficient shear-strength laboratory data could not be acquired, field measurements of Geologic Strength Index (GSI) (Marinos and others, 2007) were collected and the Hoek-Brown Failure Criterion (Hoek and others, 2002) was used to estimate the overall geologic unit strength. The non-linear Hoek-Brown criterion is a rock mass characterization method which uses equations to relate rock mass classification through a Geological Strength Index (GSI) to the angle of internal friction of a rock mass. This method allows strength assessment based on collected data, mainly discontinuity density, discontinuity condition, and geologic material properties (Hoek and others, 2002; Marinos and others, 2007). The number and distribution of GSI measurements used in this project are detailed in Appendix A.

Mean and median ϕ and c values for each geologic map unit in the project area were calculated and are summarized in Table 1.2. For the Franciscan Complex Central Belt mélange (**KJfm**) and Middle Petaluma Formation (**Mpm**), the ϕ values used in analysis were adjusted from the available raw data. In the Franciscan Complex Central Belt mélange, the shale matrix strength

was used to represent the formation strength. This is based on the understanding that slope failures can occur entirely within the matrix of the Franciscan Complex mélange. While this approach is used here at the map scale, studies have demonstrated that blocks within block-in-matrix rocks can mechanically contribute to slope strength, when present in sufficient volumetric proportion (Kim and others, 2004; Lindquist, 1994; Lindquist and Goodman, 1994). Assessments of blocks within the Franciscan Complex mélange and their strength contribution to slope stability should be carried out at the site-specific level. For the Middle Petaluma Formation, the available data were biased toward coarser grained lithofacies (conglomerate) and its ϕ value was adjusted slightly to account for the finer grained lithofacies (sandstone) present in the formation. A geologic material strength map was created assigning the selected ϕ value to each geologic map unit in the project area to be used in our slope stability analysis.

Regional adverse bedding conditions were not identified within the project area and no adverse bedding conditions were applied in analysis. However, it should be noted that a landslide investigation within the project area identified weak clay layers within the Wilson Grove Formation (**Mwg**) that dip out of slope (leaving the slope “unsupported”) as probable cause for landslide movement. Site-specific geologic and geotechnical investigations should consider the potential for adverse bedding conditions to exist within the quadrangle, especially within the Wilson Grove Formation.

As discussed in Section 4, the criteria for landslide zone mapping state that all existing landslides mapped as definite or probable are automatically included in the Seismic Hazard Zone for earthquake-induced landslides. 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 collect and compile shear strength data considered representative of existing landslides within the quadrangles if available.

The strength characteristics of existing landslides (**QIs**) 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. For the Sebastopol and adjacent quadrangles, strength parameters applicable to existing landslide planes were not available and are not included in Table 1.2.

Table 1.2. Summary of the shear strength statistics for the Sebastopol Quadrangle (Sonoma County).

Formation Name	Number of Tests	Mean/Median ϕ (deg)	Mean/Median c (psf)*	ϕ Used in Stability Analysis
Mpm	2	36/36		34
TKfs	1	33/33		33
Mrt	2	32/32		32
QPge	10	30/32		30
Qf§	5	29/34	500/500	29
Mwg	23	28/31	607/500	28
Qa‡	16	25/22	482/255	25
sp	1	25/25		25
af†	2	23/23		23
KJfm	7	30/32		22

* cohesion values only reported based on lab data, if available.
† af includes adf, alf, ac, af
‡ Qa includes Qhay, Qhb, Qhl, Qhc, Qha, Qa, Qoa, Qhty, Qht, Qt
§ Qf includes Qhf, Qf

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.
- Blake, M.C., Graymer, R.W., and Stamski, R.E., 2002, Geologic map and map database of western Sonoma, northernmost Marin, and southernmost Mendocino Counties, California, U.S. Geological Survey Miscellaneous Field Studies Map MF-2402, scale 1:100,000, https://ngmdb.usgs.gov/Prodesc/proddesc_52762.htm
- Burrough, P.A. and McDonnell, R.A., 1998, Principles of Geographic Information Systems, New York, Oxford University Press, 190p.
- California Department of Water Resources (CDWR), 2020, California's Groundwater Update 2020, Bulletin 118, https://data.cnra.ca.gov/dataset/calgw_update2020
- California Department of Water Resources (CDWR), 2024a, California Statewide Groundwater Elevation Monitoring (CASGEM) Program, <https://water.ca.gov/programs/groundwater-management/groundwater-elevation-monitoring--casgem>
- California Department of Water Resources (CDWR), 2024b, Water Data Library, <https://www.water.ca.gov/waterdatalibrary>
- California Water Resources Control Board (CWRCB), 2024, California Protection Agency, GeoTracker database, <https://geotracker.waterboards.ca.gov>

- Delattre, M.P. and Koehler, R.D., 2008, Geologic map of the Sebastopol 7.5-minute Quadrangle, Sonoma County, California: A digital database. California Geological Survey, Preliminary Geologic Maps PGM-08-01, scale 1:24,000.
- Graymer, R.W., Moring, B.C., Saucedo, G.J., Wentworth, C.M., Brabb, E.E. and Knudsen, K.L., 2006, Geologic Map of the San Francisco Bay Region (No. 2918), US Geological Survey.
- Hoek, E., Caranza-Torres, C.T., and Corkum, B., 2002, Hoek–Brown failure criterion—2002 edition *in* Bawden, H.R., Bawden, W., Curran, J., and Telesnicki, M., *editors*, Proceedings of the Fifth North American Rock Mechanics Symposium (NARMS-TAC), University of Toronto Press, Toronto, pp 267–273.
- Horn, B.K.P., 1981, Hill shading and the reflectance map: Proceedings of the IEEE, v. 69, no. 1, p.14-47.f
- Huffman, M.E., and Armstrong, C.F., Geology for Planning in Sonoma County, 1980, California Geological Survey, Special Report 120.
- Jennings, C.W., Gutierrez, C., Bryant, W., Saucedo, G., and Wills, C., 2010, Geologic Map of California, California Geological Survey, Geologic Data Map Series No. 2, scale 1:750,000.
- Jennings, C.W., and Bryant, W.A., 2010, Fault Activity Map of California, California Geological Survey, Geologic Data Map Series No. 6, map scale 1:750,000.
- Kim, C., Smell, C. and Medley, E., 2004, Shear Strength of Franciscan Complex Melange as Calculated from Back-Analysis of a Landslide, Fifth International Conference on Case Histories in Geotechnical Engineering, Paper No. 2.33.
- Lawson, A.C. and Reid, H.F., 1908, The California Earthquake of April 18, 1906: Report of the State Earthquake Investigation Commission (No. 87), Carnegie Institution of Washington.
- Langenheim, V.E., Graymer, R.W., Jachens, R.C., McLaughlin, R.J., Wagner, D.L. and Sweetkind, D.S., 2010, Geophysical framework of the northern San Francisco Bay region, California, *Geosphere*, 6(5), pp.594-620.
- Lindquist, E.S., 1994, The strength and deformation properties of mélangé, University of California, Berkeley.
- Lindquist, E.S. and Goodman, R.E., 1994, Strength and deformation properties of a physical model mélangé, In ARMA North America Rock Mechanics Symposium (pp. ARMA-1994).
- Marinos, P., Marinos, V., and Hoek, E., 2007, Geological Strength Index (GSI). A characterization tool for assessing engineering properties for rock masses *in* Olalla, C., Perucho, A., and Romana, M., *editors*, proceedings of the ISRM workshop W1: Madrid, Spain 2007: Taylor & Francis, p.13-21.
- Nishikawa, Tracy, ed., 2013, Hydrologic and geochemical characterization of the Santa Rosa Plain watershed, Sonoma County, California: U.S. Geological Survey Scientific Investigations Report 2013–5118, 178 p.
- 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., Tokimatsu, K., 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.

- Spangler, E., in preparation, Landslide inventory map of the Sebastopol 7.5-minute Quadrangle, Sonoma County, California: California Geological Survey, 1:24,000 scale map sheet.
- Sweetkind, D.S., Taylor, E.M., McCabe, C.A., Langenheim, V.E. and McLaughlin, R.J., 2010, Three-dimensional geologic modeling of the Santa Rosa Plain, California, *Geosphere*, 6(3), pp.237-274.
- Sowers, J.M., Noller, J.S., and Lettis, W.R., 1998, Quaternary Geology and Liquefaction Susceptibility, Napa, California, 1:100,000 Quadrangle, A Digital Database, U.S. Geological Survey Open File Report 98-460, available at: <https://pubs.usgs.gov/of/1998/of98-460/>
- U.S. Geological Survey (USGS), 2024, National Water Dashboard, <https://dashboard.waterdata.usgs.gov/>
- Wagner, D.L. and Gutierrez, C.I., 2017, Preliminary geologic map of the Napa and Bodega Bay 30' x 60' Quadrangles, California: version 1.0: California Geological Survey, Preliminary Geologic Maps, scale 1:100,000.
- 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, <https://pubs.usgs.gov/of/2006/1037/>.

Imagery

- Sonoma County Vegetation Mapping and LiDAR Program, NASA Roses Sonoma County LiDAR & Imagery Survey (2013), accessed at <https://sonomavegmap.org/data-downloads/>.
- Lidar Hillshade derived from the 1.5 m Lidar Digital Terrain Model (2013), source of illumination: 45° sun angle, and 90° and 315° sun azimuths.

APPENDIX A: SOURCES OF ROCK STRENGTH DATA

SOURCE	NUMBER OF LAB TESTS SELECTED	NUMBER OF HOEK-BROWN TESTS SELECTED
Sebastopol Quadrangle	10	35
Healdsburg Quadrangle	10	0
Jimtown Quadrangle	7	0
Cotati Quadrangle	2	0
Guerneville Quadrangle	4	0
Santa Rosa Quadrangle	1	0
Total Number of Tests	34	35

SECTION 2: GROUND MOTION ASSESSMENT

for the

SEBASTOPOL 7.5-MINUTE QUADRANGLE, SONOMA COUNTY, CALIFORNIA

using the

2023 NATIONAL SEISMIC HAZARD MODEL

by

Rui Chen
P.G. 8598

DEPARTMENT OF CONSERVATION
CALIFORNIA GEOLOGICAL SURVEY

Purpose of this Section

This section of the Seismic Hazard Zone Report presents an assessment of earthquake shaking hazards in the Sebastopol Quadrangle, Sonoma County (the project area). It includes an explanation of the probabilistic seismic hazard analysis (PSHA) model from which ground motion parameters are derived, and how these parameters are used to delineate liquefaction and earthquake-induced landslide hazard zones.

PROBABILISTIC SEISMIC HAZARD ANALYSIS MODEL

Probabilistic ground motions are calculated using the 2023 update of the United States Geological Survey (USGS) National Seismic Hazard Model (NSHM) (Petersen and others, 2023). This model replaces ground-motion hazard models of Petersen and others (2008, 2014, 2015, and 2018), Cao and others (2003), Frankel and others (2002), and Petersen and others (1996) used in previous official Seismic Hazard Zone maps. Like previous models, the 2023 NSHM utilizes the best available and applicable science, models and data; and is the product of an extensive effort to obtain consensus within the scientific and engineering communities regarding earthquake sources and ground motions.

In California, two earthquake source models contribute to ground motion hazards, namely the western United States (WUS) active-crust model and the Cascadia subduction model. These earthquake source models are part of a new earthquake rupture forecast (ERF) that characterizes the probabilistic locations, sizes, and rates of potential earthquakes. The ERF is described in detail by Field and others (2023).

Another important component of a PSHA is ground-motion models (GMMs) that define probabilistic levels of ground shaking conditioned on an earthquake rupture and site characteristics. For shallow crustal earthquakes in the 2023 NSHM, ground motions are calculated using the Next Generation Attenuation Relations for the WUS (NGA-West2) developed from a Pacific Earthquake Engineering Research Center ground motion research project (Bozorgnia and others, 2014). Four NGA-West2 GMMs are used in California:

Abrahamson and others (2014), Boore and others (2014), Campbell and Bozorgnia (2014), and Chiou and Youngs (2014). For subduction zone earthquakes and earthquakes of other deep sources, five GMMs developed specifically for such sources are used, including the Zhao and others (2006), Atkinson and Macias (2009), and three new semi-empirical GMMs developed as part of the NGA-Subduction GMMs project (Bozorgnia and others, 2022). The new NGA-subduction GMMs are Abrahamson and Gülerce (2021), Kuehn and others (2020), and Parker and others (2021). The 2023 NSHM also applies basin-depth amplification models based on the NGA-West2 GMMs for the San Francisco Bay Area, Los Angeles, and Great Valley.

In a PSHA, ground motion hazards from potential earthquakes of all magnitudes and distances on all potential seismic sources are integrated. GMMs are used to calculate the shaking level from each earthquake based on earthquake magnitude, rupture distance, type of fault rupture (strike-slip, reverse, normal, or subduction), and other parameters such as time-averaged shear-wave velocity in the upper 30 m beneath a site (V_{S30}). In CGS seismic hazards mapping applications prior to 2017, a uniform firm-rock site condition was assumed in PSHA calculations, and, in a separate post-PSHA step, National Earthquake Hazard Reduction Program amplification factors were applied to adjust all sites to a uniform alluvial soil condition to approximately account for the effect of site condition on ground motion amplitude. After 2017, site effect is directly incorporated in PSHA via GMM scaling. Specifically, V_{S30} is built into GMMs as one of the predictor variables and, therefore, it is an input parameter in PSHA calculations. Between 2017 and 2024, the V_{S30} value at each location is assigned from a geology- and topography-based V_{S30} map for California developed by Wills and others (2015), which consists of fifteen V_{S30} groups with group mean V_{S30} values ranging from 176 m/s to 733 m/s. These V_{S30} groups correspond to 15 geologic units and are mapped as GIS polygon features with smooth boundaries. Starting from 2025, an improved V_{S30} map for California developed by Thompson (2018, the 2022 revision) is adopted. This new V_{S30} map incorporates the V_{S30} map data by Wills and others (2015) and site-specific V_{S30} measurements. It is produced as a GIS raster at a 3-arcseconds resolution by applying the geostatistical approach of regression kriging to combine geologic, topographic and V_{S30} measurement constraints. It is to be noted that these V_{S30} values are for mapping purposes and should not be used as site-specific velocity data.

For earthquake-induced landslide hazard mapping, ground motions are calculated at each grid point of a 0.005-degree grid (approximately 500-m spacing) that adequately covers the entire project area. The V_{S30} map and grid points in the project area are depicted in Plate 2.1. For liquefaction hazard mapping, ground motions are calculated at each boring location. For site investigation, it is strongly recommended that V_{S30} be determined from site-specific shear wave velocity profile data.

PSHA provides more comprehensive characterizations of ground motion hazards compared to traditional scenario-based analysis by integrating hazards from all earthquakes above a certain magnitude threshold. However, many applications of seismic hazard analyses, including CGS' liquefaction and earthquake-induced landslide hazard mapping analyses, still rely on scenario earthquakes or some aspects of scenario earthquakes. Disaggregation enables identification of the most significant scenario or scenarios in terms of magnitude and distance pair.

Disaggregation is often performed for a particular site, a chosen ground motion parameter (such as peak ground acceleration or PGA), and a predefined exceedance probability level (i.e., hazard level). As in previous regulatory zone maps, the minimum ground motion hazard level for liquefaction and earthquake-induced landslide hazard mapping is 10% exceedance probability in 50 years or ground motions with a 475-year return period.

Probabilistic ground motion calculation and hazard disaggregation are performed using the USGS PSHA code, *nshmp-haz* version 2.0.0 (Powers and other, 2022), publicly available at: <https://code.usgs.gov/ghsc/nshmp/nshmp-haz>. This code also supports the USGS web-based site-specific ground motion calculator, the USGS Earthquake Hazard Toolbox, <https://earthquake.usgs.gov/nshmp/>. The source model used for the published 2023 NSHMs is adopted in its entirety. The source model is known as the USGS CONUS (contiguous United States) model, version 6.0.0 (or *nshmp-conus-6.0.0*). The 2023 source model is also publicly available at: <https://code.usgs.gov/ghsc/nshmp/nshms/nshm-conus>.

APPLICATION TO LIQUEFACTION AND EARTHQUAKE-INDUCED LANDSLIDE HAZARD ASSESSMENT

The current CGS liquefaction hazard analysis approach requires that PGA be scaled by an earthquake magnitude weighting factor (MWF) to incorporate a magnitude-correlated duration effect (CGS, 2004; 2008). The MWF-scaled PGA is referred to as pseudo-PGA and is used as Liquefaction Opportunity (see Section 3 of this report). The MWF calculation is straight forward for a scenario earthquake. In PSHA, however, earthquakes of different magnitudes and distances contribute differently to the total hazard at a chosen probabilistic PGA level. The CGS approach to MWF calculation is based on binned magnitude-distance disaggregation. At each location, an MWF is calculated for each magnitude-distance bin and is weighted by the contribution of that magnitude-distance bin to the total hazard. The total MWF is the sum of probabilistic hazard-weighted MWFs from all magnitude-distance bins. 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 PGA, effectively causing the cyclic stress ratio liquefaction threshold curves to be scaled probabilistically when computing factor of safety. This procedure ensures that 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).

The current CGS earthquake-induced landslide hazard analysis approach requires the probabilistic PGA and a predominant earthquake magnitude to estimate cumulative Newmark displacement for a given rock strength and slope gradient condition using a regression equation, described more fully in Section 4 of this report. The predominant earthquake magnitude is chosen to be the modal magnitude from disaggregation.

Pseudo-PGA at grid points is depicted in Plate 2.2, whereas probabilistic PGA at grid points is depicted in Plate 2.3. Modal magnitude is depicted in Plate 2.4. Ground motion generally decreases from the northeast to southwest as distance from the Rodgers Creek-Healdsburg fault zone increases. Shaking hazards are controlled predominantly by the Rodgers Creek-Healdsburg fault zone in most part of the quadrangle, with the Northern San Andreas fault making increasingly larger contribution toward the southwest and eventually dominating the ground motion hazard in the southwest corner. Other sources that contribute to shaking hazard include the Maacama fault and background (gridded) seismicity. Modal magnitudes reflect the magnitudes of earthquakes that the Rodgers Creek-Healdsburg fault zone and the Northern San Andreas fault are capable of producing. Ground motion distribution is controlled by proximity to the Rodgers Creek-Healdsburg fault and is affected by subsurface geology. In general, when fault distances are similar, PGA is higher where there are softer Quaternary sediments (lower

V_{S30} values) and lower where there are harder volcanic and crystalline rocks (higher V_{S30} values). The table below summarizes ranges of PGA, pseudo-PGA, modal magnitude, and V_{S30} values expected in the project area.

Table 2.1. Summary of ground motion parameters used for liquefaction and earthquake-induced landslide analyses.

PGA (g)	Pseudo-PGA (g)	Modal Magnitude	V_{S30} (m/s)
0.49 – 0.77	0.40 – 0.63	7.45 – 7.91	228 – 733

REFERENCES

- Abrahamson, N.A., Silva, W.J., and Kamai, R., 2014, Summary of the ASK14 ground motion relation for active crustal regions: *Earthquake Spectra*, vol. 30, p. 1025–1055.
- Abrahamson N.A. and Gülerce, Z., 2022, Summary of the Abrahamson and Gülerce NGA-SUB ground-motion model for subduction earthquakes: *Earthquake Spectra* vol. 38(4), p. 2638–2681.
- Atkinson, G.M., and Macias, M., 2009, Predicted ground motions for great interface earthquakes in the Cascadia subduction zone: *Bulletin of the Seismological Society of America*, vol. 99, p. 1,552–1,578.
- Boore, D.M., Stewart, J.P., Seyhan, E., and Atkinson, G.M., 2014. NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes: *Earthquake Spectra*, vol. 30, p. 1057–1085.
- Bozorgnia, Y., Abrahamson, N.A., Atik, L.A., Ancheta T.D., and others, 2014, NGA-West2 Research Project: *Earthquake Spectra*, vol 30, no. 3, p. 973 –987, DOI: 10.1193/072113EQS209M.
- Bozorgnia, Y., Abrahamson, N.A., Ahdi, S.K., Ancheta, T.D., Al Atik, L., Archuleta, R.J., Atkinson, G.M., Boore, D.M., Campbell, K.W., Chiou, BS-J, Contreras, V., Darragh, R.B., Derakhshan, S., Donahue, J.L., Gregor, N., Gülerce, Z., Idriss, I.M., Ji, C., Kishida, T., Kottke, A.R., Kuehn, N., Kwak, D.Y., Kwok, A.O.L., Lin, P., Mazzoni, S., Midorikawa, S., Muin, S., Parker, G.A., Rezaeian, S., Si, H., Silva, W.J., Stewart, J.P., Walling, M., Wooddell, K., and Youngs, R.R., 2022, NGA-Subduction research program: *Earthquake Spectra*, vol. 38(2), p 783–798.
- Campbell, K.W., and Bozorgnia, Y., 2014, NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra: *Earthquake Spectra*, vol. 30, p. 1087–1115.
- California Geological Survey, 2004, Recommended criteria for delineating seismic hazard zones in California: California Geological Survey Special Publication 118, 12 p. Available on-line at: <https://www.conservation.ca.gov/cgs/publications/sp118>.
- California Geological Survey, 2008, Guidelines for evaluating and mitigating seismic hazards in California: California Geological Survey Special Publication 117a, 98 p. Available on-line at: <https://www.conservation.ca.gov/cgs/publications/sp117a>.

- 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: <https://www.conservation.ca.gov/cgs/Documents/PSHA/2002%20California%20Hazard%20Maps.pdf>.
- Chiou, B.S.-J., and Youngs, R.R., 2014. Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra: *Earthquake Spectra*, vol. 30, p. 1117–1153.
- Field, E.H., Milner, K.R., Hatem, A.E., Powers, P.M., Pollitz, F.F., Llenos, A.L., Zeng, Y., Johnson, K.M., Shaw, B.E., McPhillips, D.F., Thompson Jobe J.A., Michael, A.J., Shen, Z-K., Evans, E.L., Hearn, E.H., Shumway, A.M., Mueller, C.S., Frankel, A.D., Petersen, M.D., DuRoss, C.B., Briggs, R.W., Page, M.T., Rubinstein, J.L., and Herrick, J.A., 2023, The USGS 2023 conterminous U.S. time-independent earthquake rupture forecast: *Bulletin of the Seismological Society of America*, Available at <https://doi.org/10.1785/0120230120>
- Kuehn, N., Bozorgnia, Y., Campbell, K., and Gregor, N., 2020, Partially Non-Ergodic Ground-Motion Model for Subduction Regions Using the NGA Subduction Database. *PEER Reports*, 1 September. Berkeley, Calif.: Pacific Earthquake Engineering Research Center, University of California, 187 p.
- Parker, G.A., Stewart, J.P., Boore, D.M., Atkinson, G.M., and Hassani, B., 2022, NGA-Subduction global ground motion models with regional adjustment factors: *Earthquake Spectra* vol 38(1), p. 456–493.
- 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.
- Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S., 2008, Documentation for the 2008 update of the United States National Seismic Hazard Maps: U.S. Geol. Survey Open-File Report 2008-1XXX, 60p.
- Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S., Field, N., Chen, R., Rukstales, K.S., Luco, N., Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States national seismic hazard maps, U.S. Geol. Survey. Open-File Rept. 2014-1091, 243 pp., doi: [10.3133/ofr20141091](https://doi.org/10.3133/ofr20141091).
- Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S., Field, N., Chen, R., Rukstales, K.S., Luco, N., Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2015, The 2014 United States national seismic hazard model: *Earthquake Spectra*, vol. 31, no. S1, p. S1–S30, doi: [10.1193/120814EQS210M](https://doi.org/10.1193/120814EQS210M).

- Petersen, M.D., Shumway, A.M., Powers, P.M., Mueller, C.S., Haller, K.M., Moschetti, M.P., Frankel, A.D., Rezaeian, S., McNamara, D.E., Luco, N., Boyd, O.S., Rukstales, K.S., Jaiswal, K.S., Thompson, E.M., Hoover, S.M., Clayton, B.S., Field, E.H., and Zeng, Y., 2020, The 2018 updated of the US National Seismic Hazard Model: Overview of model and implications: *Earthquake Spectra*, vol. 36, no. 1, p. 5–41, doi: [10.1177/8755293019878199](https://doi.org/10.1177/8755293019878199).
- Petersen, M.D., Shumway, A.M., Powers, P.M., Field, E.H., Moschetti, M.P., Jaiswal, K.S., Milner, K.S., Rezaeian, S., Frankel, A.D., Llenos, A.L., Michael, A.J., Altekruise, J.M., Ahdi, S.K., Withers, K.B., Mueller, C.S., Zeng, Y., Chase, R.E., Salditch, L.M., Luco, N., ... , and Witter, R.C., 2023, The 2023 U.S. 50-State National Seismic Hazard Model: Overview and implications: *Earthquake Spectra*, vol 40(1), p 5–88, doi: [10.1177/87552930231215428](https://doi.org/10.1177/87552930231215428).
- Powers, P.M., Clayton, B.S. and Altekruise, J.M., 2022, nshmp-haz: National Seismic Hazard Model Project hazard applications and web services: U.S. Geological Survey software release, doi: [10.5066/P9STF5GK](https://doi.org/10.5066/P9STF5GK).
- Real, C.R., Petersen, M.D., McCrink, T.P. and Cramer, C.H., 2000, Seismic Hazard Disaggregation 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.
- Thompson, E.M., 2018, An Updated V_{S30} Map for California with Geologic and Topographic Constraints (ver. 2.0, July 2022): U.S. Geological Survey data release, <https://doi.org/10.5066/F7JQ108S>.
- Wills, C.J., Gutierrez, C.I., Perez, F.G., and Branum, D.M., 2015, A next-generation V_{S30} map for California based on geology and topography: *Bulletin of Seismological Society of America*, vol. 105, no. 6, p. 3083–3091, doi: [10.1785/0120150105](https://doi.org/10.1785/0120150105).
- Zhao, J.X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H.K., Somerville, P.G., Fukushima, Y.A, and Fukushima, Y., 2006, Attenuation relations of strong ground motion in Japan using site classification based on predominant period: *Bulletin of the Seismological Society of America*, v. 96, p. 898–913.

SECTION 3: EVALUATION OF LIQUEFACTION HAZARD

for the

SEBASTOPOL 7.5-MINUTE QUADRANGLE, SONOMA COUNTY, CALIFORNIA

by

Alyssa Tunnelle

P.G. 10002

DEPARTMENT OF CONSERVATION
CALIFORNIA GEOLOGICAL SURVEY

Purpose of this Section

This Section of the Seismic Hazard Zone Report summarizes the analyses and criteria used to delineate Earthquake Zones of Required Investigation for liquefaction in the Sebastopol Quadrangle, Sonoma County (the project area).

ZONING TECHNIQUES

Liquefaction is a phenomenon that occurs when saturated sediments located near the ground surface lose their strength, usually as a result of seismic shaking. The resulting ground failures can damage overlying buildings, bridges, and other infrastructure, increasing the risk to public safety during an earthquake event. Liquefaction tends to occur in loose, saturated, sandy materials, such as young alluvium, and the severity is dependent on the intensity and duration of earthquake shaking. Therefore, zoning techniques involve an evaluation of soil characteristics, groundwater conditions, and earthquake probabilities to determine which deposits may have the potential to liquefy. Identifying these zones helps inform decisions regarding safe building practices and effective hazard mitigation.

This study uses a method similar to that of Tinsley and others (1985) which was first applied 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 and employs criteria adopted by the State Mining and Geology Board (CGS, 2004).

Liquefaction Susceptibility

Liquefaction susceptibility refers to a geologic material's ability to resist liquefaction and is based on in-situ soil conditions such as relative density, grain-size, compaction, saturation, and cohesion. Geologic deposits most susceptible to liquefaction tend to be materials that are relatively loose, saturated, and sandy, such as young Holocene-aged alluvium. Loose sands are considered most susceptible to liquefaction due to the lack of cohesion and presence of void

spaces in between grains, which results in increased pore water pressure build-up from the groundwater table and decreased effective stress. Low plastic silts can also be susceptible to liquefaction, especially when interlayered with sands, and are considered in this study.

Generally, cohesive soils such as clays and plastic silts are not susceptible to liquefaction, and instead can undergo strain and deformation due to cyclic softening, which is not evaluated in this study.

To assess liquefaction susceptibility, we evaluated historical occurrences of liquefaction, geologic maps, geologic cross-sections, geotechnical test data, geomorphology, and groundwater hydrology within the study area. This data allows us to characterize the physical properties of Quaternary deposits that may be susceptible to liquefaction. We then determine the potential degree of soil saturation by estimating the shallowest potential depths to groundwater based on historical groundwater data. The Quaternary geologic units mapped in the study area and their liquefaction susceptibility ratings based on Witter et al. (2006) are listed in Table 3.1.

Table 3.1. Liquefaction susceptibility of Quaternary units in the Sebastopol Quadrangle (Sonoma County).

Geologic Map Unit	Age	Sediment/Material Type	Consistency	Liquefaction Susceptibility*
af	Historical	Artificial fill	Loose to dense	Very high to very low
adf	Historical	Artificial dam fill	Loose to dense	Moderate to very low
alf	Historical	Artificial levee fill	Loose to dense	Very high to moderate
ac	Historical	Artificial stream channels	Loose	Very high to low
Qhc	Historical to late Holocene	Stream channel deposits	Loose	Very high
Qhty	Latest Holocene	Stream terrace deposits	Loose	High
Qhay	Latest Holocene	Latest alluvial deposits, undifferentiated	Loose	High
Qha	Holocene	Alluvium, undivided	Loose to dense	Moderate
Qhb	Holocene	Basin deposits	Loose to dense or soft to hard	Moderate
Qht	Holocene	Stream terrace deposits	Loose to dense	Moderate
Qhf	Holocene	Alluvial fan deposits	Loose to dense	Moderate
Qhl	Holocene	Fan levee deposits	Loose to dense or soft to hard	Moderate
Qa	Holocene to latest Pleistocene	Alluvium, undivided	Loose to dense	Moderate
Qf	Holocene to latest Pleistocene	Alluvial fan deposits	Loose to dense	Moderate to low

Geologic Map Unit	Age	Sediment/Material Type	Consistency	Liquefaction Susceptibility*
Qt	Holocene to latest Pleistocene	Stream terrace deposits	Loose to dense	Moderate
Qls	Holocene to Pleistocene	Landslides	Variable	Very low
Qoa	Late to early Pleistocene	Alluvial deposits, undivided	Medium dense to dense	Very low
QPge	Pleistocene-Pliocene	Glen Ellen Formation	Dense to very dense	Very low

*When saturated

In the past, gravelly soils were considered not to be susceptible to liquefaction because the high permeability of these soils presumably would allow the dissipation of pore pressures before liquefaction could occur. However, liquefaction in gravelly soils has been observed during earthquakes, and laboratory studies have shown that gravelly soils are susceptible to liquefaction (Ishihara, 1985; Harder and Seed, 1986; Budiman and Mohammadi, 1995; Evans and Zhou, 1995; and Sy and others, 1995). Density measurements in gravelly soils derived from standard penetration tests (SPTs) can be unreliable and higher than expected, especially when the size of the gravels exceeds the diameter of the sampler. This can result in overestimation of the density of the soil and thus result in underestimation of the liquefaction susceptibility. To identify potentially liquefiable units where the N-values appear to have been affected by gravel content, CGS makes correlations with boreholes in the same unit where the N-values do not appear to have been affected by gravel content. A reasonably adjusted N-value is then used in our liquefaction evaluation to reduce the effects of gravel interference. This study did not identify potentially gravel-affected N-values, and therefore no adjustments needed to be made.

Ground Motion for Liquefaction Opportunity

Ground motion calculations used by CGS for regional liquefaction zonation assessments are based on the probabilistic seismic hazard analysis (PSHA) model developed by the United States Geological Survey (USGS) (Petersen and others, 2024) for the 2023 Update of the United States National Seismic Hazard Maps. The model calculates ground motion in terms of peak horizontal ground acceleration (PGA) at a 10% in 50 years exceedance probability level. For liquefaction analysis, CGS modifies probabilistic PGA by a scaling factor that is a function of magnitude. Calculation of the scaling factor is based on binned magnitude-distance deaggregation of seismic source contribution to total shaking. The result is a magnitude-weighted, pseudo-PGA that CGS refers to as Liquefaction Opportunity (LOP). This approach provides an improved estimate of liquefaction hazard in a probabilistic sense, ensuring that the effects of large, infrequent, distant earthquakes, as well as smaller, more frequent, nearby events are appropriately accounted for (Real and others, 2000). These weighted, pseudo-PGA ground motion values are used to calculate the seismic load imposed on a soil column, expressed as the cyclic stress ratio (CSR). A more detailed description of the development of ground shaking opportunity data and parameters used in liquefaction hazard zoning can be found in Section 2 of this report.

Liquefaction Analysis

CGS performs a quantitative analysis of geotechnical data to evaluate liquefaction potential using an in-house developed computer program based on the Seed-Idris Simplified Procedure (National Research Council, 1985; Seed and Harder, 1990; Seed and Idriss, 1971; Seed and others, 1983; Seed and others, 1985; Youd and Idriss, 1997; Youd and others, 2001). The calculations and correction factors used in the program are taken directly from the equations in Youd and others (2001).

The program calculates the liquefaction potential of each non-clay soil layer encountered at a test-drilling site that includes at least one SPT. CGS defines soil layers with a factor of safety (FS) relative to liquefaction hazard of 1.0 or less as potentially liquefiable. The FS is defined as the ratio of cyclic resistance ratio (CRR), which reflects the resistance to liquefaction of the soil layer, to cyclic stress ratio (CSR), which represents the seismic load on the layer. Input parameters for calculation of CRR include SPT results, groundwater level, soil density, grain-size analysis, moisture content, soil type, and sample depth. The CSR is calculated using the pseudo-PGA provided in the ground motion analysis.

The FS is calculated for each layer in the soil column at a given borehole. The minimum FS value of all the layers penetrated by the borehole determines the liquefaction potential for that borehole location. The resulting factor of safety analysis, groundwater conditions, and geologic characteristics are used to determine the final liquefaction hazard zone.

Liquefaction Zoning Criteria

Areas underlain by materials susceptible to liquefaction during an earthquake are included in liquefaction zones using recommended criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (CGS, 2004). Under those recommendations, liquefaction zones are areas meeting one or more of the following criteria:

- 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 are delineated by geologic criteria as follows:
 - a) Areas containing soil deposits of late Holocene age (current river channels and their historical floodplains, marshes and estuaries), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.10 g and the anticipated depth to saturated soil is less than 40 feet; or
 - b) Areas containing soil deposits of Holocene age (less than 11,700 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50 years is greater than or equal to 0.20 g and the anticipated depth to saturated soil is less than 30 feet; or
 - c) Areas containing soil deposits of latest Pleistocene age (11,700 to 15,000 years), where the M7.5-weighted peak acceleration that has a 10% probability of being exceeded in 50

years is greater than or equal to 0.30 g and the anticipated depth to saturated soil is less than 20 feet.

Application of the above criteria allows compilation of Earthquake 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 Liquefaction Hazard Zones

Upon completion of a liquefaction hazard evaluation within a quadrangle, CGS applies the above criteria to its findings to delineate Seismic Hazard Zones for liquefaction. Since the Seismic Hazards Mapping Act Advisory Committee recommends delineating liquefaction hazard zones based on one or more of the above criteria, practical implementation of these criteria involves the sequential zoning of (1) areas of past liquefaction, (2) artificial fills, and (3) Holocene to latest Pleistocene age soils, considering the probabilistic ground motions and anticipated depth to groundwater described above. The liquefaction hazard zones delineated based on these criteria are then modified where existing geotechnical data provide sufficient supplemental information.

Based on this evaluation, about 41.9 square kilometers (16.2 square miles) of the project area are included in the Seismic Hazard Zone for liquefaction. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Maps for the project area.

Areas of Past Liquefaction

Widespread liquefaction was documented in Northern California following the 1906 M7.9 San Francisco Earthquake. Within the project area, an instance of lateral spreading was observed in the stream bank sediments of the Laguna de Santa Rosa, which was described as "... a layer of moist soil only a few feet in thickness moving down the slope" (Youd and Hoose, 1978). Resulting damage to an orchard and a water well was reported. Outside of the project area, instances of sand boils and lateral spreading were reported in the Russian River floodplain, and ground cracks, settlement, and other ground failures were documented in sediments throughout the region.

Per our zoning criteria, the stream channel deposits are included in our liquefaction zones. This is because geologic units that are known to have liquefied in previous earthquakes demonstrate their reduced ability to resist liquefaction and are likely to liquefy again. The results of our liquefaction study also show these units have the potential to liquefy due to their typical grain-size and degree of saturation.

Artificial Fills

Artificial fill areas in the project area large enough to show at the scale of project mapping (1:24,000) consist of engineered fill for river channels and levees, detention basins, elevated freeways and roadways, as well as isolated bodies of fill typically associated with construction projects of various sizes. Zoning for liquefaction in artificial fill deposits depends on soil properties and groundwater conditions in the underlying strata.

Areas with Sufficient Existing Geotechnical Data

The majority of the borehole logs evaluated for liquefaction potential using the Seed-Idriss Simplified Procedure are located in developed areas. Analysis of blow count values and other soil property measurements reported in the logs indicate that most of the boreholes situated in Holocene deposits encountered saturated layers of loose sand and silts that may liquefy under the predicted earthquake loading. These deposits include: modern stream channel deposits (**Qhc**), Holocene-aged stream terrace deposits (**Qhty**, **Qht**), undifferentiated alluvial sediments (**Qhay**, **Qha**), basin deposits (**Qhb**), alluvial fan deposits (**Qhf**), and fan levee deposits (**Qhl**), and Holocene to latest Pleistocene alluvium (**Qa**), alluvial fan deposits (**Qf**), and stream terrace deposits (**Qt**), all mapped along and adjacent to streams and creeks.

The Late to Early Pleistocene undifferentiated alluvial sediments (**Qoa**), mapped as the slightly elevated areas above the stream valleys of the Santa Rosa Plain, are generally dense and resistant to liquefaction under the expected earthquake loading. The Pleistocene-Pliocene Glen Ellen Formation (**QPge**) consists of lithified sedimentary rock that is also considered resistant to liquefaction.

Areas with Insufficient Existing Geotechnical Data

In areas with insufficient geotechnical data coverage, Quaternary sedimentary deposits were evaluated for seismic hazard zonation based on geologic factors, groundwater levels, and extrapolation of known soil conditions in adjacent areas. Adequate geotechnical borehole information is lacking for small unnamed alluvial valleys throughout the project area, such as the stream corridor along Atascadero Creek. The Quaternary units mapped in these areas typically contain varying amounts of loose, granular materials that are saturated due to the presence of near-surface groundwater following rainfall events and proximity to surficial streams. Those conditions, along with the ground motions expected to occur in the region, combine to form a sufficient basis for including these areas in the Seismic Hazard Zone for liquefaction.

ACKNOWLEDGMENTS

The authors thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project: Pattie Murphy of the City of Sebastopol and Robert Pennington of Sonoma County. At CGS, Daniel Langermann and Krista Van Der Velde assisted with geotechnical data collection and entry efforts. Bob Moskovitz and Jonathan Goergen provided database compilation and analysis support. Kate Thomas and Meerea Kang prepared the final Seismic Hazard Zone Map and prepared the graphic displays for this report. Justin LaForge, Erik Frost, and Tim Dawson provided technical review for this report.

REFERENCES

- Budiman, J.S., and Mohammadi, J., 1995, Effect of large inclusions on liquefaction of sands, in Evans, M.D., and Frigaszy, R.J., editors, Static and Dynamic properties of Gravelly Soils: American Society of Civil Engineers Geotechnical Special Publication no. 56, p. 48-63.
- California Geological Survey (CGS), 2004, Recommended criteria for delineating seismic hazard zones in California: California Geological Survey Special Publication 118, 12 p. Available on-line at: <https://www.conservation.ca.gov/cgs/publications/sp118>.
- Evans, M.D., and Zhou, S., 1995, Liquefaction behaviour of sand-gravel composites: American Society of Civil Engineers, Journal of Geotechnical Engineering, v. 121, no. 3, p. 287-298.

- Harder, L.F., and Seed, H.B., 1986, Determination of penetration resistance for coarse-grained soils using the Becker hammer drill: University of California at Berkeley, College of Engineering, Earthquake Engineering Research Center, report no. UCB/EERC-86/06, 126 p.
- Ishihara, K., 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.
- National Research Council, 1985, Liquefaction of soils during earthquakes, National Academy Press, Washington, D.C., 240 p.
- Petersen, M.D., Shumway, A.M., Powers, P.M., Field, E.H., Moschetti, M.P., Jaiswal, K.S., Milner, K.S., Rezaeian, S., Frankel, A.D., Llenos, A.L., Michael, A.J., Altekruze, J.M., Ahdi, S.K., Withers, K.B., Mueller, C.S., Zeng, Y., Chase, R.E., Salditch, L.M., Luco, N., ... , and Witter, R.C., 2023, The 2023 U.S. 50-State National Seismic Hazard Model: Overview and implications: *Earthquake Spectra*, vol 40(1), p 5–88, doi: <https://doi.org/10.1177/87552930231215428>.
- 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, I., 1983, Evaluation of liquefaction potential using field performance data: *Journal of Geotechnical Engineering*, v. 109, no. 3, p. 458-482.
- Seed, H.B., Idriss, I.M., and Arango, I., 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., Dickenson, S.E., Riemer, M.F., Bray, J.D., Sitar, N., Mitchell, J.K., Idriss, I.M., Kayen, R.E., Kropp, A., Harder, L.F., Jr., and Power, M.S., 1990, Preliminary report on the principal geotechnical aspects of the October 17, 1989 Loma Prieta earthquake, Earthquake Engineering Research Center, Report No. UCB/EERC-90/05.
- 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.
- Sy, A., Campanella, R.G., and Stewart, R.A., 1995, BPT-SPT correlations for evaluations of liquefaction resistance in gravelly soils, in Evans, M.D., and Frigaszy, 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.
- Tinsley, J.C., III, Egan, J.A., Kayen, R.E., Bennett, M.J., Kropp, A., and Holzer, T.L., 1998, Appendix: Maps and descriptions of liquefaction and associated effects: in Holzer, T.L., ed., The Loma Prieta, California, Earthquake of October 17, 1989 - Liquefaction: U.S. Geological Survey Professional Paper 1551-B.
- Youd, T.L., and Perkins, D.M., 1978, Mapping liquefaction-induced ground failure potential: Journal of Geotechnical Engineering, v. 104, p. 433-446.
- Youd, T.L., and Hoose, S.N., 1978, Historical ground failures in Northern California triggered by earthquakes: U.S. Geological Survey Professional Paper 993.
- 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.

SECTION 4: EVALUATION OF EARTHQUAKE- INDUCED LANDSLIDE HAZARD

for the

SEBASTOPOL 7.5-MINUTE QUADRANGLE, SONOMA COUNTY, CALIFORNIA

by

Justin LaForge

P.G. 9796

DEPARTMENT OF CONSERVATION
CALIFORNIA GEOLOGICAL SURVEY

Purpose of this Section

This Section of the Seismic Hazard Zone Report presents the analyses and criteria used to delineate earthquake-induced landslide hazard zones in the Sebastopol Quadrangle, Sonoma County (the project area).

ZONING TECHNIQUES

To evaluate earthquake-induced landslide hazard potential in the project area, a method of dynamic slope stability analysis developed by Newmark (1965) was used. The Newmark method as originally implemented analyzes dynamic slope stability by calculating the cumulative down-slope displacement for a given earthquake strong-motion time history. The double integration of the earthquake acceleration recording to derive displacement considers only accelerations above a threshold value that represents the inertial force required to initiate slope movement (Factor of Safety = 1). This threshold value, called the “yield acceleration,” is a function of the strength of the earth materials and the slope gradient, and therefore represents the susceptibility of a given area to earthquake-induced slope failure.

As implemented for the preparation of earthquake-induced landslide zones, susceptibility is derived by combining a geologic map modified to reflect material strength estimates with a slope gradient map. Ground motion parameters are calculated using the United States Geological Survey (USGS) National Seismic Hazard Model, and Newmark displacements are estimated from a regression equation developed by Jibson (2007) that uses susceptibility and ground motion parameters. Displacement thresholds that define earthquake-induced hazard zones are from McCrink and Real (1996) and McCrink (2001).

Earthquake-Induced Landslide Susceptibility

Earthquake-induced landslide susceptibility, defined here as Newmark’s yield acceleration (1965), is a function of the Factor of Safety (*FS*) and the slope gradient. To derive a Factor of Safety, an infinite-slope failure model under unsaturated slope conditions was assumed. In

addition, material strength is characterized by the angle of internal friction (φ) and cohesion is ignored. As a result of these simplifying assumptions, the calculation of FS becomes:

$$FS = \frac{\tan \varphi}{\tan \beta}$$

where β is the slope gradient. The yield acceleration (a_y) is then calculated 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 gradient angle (β).

These calculations are conducted in an ArcGIS environment by converting the vector (lines, points and polygons) digital geologic map to a raster (regular spaced grid) material strength map that contains the φ values assigned to the mapped geologic units (Table 1.2). Preparation of a slope gradient (β) map is discussed in Section 1.

Ground Motion for Landslide Hazard Assessment

Ground motion calculations used by CGS for regional earthquake-induced landslide zonation assessments are currently based on the USGS probabilistic seismic hazard analysis (PSHA) model for the 2023 Update of the United States National Seismic Hazard Maps (Petersen and others, 2024). The model is set to calculate ground motion hazard in terms of peak horizontal ground acceleration (PGA) at a 10% in 50 years exceedance probability level. Raster versions of the PSHA PGA and Modal Magnitude maps for the Sebastopol Quadrangle, Sonoma County were calculated from the statewide model and applied in the Newmark displacement calculations, as described below. A more detailed description of the development of ground motion parameters used in preparation of the Seismic Hazard Zone for earthquake-induced landslides can be found in Section 2 of this report.

Earthquake-Induced Landslide Hazard Potential

Earthquake-induced landslide hazard potential is derived by combining the susceptibility map (a_y) with the ground motion maps (PGA and Modal Magnitude) to estimate the amount of permanent displacement that a modeled slope might experience. The permanent slope displacement is estimated using a regression equation developed by Jibson (2007). That equation is:

$$\log D_N = -2.710 + \log \left[\left(1 - \frac{a_y}{\text{PGA}} \right)^{2.335} \left(\frac{a_y}{\text{PGA}} \right)^{-1.478} \right] + 0.424M \pm 0.454$$

where D_N is Newmark displacement and M is magnitude. Jibson's (2007) nomenclature for yield acceleration (a_c) and peak ground acceleration (a_{max}) have been replaced here by a_y and PGA, respectively, to be consistent with the nomenclature used in this report.

The above equation was applied using a_y , PGA, and Modal Magnitude maps as input, resulting in mean values of Newmark displacement at each grid cell (the standard deviation term at the end of the equation is ignored). 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, 2001; McCrink and Real, 1996).

Earthquake-Induced Landslide Zoning Criteria

Seismic Hazard Zones for earthquake-induced landslides were delineated using criteria adopted by the California State Mining and Geology Board (CGS, 2004). Under these criteria, these 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 historical 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 Earthquake-Induced Landslide Hazard Zones

Upon completion of an earthquake-induced landslide hazard evaluation within a project area, CGS applies the above criteria to its findings to delineate Earthquake Zones of Required Investigation for earthquake-induced landslides. Based on the evaluation, about 2.8 square kilometers (1.1 square miles) of the project area are included in the Seismic Hazard Zone for earthquake-induced landslides. This area encompasses terrain within the western half of the project area, including most of the hill north of River Road near Trenton, the slopes descending from the Vine Hill ridge, and moderate slopes within the low-relief hills surrounding the City of Sebastopol. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the project area.

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 Seismic Hazard Zone. Mapping and categorization of existing landslides is discussed in further detail in Section 1.

Hazard Potential Analysis

Based on the conclusions of a pilot study performed by CGS (McCrink, 2001; McCrink and Real, 1996), the Seismic Hazard Zone for earthquake-induced landslides encompasses all areas that have calculated Newmark displacements of 5 centimeters or greater.

ACKNOWLEDGMENTS

The authors thank the following individuals and organizations for their assistance in obtaining the data necessary to complete this project: Pattie Murphy of the City of Sebastopol, Raina Allan of the City of Healdsburg, and Robert Pennington of Sonoma County. At CGS, Daniel Langermann, Jacob Helmich, Alyssa Tunnelle, Maxime Mareschal, Ante Mlinarevic, Kirk Townsend, Elaine Young, and Ron Rubin, assisted with geotechnical data collection and entry efforts and field work. Bob Moskovitz and Jonathan Goergen provided database compilation and analysis support. Meerea Kang prepared the final Seismic Hazard Zone Map and prepared the graphic displays for this report. Erik Frost and Tim Dawson provided technical review for this report.

REFERENCES

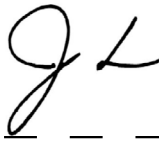
- California Geological Survey (CGS), 2004, Recommended criteria for delineating seismic hazard zones in California: California Geological Survey Special Publication 118, 12 p., originally published 1992, available on-line at:
<https://www.conservation.ca.gov/cgs/publications/sp118>.
- Jibson, R.W., 2007, Regression models for estimating coseismic landslide displacement: *Engineering Geology*, vol. 91, issue 2-4, p. 209-218.
- Keefer, D.K., 1984, Landslides caused by earthquakes: *Geological Society of America Bulletin*, v. 95, no. 4, p. 406-421.
- McCrink, T.P., 2001, Mapping earthquake-induced landslide hazards in Santa Cruz County *in* Ferriz, H., and Anderson, R., *editors*, *Engineering geology practice in northern California*: California Geological Survey Bulletin 210 / Association of Engineering Geologists Special Publication 12, p. 77-94.
- McCrink, T.P., and Real, C.R., 1996, Evaluation of the Newmark method for mapping earthquake-induced landslide hazards in the Laurel 7.5-minute Quadrangles, 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.
- Petersen, M.D., Shumway, A.M., Powers, P.M., Field, E.H., Moschetti, M.P., Jaiswal, K.S., Milner, K.S., Rezaeian, S., Frankel, A.D., Llenos, A.L., Michael, A.J., Altekruze, J.M., Ahdi, S.K., Withers, K.B., Mueller, C.S., Zeng, Y., Chase, R.E., Salditch, L.M., Luco, N., ... , and Witter, R.C., 2023, The 2023 U.S. 50-State National Seismic Hazard Model: Overview and implications: *Earthquake Spectra*, vol 40(1), p 5–88, doi: <https://doi.org/10.1177/87552930231215428>.

- 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.

AUTHORSHIP CREDITS

PUBLICATION TITLE: OFFICIAL SEISMIC HAZARD ZONE REPORT 143:THE SEBASTOPOL 7.5 MINUTE QUADRANGLE, SONOMA COUNTY, CALIFORNIA

Lead Author – Justin LaForge, Professional Geologist



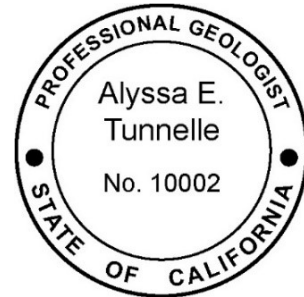


Date: November 20, 2025

Work in Responsible Charge: Geologic and geotechnical data acquisition, interpretation, and analysis; geologic mapping; digital imagery and elevation data analysis; field verification; liquefaction/landslide modeling; and final seismic hazard zone map production.

Lead Author – Alyssa Tunnelle, Professional Geologist



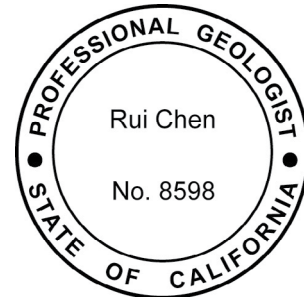


Date: November 20, 2025

Work in Responsible Charge: Geologic and geotechnical data acquisition, interpretation, and analysis; geologic mapping; digital imagery and elevation data analysis; field verification; liquefaction/landslide modeling; and final seismic hazard zone map production.

Section Author – Rui Chen, Professional Geologist





Date: November 20, 2025

Work in Responsible Charge: Probabilistic ground motion hazard assessment.



Project Manager – Erik Frost, Senior Engineering Geologist



Date: November 20, 2025

Work in Responsible Charge: Validation of mapping process and pre-release seismic hazard zone map review.

Program Manager – Timothy Dawson, Supervising Engineering Geologist



Date: November 20, 2025

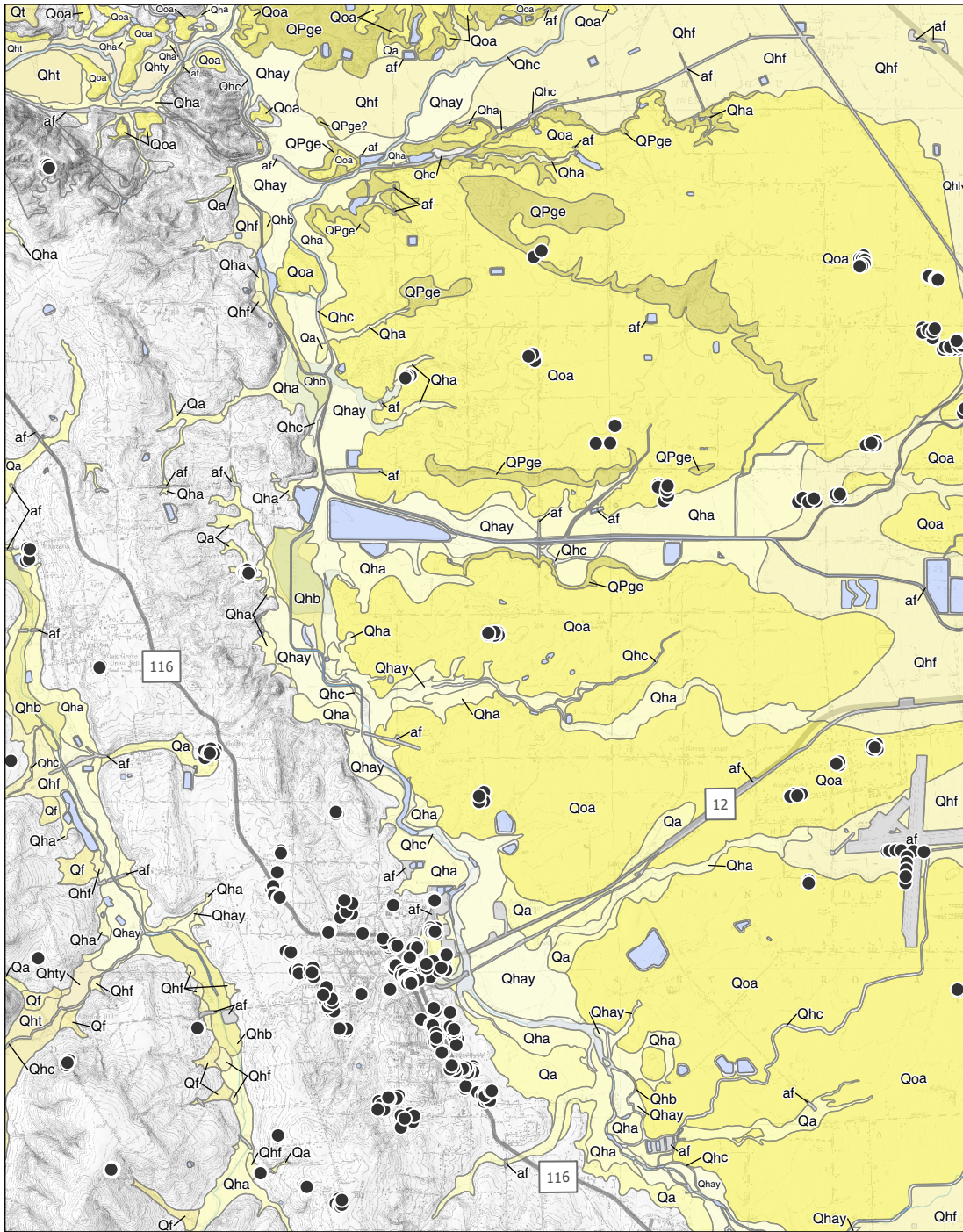
Work in Responsible Charge: Technical review and approval.

State Geologist – Jeremy Lancaster, Professional Geologist



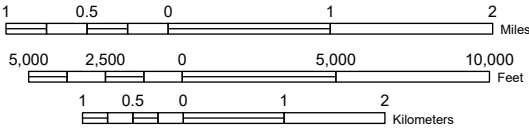
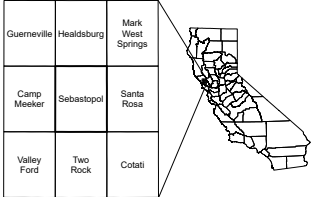
Date: November 20, 2025

Work in Responsible Charge: Technical review and approval.



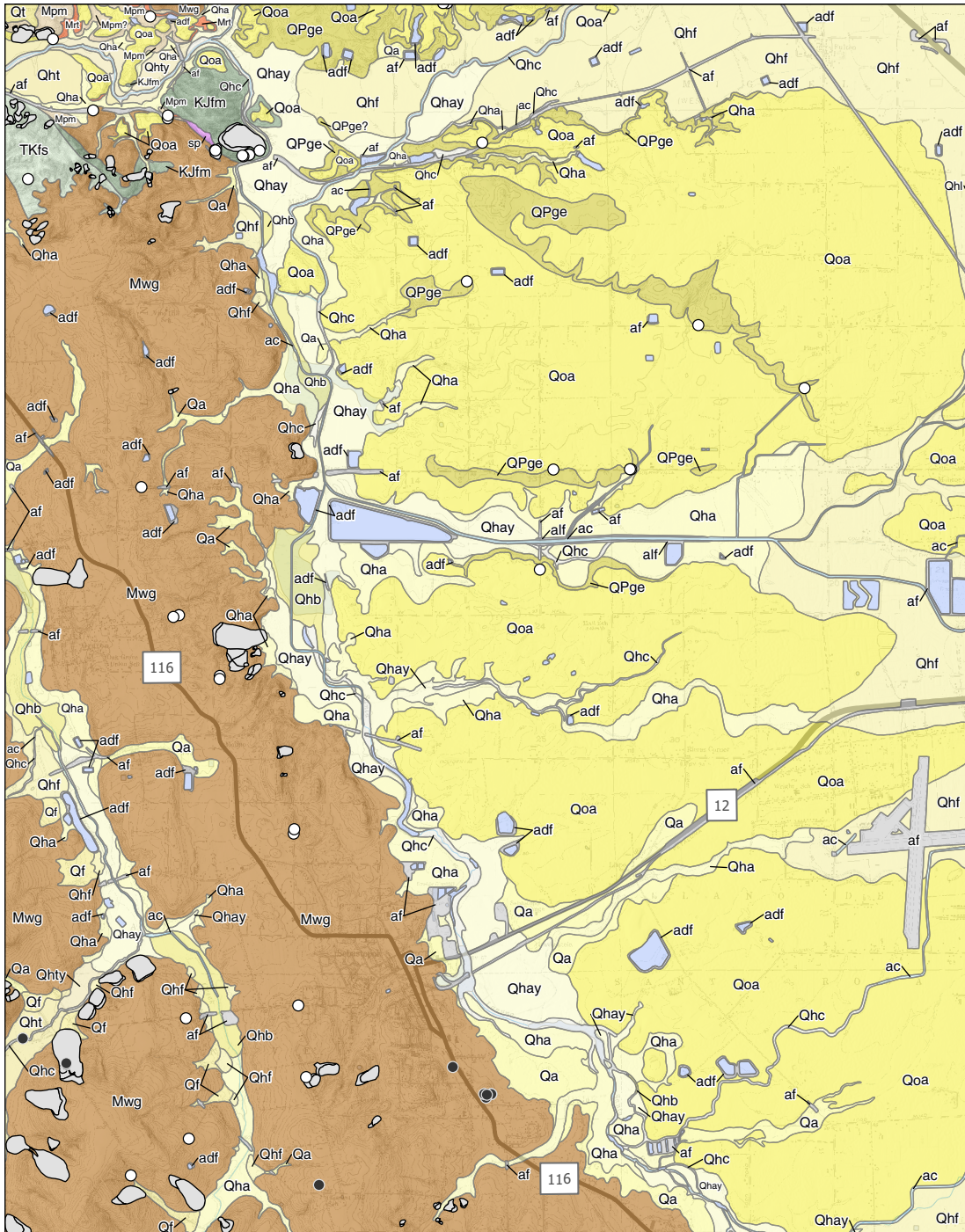
Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. See "Geology" in Section 1 of report for descriptions of units. Pre-Quaternary bedrock units shown without color. Map preparation by Meerea Kang, CGS.

SEBASTOPOL QUADRANGLE



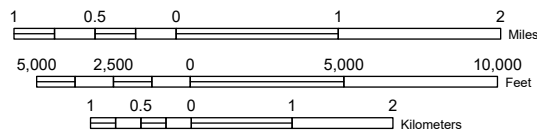
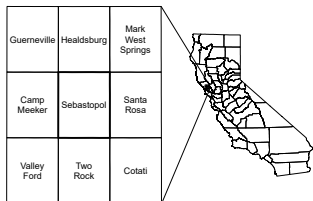
● Geotechnical boreholes used in liquefaction evaluation

Plate 1.1 Quaternary geologic materials map and locations of boreholes used in evaluating liquefaction hazard, Sebastopol Quadrangle, Sonoma County, California.



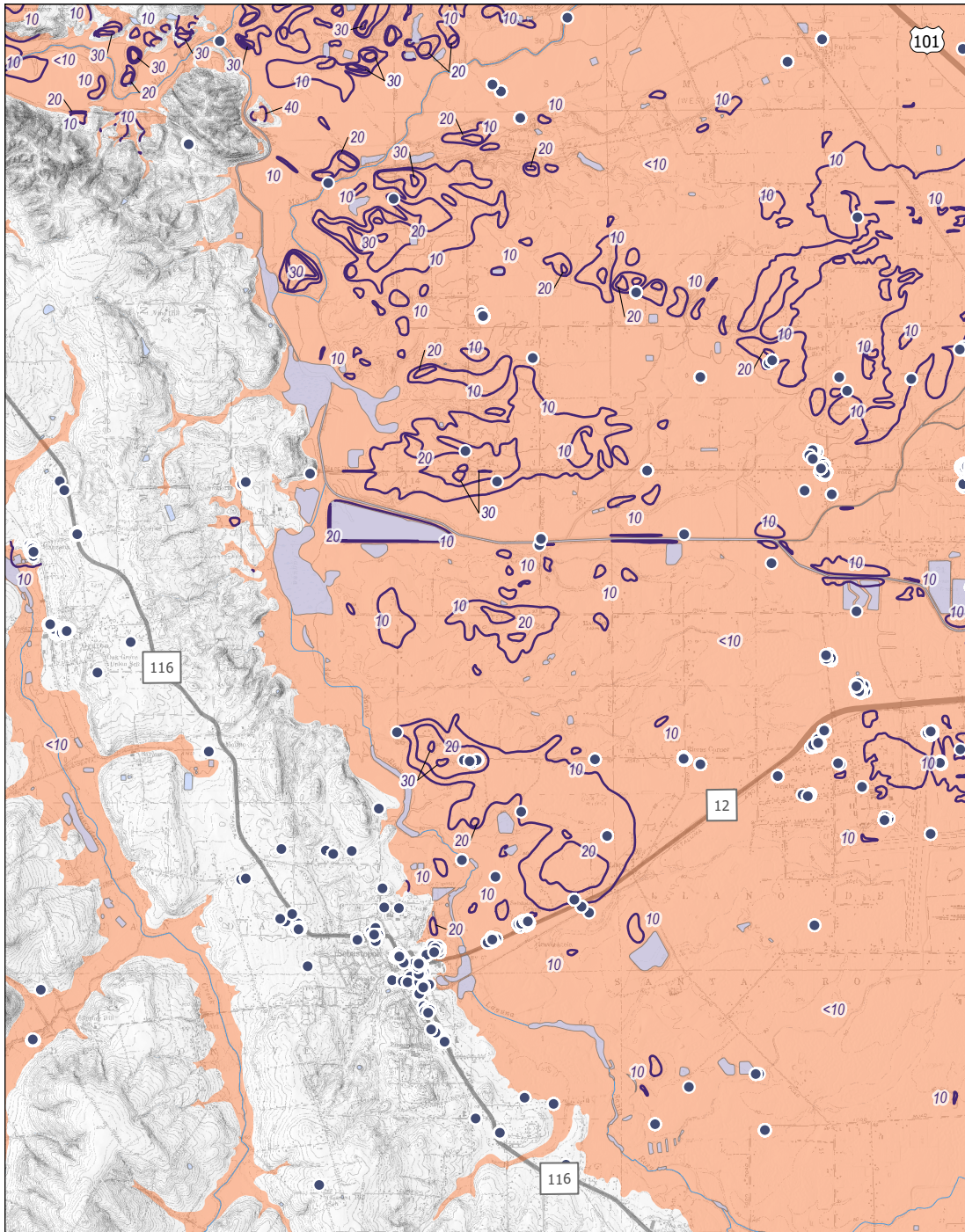
Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. See "Geology" in Section 1 of report for descriptions of units. Map preparation by Meerea Kang, CGS.

SEBASTOPOL QUADRANGLE



- Shear test sample location
- GSI measurement location
- ▭ Landslide

Plate 1.2 Geologic materials and landslide inventory map with locations of shear test samples and Geologic Strength Index (GSI) measurements used in evaluating landslide hazard, Sebastopol Quadrangle, Sonoma County, California.



Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. Map preparation by Meerea Kang, CGS.

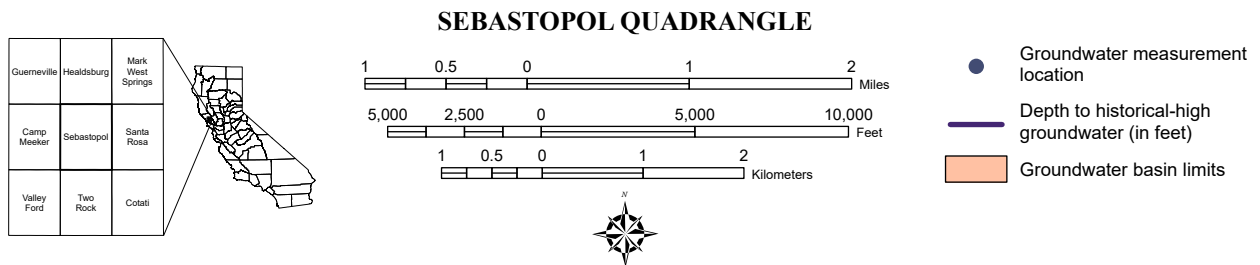
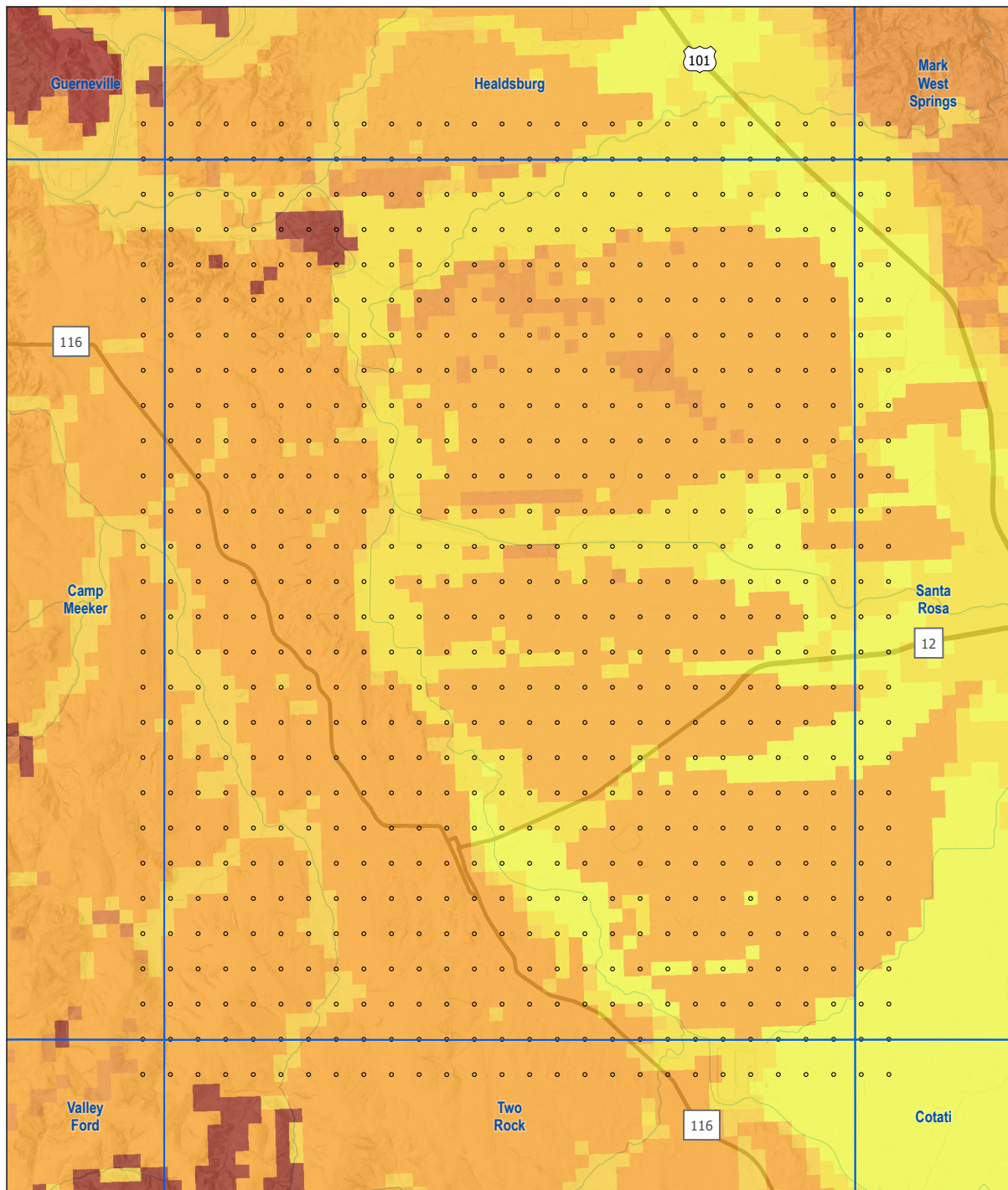


Plate 1.3 Groundwater basins, depth to historical-high groundwater levels, and groundwater data points, Sebastopol Quadrangle, Sonoma County, California.



DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Meerea Kang, CGS.

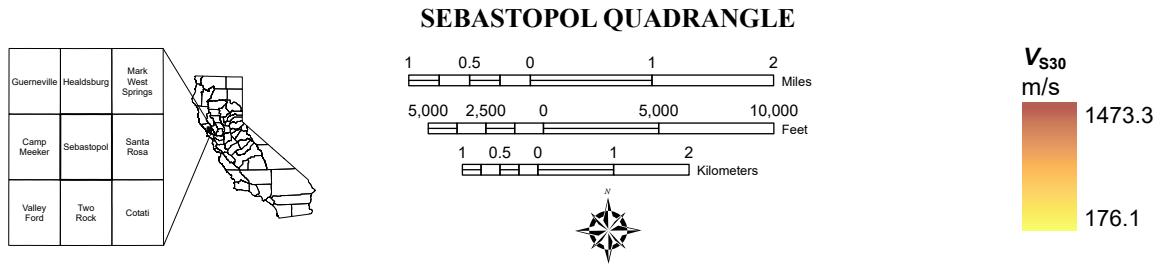
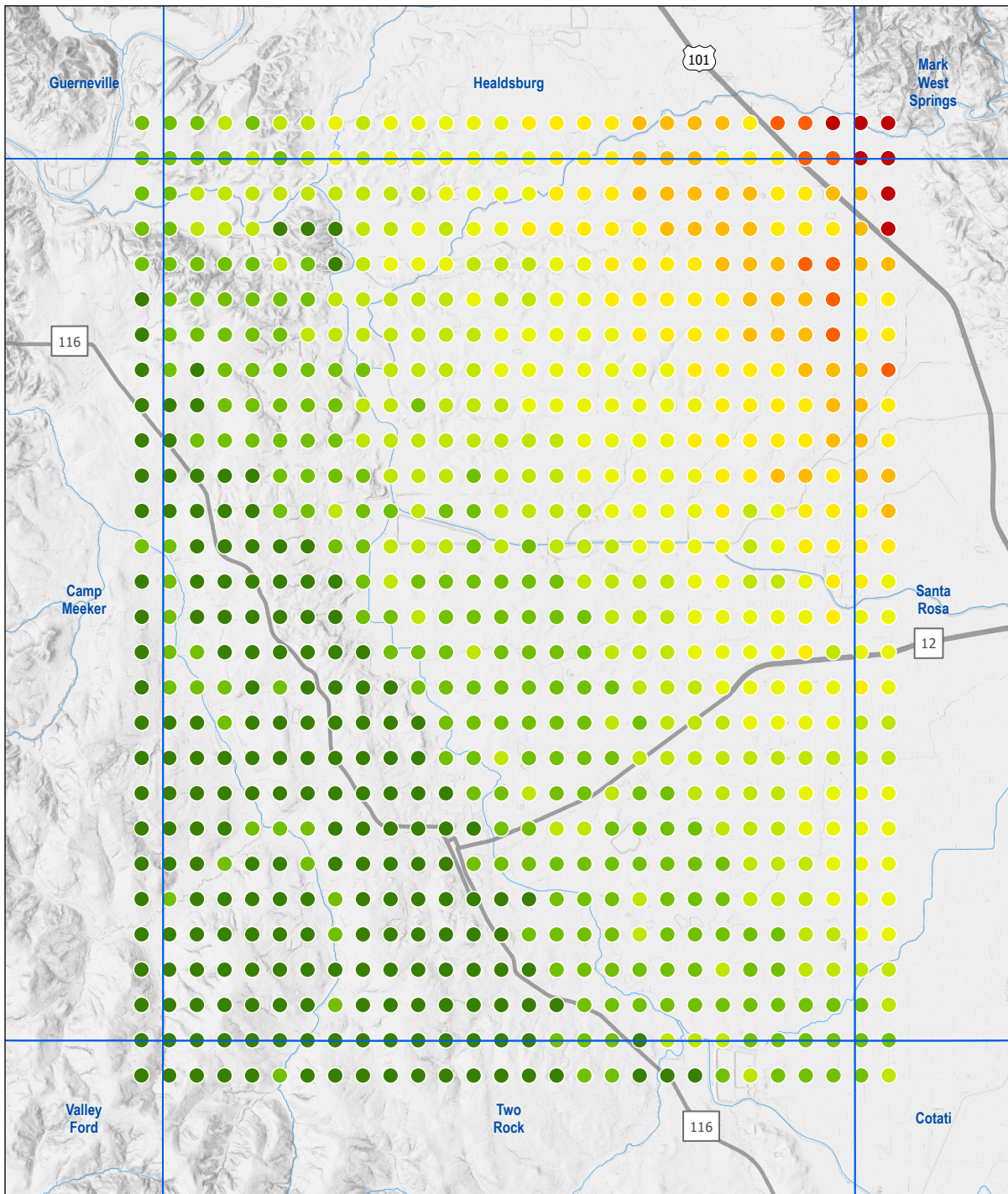


Plate 2.1 Map of V_{s30} from Thompson (2018), Sebastopol Quadrangle and surrounding area, California.



DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Meerea Kang, CGS.

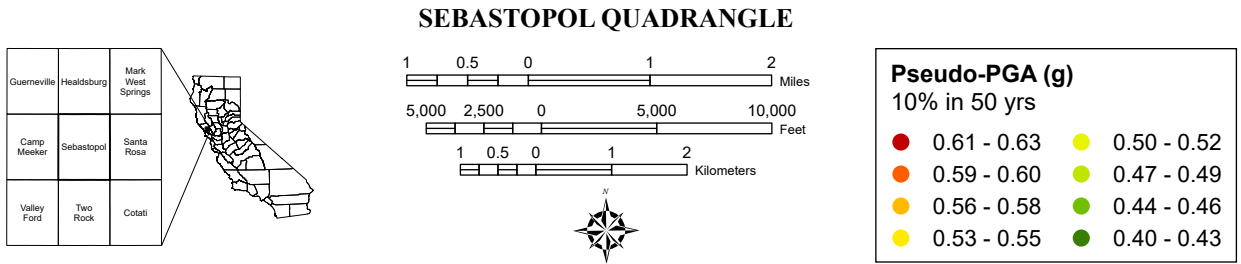
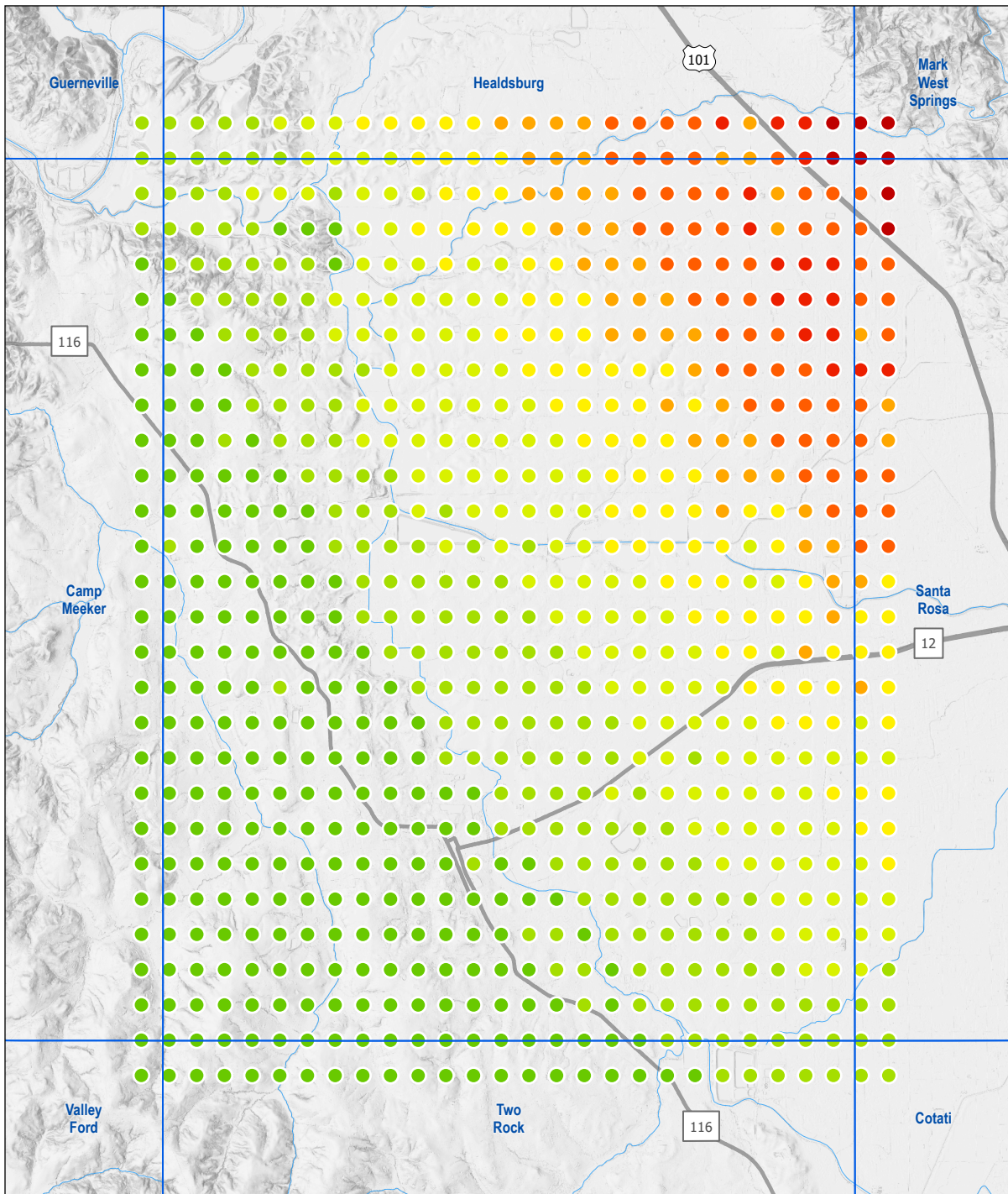


Plate 2.2 Pseudo-PGA for liquefaction hazard mapping analysis, Sebastopol Quadrangle and surrounding area, California.



DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Meerea Kang, CGS.

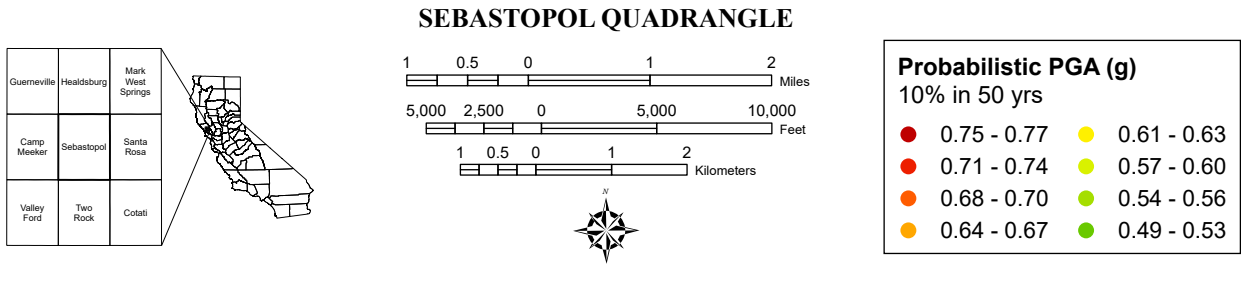
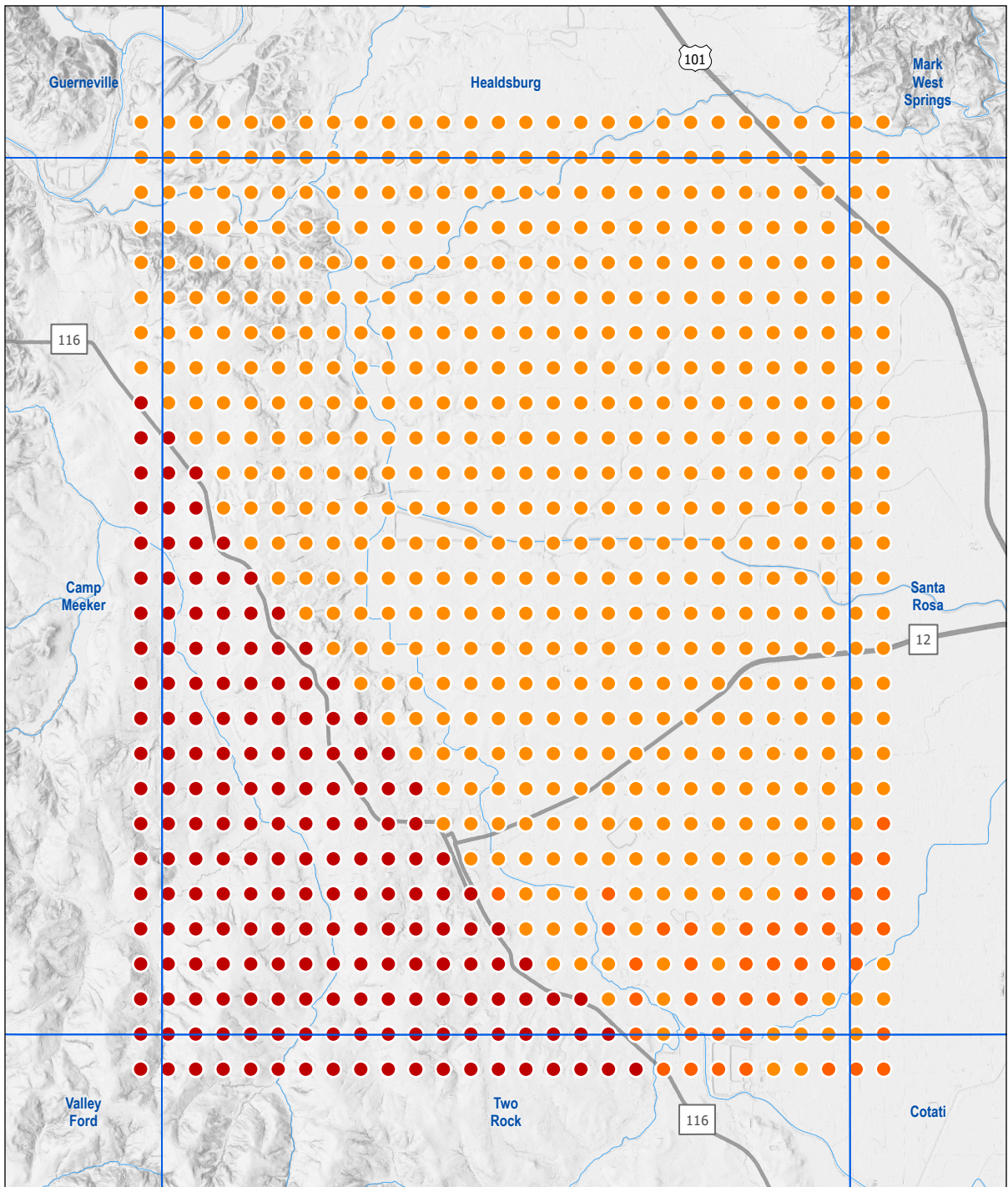


Plate 2.3 Probabilistic peak ground acceleration for landslide hazard mapping analysis, Sebastopol Quadrangle and surrounding area, California.



DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Meerea Kang, CGS.

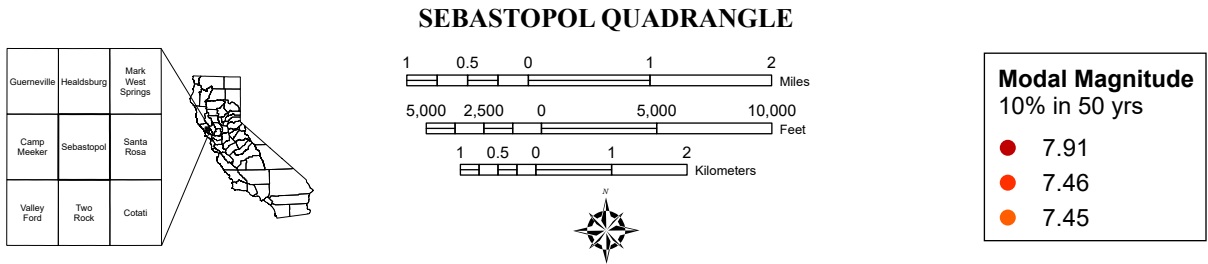


Plate 2.4 Modal magnitude for landslide hazard mapping analysis, Sebastopol Quadrangle and surrounding area, California.