SEISMIC HAZARD ZONE REPORT 132

SEISMIC HAZARD ZONE REPORT FOR THE HALF MOON BAY 7.5-MINUTE QUADRANGLE, SAN MATEO COUNTY, CALIFORNIA

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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 Half Moon Bay 7.5-Minute Quadrangle, San Mateo County, California. The topographic quadrangle map, which covers approximately 190 square kilometers (~74 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 area subject to seismic hazard mapping includes the city of Half Moon Bay and unincorporated districts of Miramar and El Granada.

This Seismic Hazard Zone Report describes the development of the Seismic Hazard Zone for the Half Moon Bay 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 2018 *Update of the United States National Seismic Hazard Maps*.

About 12.35 square kilometers (4.77 square miles) of land in the Half Moon Bay Quadrangle has been designated EZRI for liquefaction hazard, encompassing beaches and much of the alluvial plain along the Pacific coastline and extending inland and eastward along alluvial valleys and canyons dissecting the Santa Cruz Mountains. Borehole logs of test holes drilled in these areas indicate the widespread presence of near-surface soil layers composed of saturated, loose sandy sediments. Geotechnical tests conducted downhole and in labs indicate that these soils generally have a moderate to high likelihood of liquefying, given the level of strong ground motions this region could be subjected to.

About 22.88 square kilometers (8.83 square miles) of land in the Half Moon Bay Quadrangle has been designated EZRI for earthquake-induced landslides, encompassing much of the steep slopes of the Santa Cruz Mountains bounding the eastern half of the study area.

City, county, and state agencies are required by the California Seismic Hazards Mapping Act to use the Seismic Hazard Zone maps in their land-use planning and permitting processes. They must withhold building permits for sites being developed within EZRI 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 EZRI 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 on online at: http://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: http://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://www-scec.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, ground water 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 Half Moon Bay Quadrangle and laboratory tests used to categorize geologic materials within the quadrangle 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, provides map plates of the spatial distribution of key ground motion parameters, and summarizes the ground motions used to evaluate liquefaction and earthquake-induced landslide potential in the Half Moon Bay Quadrangle. Sections 3 and 4 summarize the analyses and criteria used to delineate liquefaction and earthquake-induced landslide hazard zones, respectively, in the Half Moon Bay Quadrangle.

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 Half Moon Bay Quadrangle include those associated with soft clay deformation, non-liquefaction-related settlement, ridge-top spreading, and shattered ridges. In addition, this report does not address the potential for ground failure related to precipitation-induced landslides, including debris flows.

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: http://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/.

EZRI maps and reports are also available for purchase at the CGS Sacramento office at the address presented below, or online at: http://www.conservation.ca.gov/cgs/publications.

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

Information regarding the Seismic Hazard Zonation Program is available on the CGS website: http://www.conservation.ca.gov/cgs/shzp/.

SECTION 1: GEOGRAPHY GEOLOGY AND ENGINEERING GEOLOGY

of the

HALF MOON BAY 7.5-MINUTE QUADRANGLE, SANTA MATEO COUNTY, CALIFORNIA

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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 Half Moon Bay Quadrangle and then discuss the collection, processing, and analyses of primary geologic and engineering geologic data that were used to delineate EZRI.

GEOGRAPHY

Location

The Half Moon Bay Quadrangle covers an area of approximately 190 square kilometers (74 square miles) in the San Mateo County portion of the San Francisco Peninsula. The center of the quadrangle lies about 38.5 kilometers (24 miles) south by southwest of the City of San Francisco and about 50 kilometers (31 miles) north by northwest of the City of San Jose. The map area encompasses developed areas along the Pacific coastline, including expansive agricultural fields, the city of Half Moon Bay, and the unincorporated districts of El Granada and Miramar. It also includes undeveloped and protected areas in the Santa Cruz Mountains, such as Rancho Corral de Tierra (Golden Gate National Recreation Area) and Purisima Creek Redwoods Preserve (Mid-Peninsula Regional Open Space).

The topography of the Half Moon Bay Quadrangle is typical of the Coast Ranges Geomorphic Province, including beaches and precipitous cliffs along the Pacific coast and flat alluvial plains and marine terraces to the western edge of the Santa Cruz Mountains. The rugged terrain is characterized by a series of prominent ridges generally oriented in a southwest-northeast direction with heights increasing eastward to a maximum altitude of 379 meters (1242 feet) at the edge of the mapped area. This terrain is dissected along similarly oriented valleys and perpendicular canyons by seasonal and perennial creeks that drain into the Pacific Ocean.

Land Use

Dating back to the 1840s, Half Moon Bay is the oldest settlement in San Mateo County. The community developed around an important coastal agriculture and a thriving fishing industry. It remained a center of rural life until the post-World War II era when developers, anticipating a great influx of San Franciscans, laid out the surrounding towns of El Granada, Miramar, and other unincorporated districts. Since the 1980s the San Francisco Peninsula has seen a large growth rate as part of the technology boom of the Silicon Valley. Urban and industrial developments as well as expansive agricultural fields are concentrated on relatively flat areas along the Pacific coastline, while development in hill slope areas favors low density residential structures.

Major transportation routes in the map area include northwest trending State Highway 92 crossing the Santa Cruz Mountains and State Highway 1 running alongside the Pacific coastline. They connect Half Moon Bay to San Francisco and the greater bay area. Additional access is provided by a network of city, county, and private roads in the developed areas and by fire roads and trails in undeveloped areas.

Digital Terrain Data

A digital representation of the earth’s surface is a key component in delineating liquefaction and landslide hazards. For the Half Moon Bay Quadrangle, digital topography in the form a lidar-derived digital elevation model (DEM) with a cell size of 1 meter was obtained from San Mateo County (San Mateo County, 2017).

For liquefaction hazard analyses, surface elevations derived from the DEM are differenced with historic-high ground water elevations to derive a “depth to water” map. In alluvial areas, the depth value obtained was 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 sources used to evaluate the areal distribution of bedrock units and Quaternary deposits in the Half Moon Bay Quadrangle are regional geologic maps compiled by Witter and others (2006) and Brabb and others (1998). These maps were combined to form a single 1:24,000-scale geologic materials map. CGS staff used DEMs, aerial photos, online imagery, and limited field reconnaissance to modify the Quaternary/bedrock boundary, confirm the location of geologic contacts, map recently modified ground surfaces, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units. 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 valleys 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 Quaternary and bedrock 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.

Bedrock Units

Bedrock units in the map area lie within a series of fault-bounded structural blocks and form stratigraphic assemblages that differ in depositional and deformational history.

Mesozoic rocks

Granitic rocks of Montara Mountain (**Kgr**) are mapped at the northern edge of the study area. They are part of the Salinian complex, an assemblage of Cretaceous plutonic rocks that has been displaced northward by offset on the San Andreas fault system.

Cenozoic rocks

The Tertiary strata in the Half Moon Bay Quadrangle consists of units resting unconformably on Mesozoic rocks. They are mapped on the ridges and valleys of the Santa Cruz Mountains and on outcrops at the edges and incisions of marine terraces along the Pacific coastline. They consist of the Whiskey Hill Sandstone (**Tw**, Eocene); Vaqueros Sandstone (**Tvq**, Oligocene); Mindego Basalts (**Tmb**, upper Oligocene and lower Miocene); Lambert Shale (**Tla,** upper Oligocene and lower Miocene); Lompico Sandstone (**Tlo**, lower Miocene); shale, chert , claystone, siltstone and sandstone of the Monterey Formation (**Tm**, middle Miocene); and sandstone, mudstone and siltstone of the Purisima Formation (**Tp**, **Tptu, Tpl, Tpsg, Tpp, Tpt**, Pliocene).

Quaternary Sedimentary Deposits

Quaternary sedimentary units mapped in the Half Moon Bay Quadrangle (Plate 1.1) are divided into groups based on age, origin, and composition (Table 1.1).

Pleistocene to Holocene alluvial sediments

Alluvial sediments occur along stream channels and adjoining flood prone areas in and at the mouth of valleys cutting through the Santa Cruz mountains. These deposits include undifferentiated alluvium (**Qpa**, late Pleistocene; **Qha**, Holocene), alluvial fans (**Qof**, Pleistocene; **Qpf**, late Pleistocene; **Qhf**, Holocene), stream channel deposits (**Qhc**, Holocene) and stream terrace deposits (**Qht1, Qht2**, Holocene). Alluvial sediments generally consist of poorly to moderately sorted, poorly to well bedded, loose to dense sand, gravel, silt and clay. Pleistocene age is indicated by depth of stream incision, stronger soil development and lack of historical flooding evidence.

Pleistocene to Holocene marine sediments

Marine Terraces (**Qmt**, **Qmt1, Qmt2, Qmt3**, Pleistocene) are present on uplifted abrasion platforms between the Santa Cruz Mountains and the Pacific Ocean and consist of moderately to well sorted, moderately to well bedded sand and gravel. Beach Sand (**Qhbs**, Latest Holocene) is mapped along the Pacific coastline and consists of well sorted, fine to coarse sand with some fine gravel.

Pleistocene to Holocene detrital sediments

Colluvium deposits (**Qco**, Pleistocene to early Holocene; **Qcy**, Holocene) occur on lower slopes in the Santa Cruz mountains and consist of friable unsorted sand, silt, clay, gravel, rock debris, and organic materials in varying proportions.

Holocene eolian sediments

Dune Sands (**Qds**, Latest Pleistocene to Holocene; **Qhds**, Holocene) occur just inland of the Pacific coastline and consist of very well sorted, fine to medium grained eolian sand that is semi-consolidated and weakly cemented.

Historical artificial fills

Artificial undifferentiated fill (**af**) is material deposited by human activity and is found throughout the Half Moon Bay Quadrangle. Fill may be engineered or non-engineered material, both of which may occur within the same area on the map. Large earthen dams are mapped as artificial dam fill (**adf**). Artificial channel fill (**acf**) is material emplaced in historically active stream channels to re-route water flow. Artificial levee fill (**alf**) composes constructed levees to contain flood or tidal waters.

Table 1.1. Quaternary units mapped in the Half Moon Bay Quadrangle.

Map Unit	Environment of Deposition	Age
af	Artificial	historical
adf	Artificial	historical
acf	Artificial	historical
alf	Artificial	historical
Qhbs	Marine	Latest Holocene
Qhc	Alluvial	Holocene
Qha	Alluvial	Holocene
Qhf	Alluvial	Holocene
Qcy	Detrital	Holocene
Qhds	Eolian	Holocene
Qht1, Qht2	Alluvial	Holocene
Qds	Eolian	Latest Pleistocene to Holocene
Qco	Detrital	Pleistocene to Early Holocene
Qpa	Alluvial	Late Pleistocene
Qpf	Alluvial	Late Pleistocene
Qof	Alluvial	Pleistocene
Qmt, Qmt1, Qmt2, Qmt3	Marine	Pleistocene

Geologic Structure

The Half Moon Bay Quadrangle is located within the Coast Ranges geomorphic province. The Coast Ranges are northwest-trending mountain ranges and valleys subparallel to the San Andreas Fault system marking the transform boundary between the Pacific and North American plates. Shearing is distributed across a complex system of primarily northwest-trending, right-lateral, Tertiary and Quaternary age strike-slip faults truncating and juxtaposing stratigraphic assemblages.

Two parallel 1.25 kilometer (0.75 mile) queried segments of the Seal Cove Fault are mapped east of Pillar Point in the northwestern corner of the map area. The Seal Cove Fault is a right-lateral, strike-slip fault that is part of the larger offshore San Gregorio Fault Zone. It has been designated by CGS as an Earthquake Zone of Required Investigation under the Alquist-Priolo Earthquake Fault Zoning Act.

Folds are also present in the region and can be divided in two categories based on axial trend and style of deformation. The first category includes tight folds and overturned folds with inclined axial planes whose axes trend obliquely to the major strike-slip faults and were probably caused by the same regional stress. The second category contains tight, upright folds whose axes strike roughly parallel to the major strike-slip faults; these folds have been formed by a perpendicular component of regional compression. In the map area, the nonconformity at the base of the middle Miocene strata and an angular unconformity at the base of the Pliocene strata indicate two periods of pre-Pliocene Tertiary uplift and folding.

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 Half Moon Bay Quadrangle has been prepared through field reconnaissance and a review of previously published landslide mapping (Brabb and others, 2009), but primarily from geomorphic analyses of LIDAR-derived elevation data and digital aerial photography. The LIDAR dataset consists of 1-meter bare earth DEM derived hillshade, contour, slope, and other derivative layers. This data was acquired by San Mateo County in 2017 and meets QL2 accuracy with 4 points per meter pulse density. Digital aerial photography utilized in the preparation of this inventory consists of 2012 NAIP color imagery with a spatial resolution of 1-meter ground sample distance, and Google Earth Pro color and black and white imagery of varied resolution, collected between 1984 and 2020. All landslides in this inventory were digitized in an ArcGIS environment at a resolution of no larger than 1:2,000.

For each landslide included on the map, several characteristics (attributes) were compiled. These characteristics include the confidence of interpretation (definite, probable, or questionable) and other properties, such as 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 zone as described in Section 4. A small-scale version of this landslide inventory is included on Plate 1.2.

A total of 440 landslides were mapped in the Half Moon Bay Quadrangle. There are 340 rock slides, 45 debris flows, 31 earth flows, 22 debris fans, and 2 debris slides. These landslides have mostly developed on moderate to steep slopes in the Santa Cruz Mountain. The coastline is also particularly prone to slope failure due to the wave action that has accelerated erosion of the base of the coastal bluffs.

The largest amount of land covered by landslides occurs in the Purisima Formation (**Tp**), followed by the Monterey Formation (**Tm**) and Vaqueros Sandstone (**Tvq**) In terms of area percentage affected by landslides, the bedrock geologic units most susceptible to landsliding are the Lambert Shale (**Tla**, 37%), Mindego Basalt (**Tmb**, 31%) and Vaqueros Sandstone (**Tvq**, 18%).

ENGINEERING GEOLOGY

Historic-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 present or historic-high depth to groundwater surface within the Half Moon Bay Quadrangle.

Groundwater Basins

The study area lies within the San Francisco Bay hydrologic region and covers the most part of the California Department of Water Resources (CDWR, 2003) designated Half Moon Bay Terrace Groundwater Basin (number 2-22). The basin is bounded by Martini Creek on the north, by the Pacific Ocean on the west, by Tunitas Creek on the south, and by the Montara Mountains on the east. Elevations within the basin range from sea level to nearly 90 meters (300 feet) along the eastern boundary. Many creeks flow through the basin toward the Pacific Ocean including the Frenchmans, Apanolio, Corinda Los Trancos, Nuff, Pilarcitos, Mills, Canada Verde, Purisima, Lobitos, and Tunitas creeks. The basin is filled by sedimentary materials and underlain by Montara Mountain granitic rocks. Water bearing formations are Quaternary alluvial and marine deposits and, to a lesser degree, the highly fractured sediments of the Purisima Formation. Aquifer storage coefficients typically indicate unconfined conditions at depths less than 100 feet. Natural recharge occurs by infiltration of water from streams emanating from the upland areas and direct rainfall percolation. Mean annual precipitation in the study area is in the range of 26 inches. The region has a Mediterranean climate with most of the precipitation in the region occurring as rain during the winter and spring. Although the summer is generally dry, regional fog helps moderate the average temperature, reduces evapotranspiration, and meets some moisture demands from plants.

Groundwater Data

For this study, groundwater conditions were investigated in the alluvial valleys, alluvial plains, and marine terraces within the Half Moon Bay Quadrangle. The evaluation was based on first-encountered, unconfined water noted in geotechnical borehole logs acquired from San Mateo County and depth to water levels recorded by the State Water Resources Control Board on GeoTracker (CWRCB, 2018a) and GeoTracker Groundwater Ambient Monitoring & Assessment (CWRCB, 2018b). These datasets reflect water levels from 1970 to present. As they represent a measurement at a point in time, this information is only valuable when compared to measurements in neighboring boreholes with an understanding of local seasonal variability. Additional groundwater measurements were collected from the California Department of Water Resources Statewide Groundwater Elevation Monitoring (CDWR, 2018). The data collected from this source is generally of higher quality as they consist of monitoring wells with strict measurement protocols. Water levels are recorded on hydrographs and account for variability throughout the last decade.

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

Groundwater Levels

Historic-high groundwater levels are shallow along the Pacific Ocean coastline and adjoining flatlands, reflecting open water sources: ocean, lakes, reservoirs, and flowing creeks, as well as water recharge from upland areas. As the altitude increases south and eastward, on higher, older terraces and in the direction of the Santa Cruz Mountains the depth to measured groundwater typically increases.

Shallow water was also encountered and mapped in alluvium alongside river channels. These materials are seasonally saturated with increased precipitation, heavy runoff and stream flow.

Historic-high groundwater contours were not extended into pre-Quaternary formations mapped at the surface as these areas were not evaluated for liquefaction hazard potential.

Geologic Material Testing

Liquefaction Hazard Zoning: In-Situ Penetration Resistance

Of particular value in liquefaction evaluations are logs that report the results of downhole standard penetration tests in alluvial materials. The Standard Penetration Test (SPT) provides a standardized measure of the penetration resistance of 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 percent using a method described by Seed and Idriss (1982) and Seed and others (1985). This normalized blow count is referred to as $(N_1)_{60}$. Geotechnical borehole logs provided information on lithologic and engineering characteristics of Quaternary deposits within the study area.

For liquefaction hazard zoning in the Half Moon Bay Quadrangle, soils reports were collected from San Mateo County. The data were entered into the CGS geotechnical geographical information system (GIS) database. After an initial review, process and data quality controls, 74 borehole logs were selected for this study.

Of the 74 geotechnical borehole logs analyzed in this study (Plate 1.1), 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, however, include all of the information (e.g. soil density, moisture content, sieve analysis, etc.) required for an ideal analysis using the Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed using 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 ranked and grouped based on their shear strength. Generally, the primary source for shear-strength measurements is geotechnical reports prepared by consultants on file with local government permitting departments. A total of 9 shear tests were collected in the Half Moon Bay Quadrangle.

Shear strength data were compiled for each geologic map unit in the Half Moon Bay Quadrangle with additional data from adjoining quadrangles (Montara Mountain, San Mateo and Woodside, 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 locations of rock and soil samples taken for shear testing and GSI field measurements (Hoek-Brown) within the study area are shown on Plate 1.2.

In his investigation of direction and amount of bedding dip of sedimentary rocks in San Mateo County, Brabb (1983) identified adverse bedding conditions in outcrops of the Purisima Formation (**Tp**), Monterey Formation (**Tm**) and Lambert shale (**Tla**). Therefore, these formations were subdivided based on shear strength differences between coarse-grained (higher strength) and fine-grained (lower strength) lithologies. Shear strength values for the fine- and coarse-grained lithologies were then applied to areas of favorable and adverse bedding orientation, which were determined from structural and terrain data as discussed above. It was assumed that coarse-grained material (higher strength) dominates where bedding dips into a slope (favorable bedding), whereas fine-grained (lower strength) material dominates where adverse bedding occurs. The geologic material strength map was modified by assigning the lower, fine-grained shear strength values to areas where potential adverse bedding conditions were identified.

Geologic units were grouped based on average angle of internal friction (average phi) and lithologic character. Mean and median phi values for each geologic map unit and corresponding strength groups are summarized in Table 1.2. For each geologic strength group (Table 1.3) in the map area, the mean shear strength value was assigned and used in our slope stability analysis. A geologic material strength map was made based on the groupings presented in Table 1.2 and Table 1.3, and this map provides a spatial representation of material strength for use in the slope stability analysis.

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 quadrangle if available.

The strength characteristics of existing landslides (**Qls**) must be based on tests of the materials along the landslide slip surface. Ideally, shear tests of slip surfaces formed in each mapped geologic unit would be used. However, this amount of information is rarely available. 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 Half Moon Bay Quadrangle, strength parameters applicable to existing landslide planes were not available and are not included in this analysis.

Table 1.2. Summary of the shear strength statistics for the Half Moon Bay Quadrangle.

	Formation Name	Number of Test	Mean/Median Phi (deg)	Mean/Median Group Phi (deg)	Mean/Median Group Cohesion (psf)	No Data: Similar Lithology	Phi Values Used in Stability Analysis
GROUP 1	Kgr		36 / 38	36 / 38	964 / 1100		36
GROUP 2	Tp(fbc) Tw Tla(fbc)	6 14 3	33 / 32 33 / 33 32 / 31	33 / 32	1143 / 550	Tlo Tvq	33
GROUP 3	Qmt2 Qmt3 Qpf	13 3 14	29 / 31 29 / 24 28 / 28	29 / 28	929 / 900	Qof Tmb	29
GROUP 4	af	12	26 / 26	26 / 27	518 / 575	acf adf alf Tla(abc) Tm(fbc)	26
GROUP 5	Qhf Qmt1 Tp(abc) Tpl	53 6 3 2	25 / 23 24 / 22 24 / 26 24 / 25	24 / 23	1053 / 900	Qmt Qpt Tptu Tpsg Tpp Tpt Tm(abc)	23
GROUP 6	Qha Qhc Qcy	7 1 1	21 / 17 17 / 17 20 / 20	20 / 18	497 / 350	Qpa Qco Qhbs Qhds Qds Qht1 Qht2	20

Table 1.3. Summary of shear strength groups for the Half Moon Bay Quadrangle, San Mateo County.

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5	GROUP 6
Kgr	Tp(fbc)	Qmt2	af	Qhf	Qha
	Tw	Qmt3	acf	Qmt1	Qhc
	Tla(fbc)	Qpf	adf	Tp(abc)	Qcy
	Tlo	Qof	alf	Tpl	Qpa
	Tvq	Tmb	Tla(abc)	Qmt	Qco
			Tm(fbc)	Qpt	Qhbs
				Tptu	Qhds
				Tpsg	Qds
				Tpp	Qht1
				Tpt	Qht2
				Tm(abc)	

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Air Photos and Imagery

Google Earth Pro DigitalGlobe, >1-m resolution, 2003-2005, 2007, and 2009.

Google Earth Pro Historical Imagery, various resolutions, 1991, 1993, 2002-2010, and 2014.

Lidar Hillshade derived from the 1.5 m Lidar Digital Terrain Model (2017), source of illumination: 45° sun angle, and 90° and 315° sun azimuths.

USGS 7.5-minute Digital Raster Graphics, 1;24000 scale, scanned at 250 dpi, 2001

APPENDIX A: SOURCES OF ROCK STRENGTH DATA

SOURCE	NUMBER OF TESTS SELECTED
San Mateo County	**9**
San Mateo Quadrangle	**63**
Montara Mountain Quadrangle	**48**
Woodside Quadrangle	**25**
Hoek-Brown rock mass characterization samples	**8**
Total Number of Shear Tests	**153**

SECTION 2: GROUND MOTION ASSESSMENT

for the

HALF MOON BAY 7.5-MINUTE QUADRANGLE, SAN MATEO COUNTY, CALIFORNIA

using the

2018 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 Half Moon Bay Quadrangle. It includes an explanation of the probabilistic seismic hazard analysis 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 United States Geological Survey (USGS) probabilistic seismic hazard analysis (PSHA) model for the 2018 Update of the National Seismic Hazard Maps (NSHMs) (Petersen and others, 2020). This model replaces ground-motion models of Petersen and others (2015, 2014, and 2008), Frankel and others (2002), Cao and others (2003) and Petersen and others (1996) used in previous official Seismic Hazard Zone maps. Like previous models, the 2018 USGS PSHA model utilizes the best available 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 control ground motion hazards, namely version three of the Uniform California Earthquake Rupture Forecast Model (UCERF3) (Field and others, 2013; 2014) and the Cascadia Subduction Zone model (Frankel and others, 2014). For shallow crustal earthquakes, ground motions are calculated using the Next Generation Attenuation Relations for Western U.S. (NGA-West2) developed from a Pacific Earthquake Engineering Research Center ground motion research project (Bozorgnia and others, 2014). The NGA-West2 used in the 2018 update of the NSHMs includes four ground motion models (GMMs): 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, GMMs developed specifically for such sources are used, including the Zhao and others (2006), Atkinson and Macias (2009), and BC Hydro (Addo and others, 2012).

In 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-average 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 calculation and, in a separate post-PSHA step, National Earthquake Hazard Reduction Program (NEHRP) 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. In the current application, 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 the PSHA calculation. V_{S30} value at each grid point is assigned based on a geology- and topography-based V_{S30} map for California developed by Wills and others (2015). The statewide V_{S30} map consists of fifteen V_{S30} groups with group mean V_{S30} values ranging from 176 m/s to 733 m/s. It is to be noted that these values are not determined from site-specific velocity data. Some group values have considerable uncertainties as indicated by a coefficient of variation ranging from 11% in Quaternary (Pleistocene) sand deposits to 55% in crystalline rocks.

For zoning purpose, ground motions are calculated at each grid point of a 0.005-degree grid (approximately 500-m spacing) that adequately covers the entire quadrangle. V_{S30} map and grid points in the Half Moon Bay Quadrangle are depicted in Plate 2.1. 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 liquefaction and induced landslide hazard mapping analyses, still rely on scenario earthquakes or some aspects of scenario earthquakes. Deaggregation enables identification of the most significant scenario or scenarios in terms of magnitude and distance pair. Deaggregation 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 ground motion hazard level for liquefaction and landslide hazard zoning is 10% exceedance probability in 50 years or 475-year return period.

Probabilistic ground motion calculation and hazard deaggregation are performed using USGS hazard codebase, nshmp-haz version 1.3.0, a Java library developed in support of the USGS NSHM project. The Java code library is hosted in GitHub and is publicly available at: https://github.com/usgs/nshmp-haz/. This codebase also supports the USGS web-based site-specific ground motions calculator, the Unified Hazard Tool, https://earthquake.usgs.gov/hazards/interactive/. The source model used for the published 2018 NSHMs is adopted in its entirety. The 2018 source model is also hosted in GitHub and is publicly available at: https://github.com/usgs/nshm-cous-2018.

APPLICATION TO LIQUEFACTION AND 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 (California Geological Survey, 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 deaggregation. 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 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 deaggregation.

Pseudo-PGA and probabilistic PGA at grid points are depicted in Plates 2.2 and 2.3, respectively. Modal magnitude is depicted in Plate 2.4. Ground motion generally increases from the coast to the northeast corner as distance to the San Andreas fault zone and the Pilarcitos fault decreases. Shaking hazards are controlled predominantly by the Peninsula section of the northern San Andreas fault zone, with increasing contribution from San Gregorio fault toward the coast. Other sources that contribute to shaking hazards include the Pilarcitos fault , Monte Vista – Shannon fault, and background (gridded) seismicity. Modal magnitudes (Plate 2.4) reflects the magnitudes of earthquakes that the Peninsula section of the northern San Andreas fault zone is capable of producing. Ground motion distribution is controlled by proximity to these faults and is affected by subsurface geology. In general, when fault distances are similar, expected 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 quadrangle.

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)
0.45 – 0.63	0.39 – 0.54	7.70 – 7.87	176 – 733

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SECTION 3: EVALUATION OF LIQUEFACTION HAZARD

in the

HALF MOON BAY 7.5-MINUTE QUADRANGLE, SAN MATEO COUNTY, CALIFORNIA

by

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Purpose of this Section

This Section of the Seismic Hazard Zone Report summarizes the analyses and criteria used to delineate liquefaction hazard zones in the Half Moon Bay Quadrangle.

ZONING TECHNIQUES

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

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

Liquefaction Susceptibility

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

Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is treated as liquefiable in this investigation. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may be vulnerable to strength loss with remolding and represent a hazard that is not specifically addressed in this investigation. Soil characteristics that result in higher measured penetration resistances generally indicate lower liquefaction susceptibility. In summary, soils that lack resistance (susceptible soils) typically are saturated, loose, and granular. Soils resistant to liquefaction include all soil types that are dry, cohesive, or sufficiently dense.

CGS's inventory of areas containing soils susceptible to liquefaction begins with evaluation of historical occurrences of liquefaction, geologic maps, cross-sections, geotechnical test data, geomorphology, and groundwater hydrology. Soil properties and soil conditions such as type, age, texture, color, and consistency, along with historic-high depths to groundwater are used to identify, characterize, and correlate susceptible soils. Because Quaternary geologic mapping is based on observable similarities between soil units, liquefaction susceptibility maps typically are often similar to Quaternary geologic maps, depending on local groundwater levels. CGS's qualitative relations among susceptibility, geologic map unit, and depth to ground water are summarized in Table 3.1.

Table 3.1. Liquefaction susceptibility of Quaternary units in the Half Moon Bay Quadrangle.

Geologic Map Unit	Age	Sediment/Material Type	Consistency	Liquefaction Susceptibility*
af, acf, adf, alf	Historical	Sand, silt, gravel, clay, cobbles, concrete	Loose to dense	Variable
Qhbs	Latest Holocene	Sand, fine gravel	Loose	Very High
Qhc	Holocene	Sand, gravel, cobbles, silt, clay	Loose	Very High
Qhds	Holocene	Sand	Loose to dense	High
Qht1, Qht2	Holocene	Sand, gravel, silt, clay	Loose to dense	High
Qha, Qhf,	Holocene	Gravel, sand, silt, clay	Loose to dense	High
Qds	Latest Pleistocene to Holocene	Sand	Loose to dense	High
Qpa, Qpf	Late Pleistocene	Gravel, sand, silt, clay	Dense to very dense	Low
Qmt, Qmt1, Qmt2, Qmt3	Pleistocene	Sand, gravel, silt, clay	Dense to very dense	Low
Qof	Pleistocene	Sand, gravel, silt, clay	Dense to very dense	Low

*When saturated

Borehole logs show that Holocene and latest Pleistocene alluvial layers containing gravel may occur in the stream valleys and canyons in the study area. In the past, gravelly soils were considered not to be susceptible to liquefaction because the high permeability of these soils presumably would allow the dissipation of pore pressures before liquefaction could occur. However, liquefaction in gravelly soils has been observed during earthquakes, and recent laboratory studies have shown that gravelly soils are susceptible to liquefaction (Ishihara, 1985; Harder and Seed, 1986; Budiman and Mohammadi, 1995; Evans and Zhou, 1995; and Sy and others, 1995). SPT-derived density measurements in gravelly soils are unreliable and generally too high. They are likely to lead to overestimation of the density of the soil and, therefore, result in an underestimation of the liquefaction susceptibility. To identify potentially liquefiable units where the N values appear to have been affected by gravel content, correlations were made with boreholes in the same unit where the N values do not appear to have been affected by gravel content.

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, 2020) for the 2020 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 percent 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 (Seed and Idriss, 1971; Seed and others, 1983; National Research Council, 1985; Seed and others, 1985; Seed and Harder, 1990; Youd and Idriss, 1997; Youd and others, 2001). The 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. CGS geologists use the results of this analysis, the groundwater analysis, and geologic conditions 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 criteria developed by the Seismic Hazards Mapping Act Advisory Committee and adopted by the SMGB (CGS, 2004). Under those guideline criteria, liquefaction zones are areas meeting one or more of the following:

1) Areas known to have experienced liquefaction during historical earthquakes
2) All areas of uncompacted artificial fill that are saturated, nearly saturated, or may be expected to become saturated
3) Areas where sufficient existing geotechnical data and analyses indicate that the soils are potentially liquefiable
4) Areas where existing subsurface data are not sufficient for quantitative evaluation of liquefaction hazard. Within such areas, zones may be delineated by geologic criteria as follows:
    a) Areas containing soil deposits of late Holocene age (current river channels and their historic floodplains, marshes and estuaries), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.10 g and the anticipated depth to saturated soil is less than 40 feet; or
    b) Areas containing soil deposits of Holocene age (less than 11,700 years), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.20 g and the anticipated depth to saturated soil is less than 30 feet; or
    c) Areas containing soil deposits of latest Pleistocene age (11,700 to 15,000 years), where the M7.5-weighted peak acceleration that has a 10 percent probability of being exceeded in 50 years is greater than or equal to 0.30 g and the anticipated depth to saturated soil is less than 20 feet.

Application of the above criteria allows compilation of 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 project quadrangle, CGS applies the above criteria to its findings to delineate Seismic Hazard Zones for liquefaction. Based on the evaluation, about 20 square kilometers (8 square miles) of the quadrangle 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 Map for the Half Moon Bay Quadrangle.

Areas of Past Liquefaction

Knudsen and others (2000a) developed a spatial database of historical earthquake-related ground failures containing historical observations of earthquake-triggered damage in the San Francisco Bay Area, including the two most damaging events: the 1906 San Francisco earthquake (Mw=7.7-7.9) (Youd and Hoose, 1978), and the 1989 Loma Prieta earthquake (Mw=7) (Plafker and Galloway, 1989; Seed and others, 1990; Tinsley and others, 1998). Other earthquakes that generated liquefaction failures in the study area include the 1838, 1865, 1868, and 1957 earthquakes (Youd and Hoose, 1978). Several liquefaction features have been recorded in the Half Moon Bay Quadrangle. Lateral spreading and sand boils were observed in beach sand (**Qhbs**) at the edges of impounded lagoons at the mouth of streams, inboard of the surf zone and in stream terrace deposits (**Qht**) on the banks of Pilarcitos Creek.

Artificial Fills

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

Areas with Sufficient Existing Geotechnical Data

The majority of the 74 borehole logs evaluated for liquefaction potential using the Seed-Idriss Simplified Procedure are located in developed areas along the Pacific coastline. Analysis of blow count values and other soil property measurements reported in the logs indicate that most of the boreholes situated in Holocene deposits penetrate saturated layers of loose sand, gravel, and silt that may liquefy under the expected earthquake loading.

In the northwestern corner of the study area liquefiable deposits were observed in modern stream channel deposits (**Qhc**), Holocene stream terrace deposits (**Qht1, Qht2**), Holocene undifferentiated alluvial sediments (**Qha**) and Holocene alluvial fans (**Qhf**) mapped along and adjacent to the downstream end of creeks running through Miramar and Half Moon Bay.

The Pleistocene Marine terrace deposits (**Qmt, Qmt1, Qmt2, Qmt3**) mapped south of Half Moon Bay do not contain liquefiable layers according to the Seed-Idriss Simplified Procedure. Boreholes recording these lithologies display saturated and unsaturated alluvium with high densities resistant to liquefaction under the expected loading.

Areas with Insufficient Existing Geotechnical Data

Adequate geotechnical borehole information is lacking for modern stream channel deposits (**Qhc**), Holocene alluvial fan (**Qhf**), Holocene alluvial terrace (**Qht1, Qht2**), Holocene undifferentiated alluvium (**Qha**) deposited in creeks and alluvial valleys through the Santa Cruz Mountains, and for beach sands (**Qhbs**) and dune sands (**Qds**, **Qhds**) mapped along the Pacific shoreline. These deposits contain varying amounts of loose, granular materials that are likely to be saturated because of the presence of near-surface groundwater and the proximity to open water. Those conditions, along with the ground motions expected to occur in the region, combine to form a sufficient basis for including areas underlain by these types of deposits in the Seismic Hazard Zone for liquefaction.

Geotechnical information for colluvium (**Qco** and **Qcy**) is also lacking. These deposits are mapped as thin veneers on slopes and can contain unconsolidated granular material, but they are not subject to groundwater saturation. Areas underlain by these deposits were not included in the Seismic Hazard Zone for liquefaction.

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SECTION 4: EVALUATION OF EARTHQUAKE-INDUCED LANDSLIDE HAZARD

in the

HALF MOON BAY 7.5-MINUTE QUADRANGLE, SAN MATEO COUNTY, CALIFORNIA

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Purpose of this Section

This Section of the Seismic Hazard Zone Report presents the analyses and criteria used to delineate of earthquake-induced landslide hazard zones in the Half Moon Bay Quadrangle.

ZONING TECHNIQUES

To evaluate earthquake-induced landslide hazard potential in the study area, a method of dynamic slope stability analysis developed by Newmark (1965) was used. The Newmark method 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

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

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 on a Geographic Information System (GIS) 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 2020 Update of the United States National Seismic Hazard Maps (Petersen and others, 2020). The model is set to calculate ground motion hazard in terms of peak horizontal ground acceleration (PGA) at a 10 percent in 50 years exceedance probability level. Raster versions of the PSHA PGA and Modal Magnitude maps for the Half Moon Bay Quadrangle 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:

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

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 and Real, 1996; McCrink, 2001).

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

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

Delineation of Earthquake-Induced Landslide Hazard Zones

Upon completion of an earthquake-induced landslide hazard evaluation within a project quadrangle, CGS applies the above criteria to its findings in order to delineate Earthquake Zones of Required Investigation for earthquake-induced landslides. Based on the evaluation, about 78 square kilometers (30 square miles) of the quadrangle are included in the Seismic Hazard Zone for earthquake-induced landslides. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Map for the Half Moon Bay Quadrangle.

Existing Landslides

Existing landslides typically consist of disrupted soils and rock materials that are generally weaker than adjacent undisturbed rock and soil materials. Previous studies indicate that existing landslides can be reactivated by earthquake movements (Keefer, 1984). Earthquake-triggered movement of existing landslides is most pronounced in steep head scarp areas and at the toe of existing landslide deposits. Although reactivation of deep-seated landslide deposits is less common (Keefer, 1984), a significant number of deep-seated landslide movements have occurred during, or soon after, several recent earthquakes. Based on these observations, all existing landslides with a definite or probable confidence rating are included within the 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 and Real, 1996; McCrink, 2001), the Seismic Hazard Zone for earthquake-induced landslides encompass all areas that have calculated Newmark displacements of 5 centimeters or greater.

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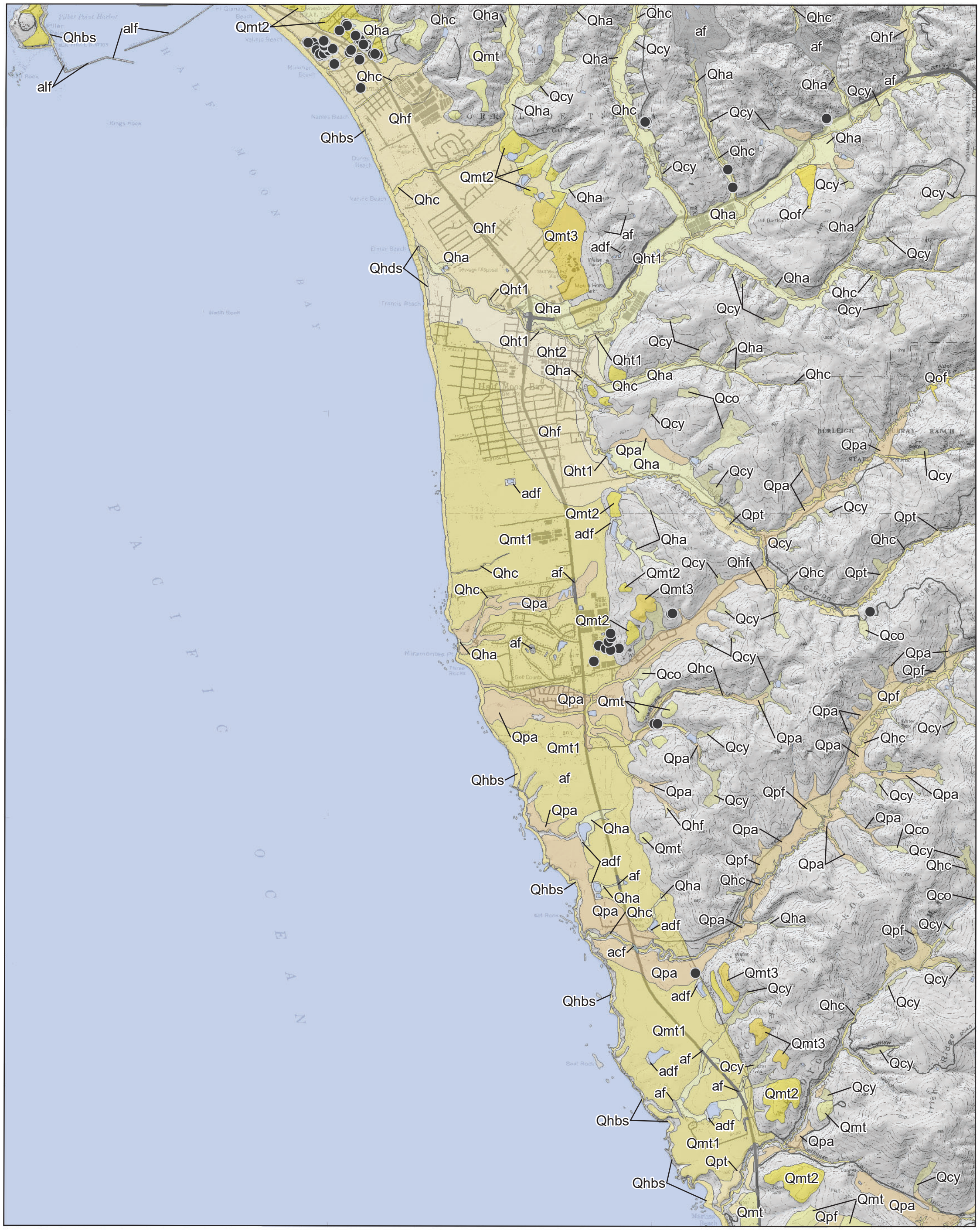
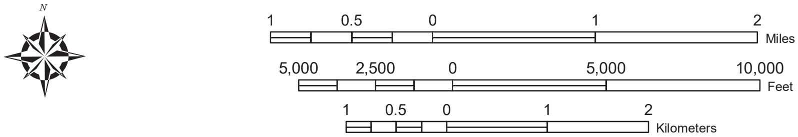


Topographic base map from USGS. Contour interval 20 feet. Scale 1:75,000. Map preparation by Janine Bird, CGS.

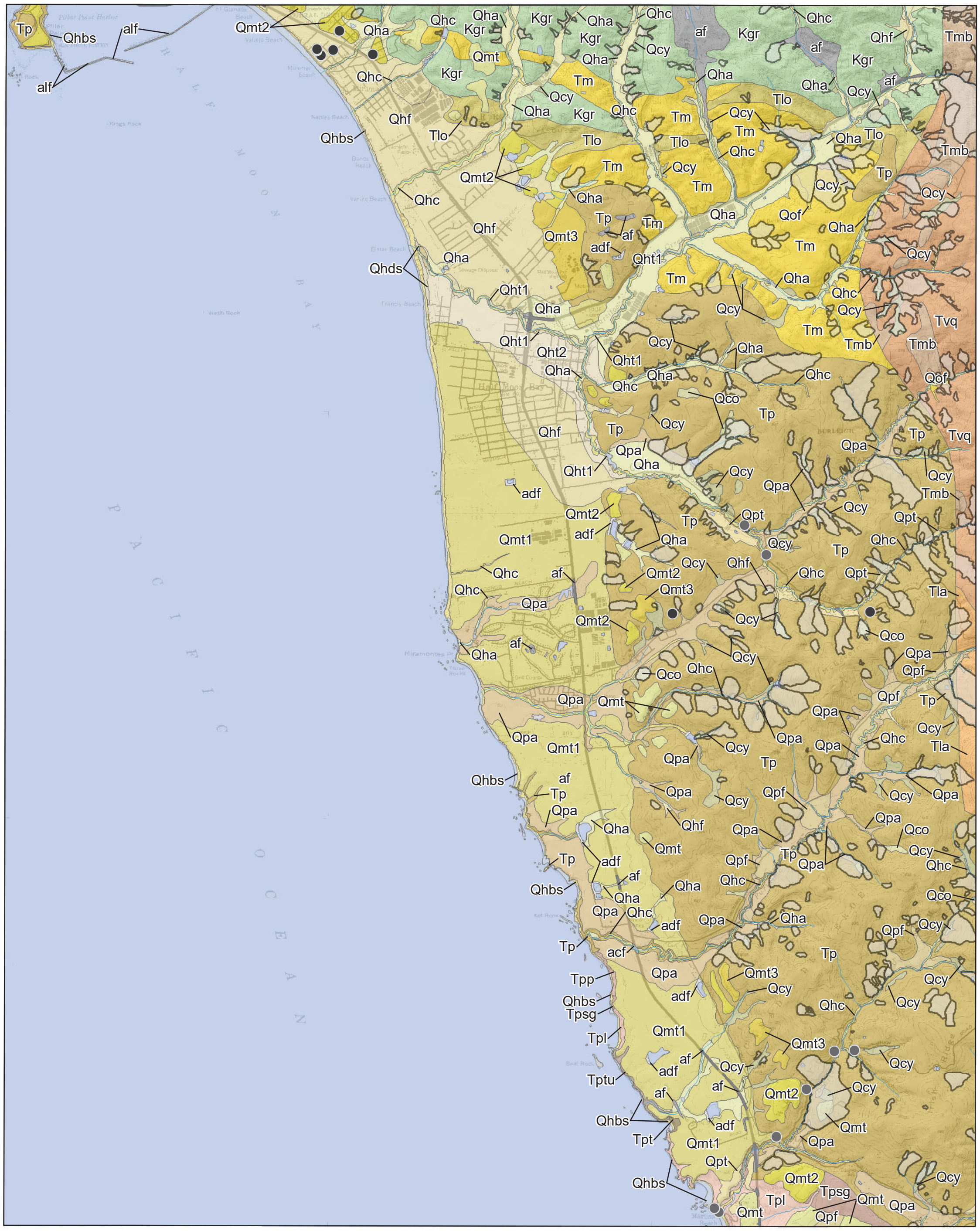
HALF MOON BAY QUADRANGLE



See "Geology" in Section 1 of report for descriptions of units.
Pre-Quaternary bedrock units shown without color.

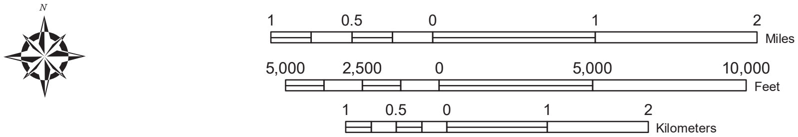
● Geotechnical boring used in liquefaction evaluation

Plate 1.1 Quaternary geologic materials map and locations of boreholes used in evaluating liquefaction hazard, Half Moon Bay Quadrangle, San Mateo County, California.



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

HALF MOON BAY QUADRANGLE



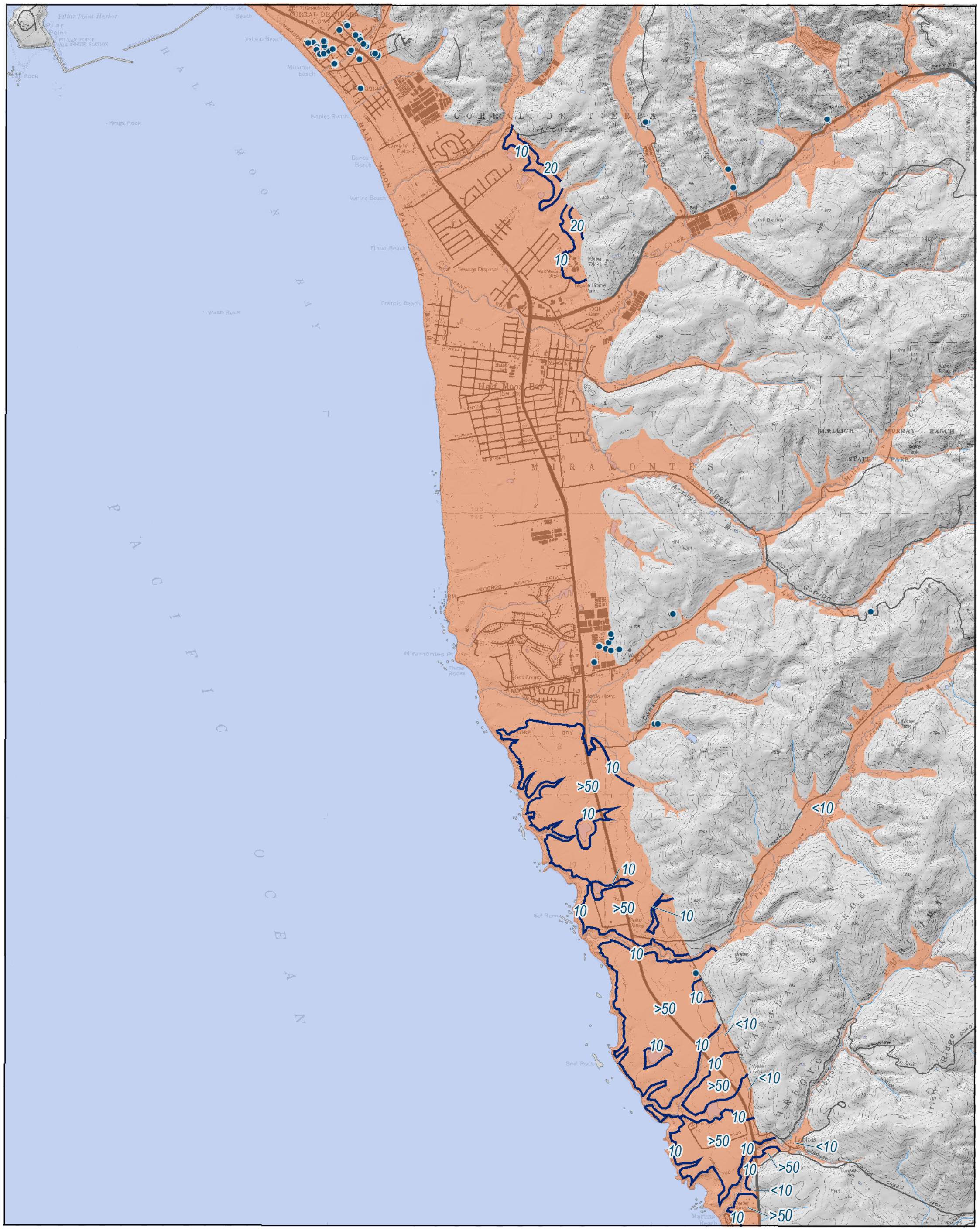
See "Geology" in Section 1 of report for descriptions of units.

● Shear test sample location

● GSI measurement location

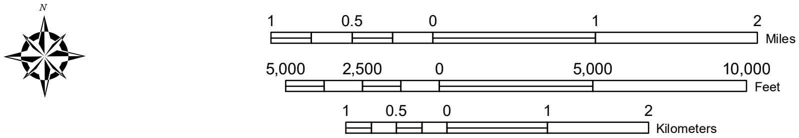
☁ Landslide

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, Half Moon Bay Quadrangle, San Mateo County, California.



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

HALF MOON BAY QUADRANGLE

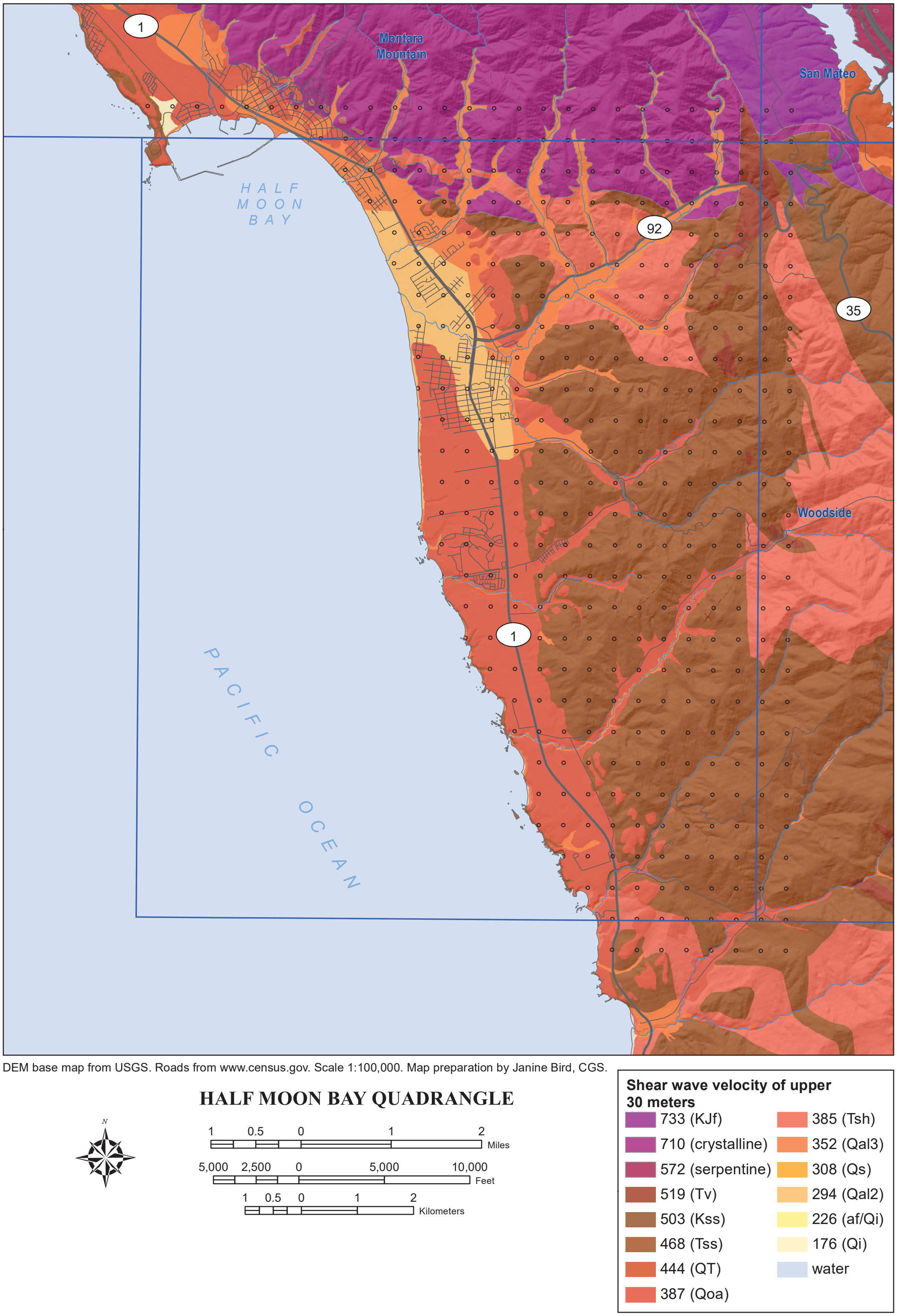


● Groundwater measurement location

—10— Depth to historic-high groundwater (in feet)

🟧 Groundwater basin limits

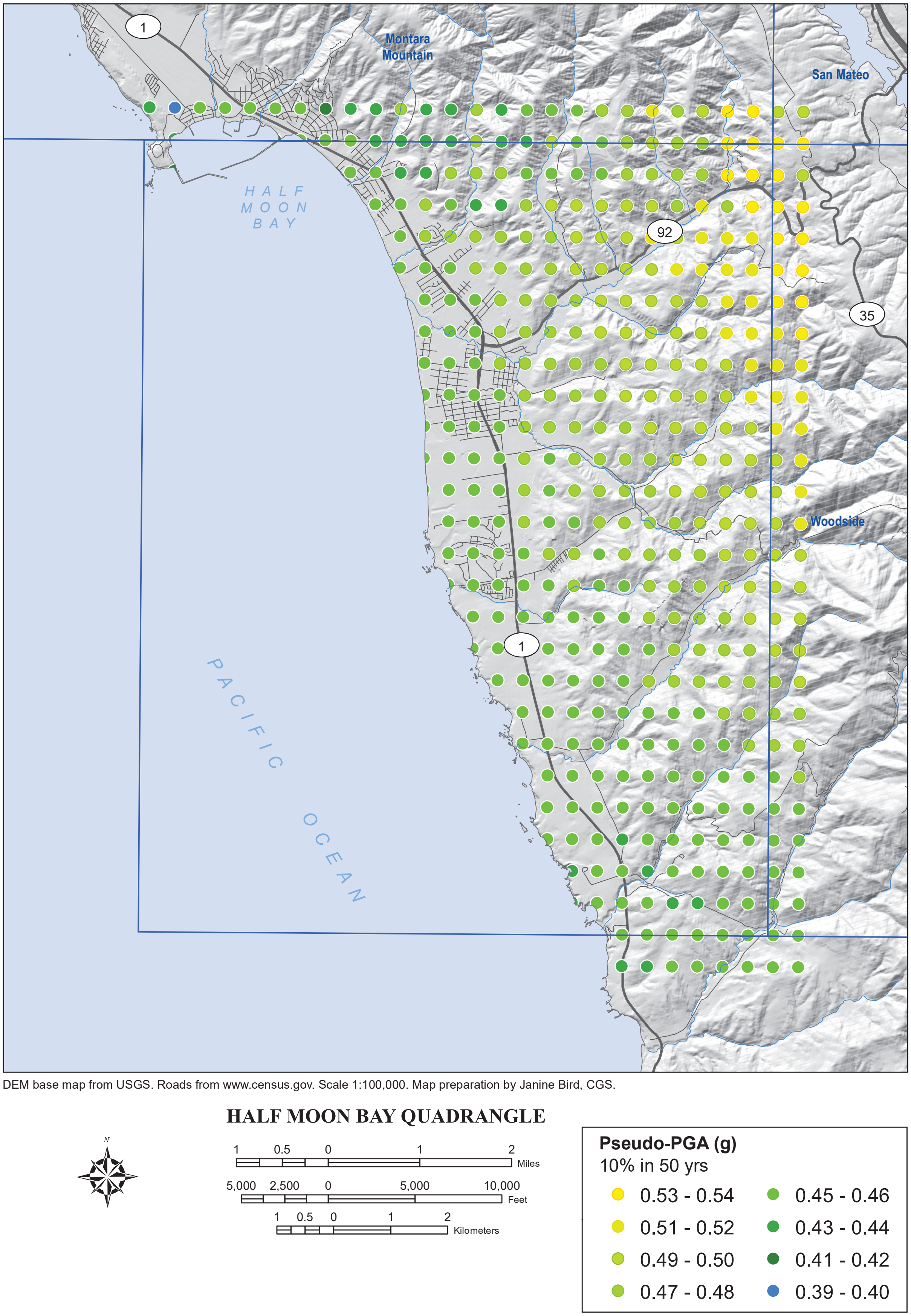
Plate 1.3 Groundwater basins, depth to historic-high groundwater levels, and groundwater data points, Half Moon Bay Quadrangle, San Mateo County, California. Abrupt changes in depth to groundwater occur adjacent to coastal bluffs in the southern portion of the quadrangle.



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

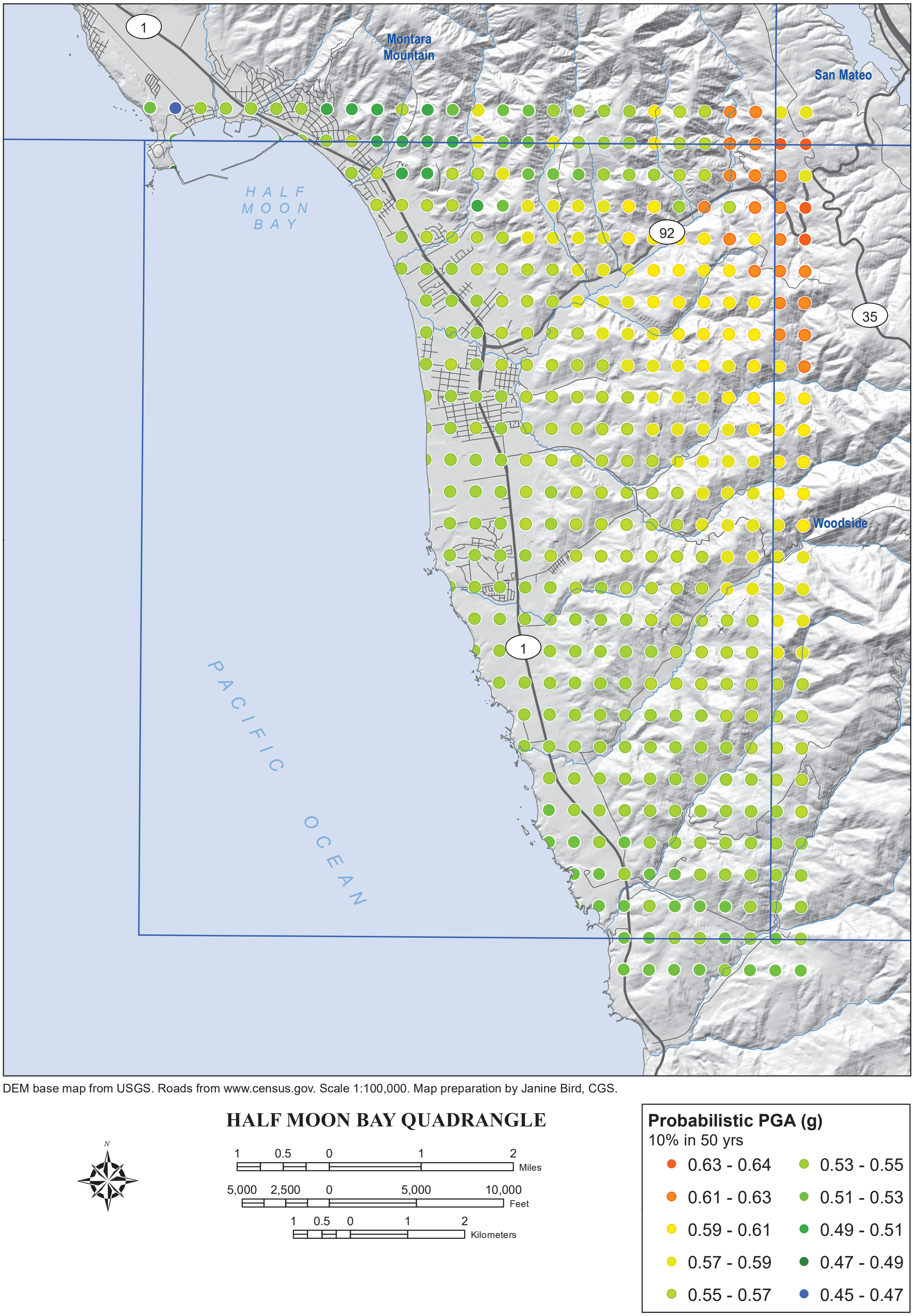
HALF MOON BAY QUADRANGLE

Plate 2.1 Map of V_{S30} groups and corresponding geologic units extracted from the state-wide V_{S30} map developed by Wills and others (2015), Half Moon Bay Quadrangle and surrounding area, California.



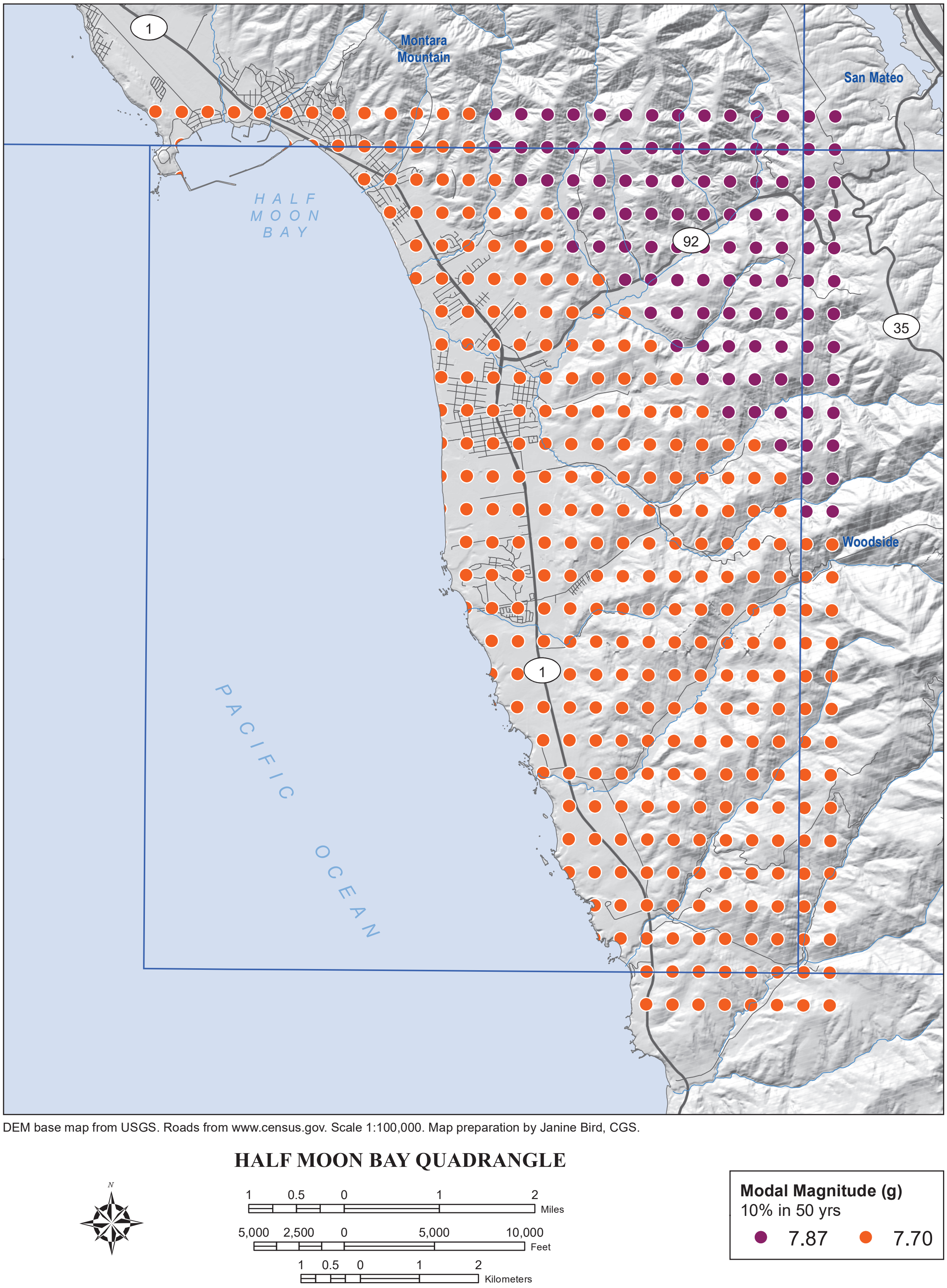
DEM base map from USGS. Roads from www.census.gov. Scale 1:100,000. Map preparation by Janine Bird, CGS.

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



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

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



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

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