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California Geological Survey Zones of Required Investigation for Liquefaction – Livermore Valley, California

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Abstract

Official Seismic Hazard Zone Maps of Dublin, Livermore, and Altamont 7.5-minute quadrangles (1:24,000 scale) show areas that may be susceptible to earthquake-induced liquefaction. The maps are the result of the three-dimensional integration of geotechnical and geological data. Approximately 450 geotechnical borehole logs were collected, analyzed, entered into a geotechnical Geographic Information System database, correlated with surficial geologic units, and evaluated for the susceptibility of deposits to liquefaction. In addition, a map showing depth to historically highest groundwater level was prepared. The continuous relocation over the years of temporary water-filled pits associated with gravel mining in central Livermore Valley has caused localized changes to permeability, resulting in variable groundwater conditions.

The boundary for the Zone of Required Investigation (ZORI) is in most places defined by the contact of Holocene deposits with late Pleistocene deposits or with bedrock, and extends along the base of the foothills surrounding the Livermore Valley. Near Hacienda Drive and Central Parkway, sediment mapped as late Pleistocene to Holocene alluvial fan deposits (Qf) is included in the ZORI. Although the age of the unit suggests that the sediment has had sufficient time to consolidate, thus rendering it unlikely to liquefy, subsurface data indicate the deposit includes a greater abundance of silt, and lower penetration resistance, compared to occurrences of Qf mapped in other portions of the western margin of the Livermore Valley. Near the intersection of Hopyard Road and Arroyo Mocho, an area once known as "Willow Swamp" is excluded from the ZORI. Groundwater is within 10 to 20 feet of the ground surface throughout much of this area; however, the area is underlain by Holocene basin sediments (Qhb) locally composed of approximately 32 percent clay. Although soft soil failures are possible in young clay sediments, liquefaction is unlikely.

Introduction

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

Localities most susceptible to liquefaction-induced damage are underlain by loose, water-saturated, granular sediment within 50 feet (ft) of the ground surface. These geological and groundwater conditions are widespread in the San Francisco Bay Area, most notably in some densely populated valley regions and alluviated floodplains. In addition, the potential for strong-earthquake ground shaking is high because of the many active faults in the region. The combination of these factors constitutes a significant seismic hazard for areas in the Livermore Valley.

This paper summarizes the methods and sources of information used to prepare the Seismic Hazard Zone Maps prepared in the vicinity of the Livermore Valley, including the Dublin, Livermore, and Altamont 7.5-minute quadrangles in Alameda County, California. For more detailed information regarding topics discussed in this paper, please see the official Evaluation Report for Liquefaction Hazard in these quadrangles (Rosinski, 2008a, b, c). The quadrangles cover a total of approximately 180 square miles in eastern Alameda and Contra Costa Counties at a scale of 1 inch = 2,000 ft and display the boundaries of preliminary *Zones of Required Investigation* for liquefaction. The areas subject to seismic hazard mapping include parts of the cities of Livermore, Pleasanton, and Dublin. A total of approximately 11 square miles in the Livermore and Altamont quadrangles falls within Contra Costa County, and was not included in this study.

About 19 square miles within the Alameda County part of the Livermore quadrangle, 10 square miles of land in the Dublin Quadrangle, and 9 square miles of the Altamont quadrangle are designated as *Zones of Required Investigation* for liquefaction hazard. These zones encompass about two-thirds of the Livermore Valley and most of the stream valleys and canyons that originate in the surrounding hills. Borehole logs of test holes in alluviated areas indicate the widespread presence of near-surface soil layers composed of saturated, loose sandy and silty sediments. Geotechnical tests conducted downhole and in soil labs indicate that these soils generally have a moderate to high likelihood of liquefying, given the levels of strong ground motion expected for this region.

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

Methodology

CGS's evaluation of liquefaction hazard and preparation of Seismic Hazard Zone Maps requires the collection, compilation, and analysis of various geotechnical information and map data. The data are processed into a series of GIS layers using commercially available software. The following principal tasks are completed to generate a Seismic Hazard Zone Map for liquefaction hazard:

- Compile digital geologic maps to delineate the spatial distribution of Quaternary sedimentary deposits
- Collect geotechnical borehole log data from public agencies and engineering geologic consultants
- Enter boring log data into the GIS
- Generate digital cross sections to evaluate the vertical and lateral extent of Quaternary deposits and their lithologic and engineering properties
- Evaluate and digitize historically highest groundwater levels in areas containing Quaternary deposits
- Characterize expected earthquake ground motion, also referred to as ground-shaking opportunity
- Perform quantitative analyses of geotechnical and ground motion data to assess the liquefaction potential of Quaternary deposits
- Synthesize, analyze, and interpret above data to create maps delineating *Zones of Required Investigation* according to criteria adopted by the State Mining and Geology Board (SMGB) (California Department of Conservation, 2004).

Geology

Geologic units that generally are susceptible to liquefaction are limited to late Quaternary alluvial sedimentary deposits and artificial fill. To evaluate the areal and vertical distribution of Quaternary deposits in the Dublin, Livermore, and Altamont quadrangles, recently completed geologic maps of the nine-county San Francisco Bay Area showing Quaternary deposits (J.M. Sowers, USGS, unpublished photo-interpretation map, 2006; Knudsen and others, 2000; Witter and others, 2006) and bedrock units (R.W. Graymer, USGS, unpublished digital database of geologic mapping of the Stockton 1:100,000-scale quadrangle, 2004; Wentworth and others, 1999; Graymer and others, 1996) were obtained from the U.S. Geological Survey in digital form. The GIS maps and layers covering the Dublin, Livermore, and Altamont quadrangles were combined, with minor modifications along the bedrock/Quaternary contact to form a single 1:24,000-scale *geologic materials map* for each quadrangle that displays map unit polygons only (no faults, fold axes, or point data). This map can be used later in compilation of a new geologic map of the area. The distribution of Quaternary deposits on these maps was used in combination with other data, discussed below, to evaluate liquefaction susceptibility and to develop the Seismic Hazard Zone Maps (fig. 1).

Air photos were used, and limited field reconnaissance was conducted, to confirm the location of geologic contacts, map recently modified ground surfaces, observe properties of near-surface deposits, and characterize the surface expression of individual geologic units. In addition, digital data, including Intermap Digital Terrain Model (DTM) at 5-meter resolution (2003) and Google Digital Globe Color Imagery at a 1-meter resolution (2006) were used extensively to validate minor modifications to bedrock/Quaternary contacts in the Livermore quadrangle.

Figure 1. Excerpt of the map showing Zones of Required Investigation for Liquefaction of the Dublin 7.5-minute quadrangle in the vicinity of the intersection of Hopyard Road and Arroyo Mocho.

Engineering Geology

Groundwater

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

During the course of this study, groundwater conditions were investigated for alluvial basins within the Dublin, Livermore, and Altamont quadrangles. The evaluation was based on first-encountered (shallowest), unconfined water noted in geotechnical borehole logs acquired from the cities of Dublin and Livermore, Alameda County, and the California Department of Transportation (CalTrans). Additional data were collected from the State Water Resources Control Board (SWRCB), and the Alameda County Flood Control and Water Conservation District Zone 7 Water Agency (Zone 7 Water Agency). Natural hydrologic processes and human activities can cause groundwater levels to fluctuate over time. Therefore, it is impossible to predict depths to saturated soils when future earthquakes strike. One method of addressing time-variable depth to saturated soils is to establish an anticipated high groundwater level based on historical groundwater data. Thus, in this study a contour map was developed to depict the highest level of groundwater anticipated within a land-use planning interval of 50 years (fig. 2). It is important to note that the contour lines on the map do not generally represent present-day conditions as usually presented on typical groundwater contour maps. Also, large-scale, artificial recharge programs, such as the ones already established in Livermore Valley, could significantly affect future groundwater levels. In such cases, CGS will periodically evaluate groundwater impact relative to liquefaction potential and revise official Seismic Hazard Zone Maps if necessary.

The Zone 7 Water Agency, which is responsible for managing both surface and groundwater supplies in the Livermore Valley basin, has been monitoring groundwater levels for over 30 years. Well data span the period from 1900 through 2005 and show significant fluctuation in overall water depth during that period. It is the practice of the Zone 7 Water Agency to use water levels measured in 1983-1984 as the historical maximum groundwater level for basin management purposes (Jones and Stokes Associates, Inc., 2006).

In this study, the groundwater elevation map prepared by Zone 7 Water Agency was digitized, and, by converting it and

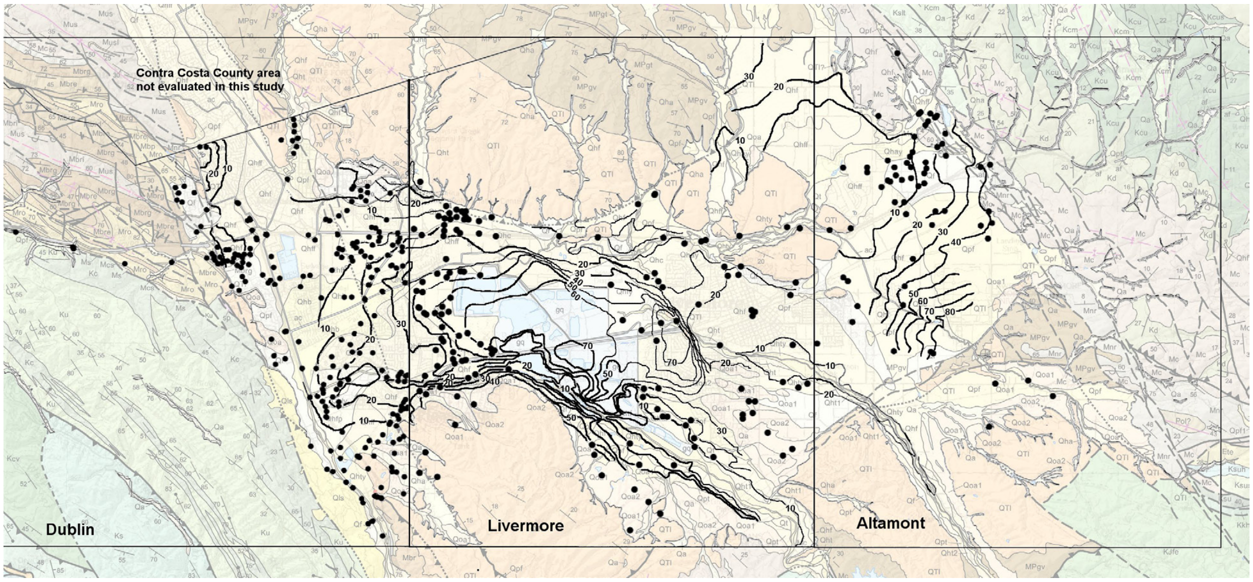

Figure 2. Locations of subsurface data and groundwater depth contours for the Dublin, Livermore, and Altamont quadrangles. Geologic base map from E.E. Brabb and others (USGS, unpub. map data, 2009), which includes revised mapping for Quaternary units in the Livermore Valley from seismic hazards zoning studies described here.

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

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

As defined by the Zone 7 Water Agency, historically highest groundwater depths in the Livermore Valley range from approximately 0 to 170 ft (fig. 2). Historically highest groundwater levels are generally deepest toward the center of the basin, ranging in depth between 40 and 90 ft and becoming progressively shallower toward the basin's boundaries. Measured depth to groundwater for many of the borings located in the foothills outside of the groundwater basin is greater than 60 ft.

Soil Testing

A total of 442 borehole logs were collected for this investigation from the files of Alameda County, CalTrans, the Division of the State Architect, and the cities of Livermore, Dublin, and Pleasanton (fig. 2). Data from these borehole logs were entered into a CGS geotechnical GIS database.

Lithologic descriptions and soil test results reported in geotechnical borehole logs provide valuable information regarding subsurface geology, groundwater levels, and the engineering characteristics of sedimentary deposits. Of particular value in liquefaction evaluations are logs that report the results of downhole standard penetration tests (SPT) in alluvial materials. The SPT provides a standardized measure of the penetration resistance of soil and, therefore, is commonly used as a tool to index soil density. For this reason, SPT results are also a critical component of the Seed-Idriss Simplified Procedure, a method used by CGS and the geotechnical community to quantitatively analyze liquefaction potential of sandy and silty material.

Of the 442 geotechnical borehole logs analyzed in this study, most include blow-count data from SPTs or penetration tests that allow reasonable blow count conversions to SPT-equivalent values. Few of the borehole logs collected, however, include all of the information (for example, soil density, moisture content, sieve analysis) required for an ideal analysis using the Seed-Idriss Simplified Procedure. For boreholes having acceptable penetration tests, liquefaction analysis is performed using recorded density, moisture, and sieve test values or averaged test values of similar materials.

Liquefaction Hazard Assessment

Mapping Techniques

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

Liquefaction Susceptibility

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

Grain-size characteristics of a soil also influence susceptibility to liquefaction. Sand is more susceptible than silt or gravel, although silt of low plasticity is liquefiable. Cohesive soils generally are not considered susceptible to liquefaction. Such soils may be vulnerable to strength loss with remolding and represent a hazard that is not specifically addressed in this investigation.

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

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

Ground Shaking Opportunity

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

Calculated LOP for alluviated areas in the Livermore Valley range from 0.33 to 0.57 g (standard gravity or acceleration due to free fall). These values were obtained by applying the NEHRP corrections (FEMA, 1994; Table 3.1) to the firm-rock LOP values derived from the CGS liquefaction application of the 2002 probabilistic ground motion model. In the Livermore and Altamont quadrangles, the calculations are based on an earthquake moment magnitude ranging from approximately 6.6 to 7.0 with a modal distance of 3 to 15 kilometers (km). In the Dublin quadrangle, the calculations are based on an earthquake moment magnitude of approximately 6.75 with a modal distance of 0 to 14.5 km.

Liquefaction Analysis

CGS performs quantitative analysis of geotechnical data to evaluate liquefaction potential using an in-house computer program based on the Seed-Idriss Simplified Procedure (Seed and Idriss, 1971; Seed and others, 1983; National Research Council, 1985; Seed and others, 1985; Seed and Harder, 1990; Youd and Idriss, 1997; Youd and others, 2001). The procedure first calculates the resistance to liquefaction of each soil layer penetrated at a test-drilling site, expressed in terms of cyclic resistance ratio (CRR). The calculations are based on SPT results, groundwater level, soil density, grain-size analysis, moisture content, soil type, and sample depth. The procedure then estimates the factor of safety relative to liquefaction hazard for each of the soil layers logged at the site by dividing their calculated CRR by the pseudo PGA-derived CSR described in the previous section.

CGS uses a factor of safety (FS) of 1.0 or less, where CSR equals or exceeds CRR, to indicate the presence of potentially liquefiable soil layers. The liquefaction analysis program calculates an FS for each geotechnical sample where blow counts were collected. Typically, multiple samples are collected for each borehole. The program then independently calculates an FS for each non-clay layer that includes at least one penetration test using the minimum normalized blow count [$N_{1(60)}$] value for that layer. The minimum FS value of the layers penetrated by the borehole is used to calculate the liquefaction potential for each borehole location. The reliability of FS values varies according to the quality of the geotechnical data. In addition to FS, consideration is given to the proximity to stream channels, which accounts in a general way for factors such as sloping ground or free face that contribute to severity of liquefaction-related ground deformation.

Liquefaction Zonation 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 (California Department of Conservation, 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; and (4) areas where existing subsurface data are not sufficient for quantitative evaluation of liquefaction hazard.

Within areas where sufficient subsurface data are not available, zones may be delineated by geologic criteria, primarily deposits likely to contain loose, granular materials that are saturated because of near-surface groundwater. Those conditions, along with the strong ground motions expected to occur in the region, combine to form a sufficient basis for designating areas underlain by these types of deposits *Zones of Required Investigation* for liquefaction. The criteria are considered as follows: (1) 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-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 ft; (2) areas containing soil deposits of Holocene age (less than 11,000 years), where the M7.5-weighted peak acceleration that has a 10-percent probability of being exceeded in 50 years is greater than or equal to 0.20 g and the anticipated depth to saturated soil is less than 30 ft; or (3) areas containing soil deposits of latest Pleistocene age (11,000 to 15,000 years), where the M7.5-weighted peak acceleration that has a 10-percent probability of being exceeded in 50 years is greater than or equal to 0.30 g and the anticipated depth to saturated soil is less than 20 ft.

Results: Delineation Of Liquefaction Hazard Zones

Upon completion of a liquefaction hazard evaluation for a project quadrangle, CGS applies the above criteria to its findings in order to delineate *Zones of Required Investigation*. Following is a description of the criteria-based factors that governed the construction of the Seismic Hazard Zone Maps for the Dublin, Livermore, and Altamont 7.5-minute quadrangles.

Areas of Past Liquefaction

There is no known documentation of historical surface liquefaction or paleoseismic liquefaction in the Livermore or Altamont quadrangles. In the Dublin quadrangle, Lawson and others (1908) reported one instance of historical liquefaction in association with the 1906 earthquake. The incident recorded occurred near the northeast corner of the intersection of Santa Rita Road and State Highway 580, along the east bank of Tassajara Creek. Lawson and others (1908) reported "…several somewhat crescentic cracks along which the ground had slipt down and toward the creek from 1 to 3 inches. These cracks extended farther south, according to local settlers, and crost the road" (Lawson and others (1908) cataloged and mapped by Youd and Hoose (1978) and Knudsen and others (2000)).

Areas with Sufficient Existing Geotechnical Data

Most of the subsurface data evaluated for this study represent boreholes drilled into the sediments at the surface of Livermore Valley. Collectively, the logs provide the level of subsurface information needed to conduct a regional assessment of liquefaction susceptibility with a reasonable level of certainty. Analysis of blow count values and other soil property measurements reported in the logs indicates that most of the boreholes penetrated one or more layers of liquefiable material whose CSR is greater than the soil's CRR. Accordingly, all areas covered by Holocene alluvium that is saturated within 40 ft of the surface are designated *Zones of Required Investigation*.

The majority of boundaries for the *Zones of Required Investigation* are defined by the contact between Holocene and late Pleistocene deposits and (or) bedrock, and extend along the base of the foothills that surround Livermore Valley. Although the groundwater conditions in the center of the

Livermore Valley have been complicated by gravel mining operations, groundwater elevations increase by tens of feet toward the center of the valley. Analysis of blow count values and other soil property measurements reported in the logs of borings drilled inside the zone boundary indicate that most of the boreholes penetrated one or more layers of liquefiable material having a CSR greater than the soil's CRR.

Along the northern margin of the valley within the Dublin quadrangle, in the vicinity of the intersection of Hacienda Drive and Central Parkway, sediment mapped as late Pleistocene to Holocene alluvial fan deposits (Qf) is included in the *Zones of Required Investigation*. Although the age of the unit suggests that the sediment has had sufficient time to consolidate, thus rendering it unlikely to liquefy, subsurface data indicate that the deposit in question includes a greater abundance of silt and lower penetration resistance compared to occurrences of Qf mapped in other portions of the Dublin quadrangle; it therefore is included in the *Zones of Required Investigation*.

Further, an area in the Dublin quadrangle near the intersection of Hopyard Road and Arroyo Mocho, which was once occupied by what was known as "Willow Swamp," is excluded from the *Zones of Required Investigation*. Although groundwater is within 10 to 20 ft of the ground surface throughout much of this area, it is underlain by Holocene basin sediments (Qhb) locally made up of approximately 32 percent clay. According to the geologic model of the Livermore basin developed by the California Department of Water Resources (DWR) in the early 1970's (California Department of Water Resources, 2003; 2007), "Up to 60 feet of clay was deposited in this lake [swamp] that now forms a clay cap referred to as the upper aquiclude." CGS analysis of borehole data in the vicinity of the lake shows that the shallowest liquefiable layers are overlain by a minimum of 35 ft of sediment and are less than approximately 5 ft thick. Therefore, even if these sediments were to liquefy, they likely would not produce surface deformation. An exception is a small Holocene basin deposit (Qhb) near the intersection of State Highway 680 and the Western Pacific Rail line, in the southeastern corner of the Dublin quadrangle. This area is included in the *Zones of Required Investigation* because the underlying sedimentary deposits contain a significantly smaller percentage of clay than Holocene basin deposits (Qhb) elsewhere in the Dublin quadrangle.

Areas with Insufficient Existing Geotechnical Data

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

Engineering Geology Characteristics of Livermore Valley Sediments

The Livermore Valley is divided among three quadrangle maps, but because it represents one geologic region, the liquefaction potential of soils in the Dublin, Livermore, and Altamont quadrangles was analyzed in one basin-wide investigation. Tables 1 and 2 summarize the frequency of soil sampling and the number of layers with a minimum $N_{1(60)}$ value less than 15 basin-wide for all textures and for liquefiable textures only, respectively. This range of $N_{1(60)}$ values represents an important input parameter for empirical models for predicting lateral spread displacements, a variety of liquefaction-induced ground failure. Soil sampling data from more than 440 boring logs collected for this investigation show that Holocene sediment in the Livermore Valley is composed primarily of clays and silts with interbedded layers of loose sands and gravels. Locally however, the general composition of the same geologic units mapped within each quadrangle may differ from average basin-wide composition for the same unit. For example, of the samples collected in the Livermore quadrangle for modern stream channel (Qhc), Holocene alluvial fan (Qhf), Holocene stream terrace (Qht), and late Pleistocene alluvial, undifferentiated (Qpf) deposits, they appear to be somewhat less clay rich than the basin-wide average. On the other hand, of the samples collected for latest Holocene alluvial fan (Qhfy), Holocene alluvial fan (Qhf), Holocene stream terrace (Qht), and late Pleistocene to Holocene alluvial fan (Qf) deposits, they appear to be somewhat more silt rich than the basin-wide average. It should be noted that the apparent change in the relative abundance of the various lithologic materials might simply reflect an increase or decrease in the frequency that the material was sampled, rather than a change in the actual abundance of the material.

Table 1. Summary of borehole data for all textures of sediments in the Livermore Valley.

Stratigraphic Age of Layer	Thickness (feet)		Thickness of Saturated Layers (feet)		Number of Layers		Number of Layers with a Penetration Test		Number of Layers with a Minimum $N_{1(60)} < 15$	
All	13457	100.0%	6570	48.8%	2170	100%	1551	100.0%	690	44.5%
Historical	1199	8.9%	272	2.0%	233	10.7%	141	9.1%	56	3.6%
Latest Holocene	752	5.6%	351	2.6%	132	6.2%	94	6.1%	69	4.4%
Holocene	6572	48.8%	3553	26.4%	965	44.4%	706	45.5%	422	27.2%
Latest Pleistocene to Holocene	2514	18.7%	1363	10.1%	489	22.5%	362	23.3%	113	7.3%
Latest Pleistocene	1159	8.6%	607	4.5%	169	7.9%	119	7.7%	20	1.3%
Early to Late Pleistocene	578	4.3%	64	0.5%	100	4.7%	65	4.2%	8	0.5%
Pre-Quaternary	683	5.1%	359	2.7%	82	3.8%	64	4.1%	2	0.1%

Table 2. Summary of borehole data for liquefiable textures only for sediments in the Livermore Valley.

	LIQUEFIABLE TEXTURES ONLY									
Stratigraphic Age of Layer	Thickness of Liquefiable Textures (feet)		Thickness of Saturated Liquefiable Textures (feet)		Number of Layers with Liquefiable Textures		Number of Layers with a Penetration Test		Number of Layers with a Minimum $N_{1(60)} < 15$	
All	6824	50.7%	2922	21.7%	1230	56.4%	853	55.0%	364	23.5%
Historical	1049	7.8%	192	1.4%	200	9.2%	129	8.3%	52	3.4%
Latest Holocene	432	3.2%	160	1.2%	81	3.7%	58	3.7%	48	3.1%
Holocene	2735	20.3%	1272	9.5%	469	21.5%	326	21.0%	192	12.4%
Latest Pleistocene to Holocene	1173	8.7%	651	4.8%	268	12.3%	197	12.7%	56	3.6%
Latest Pleistocene	693	5.2%	404	3.0%	103	4.7%	69	4.4%	9	0.6%
Early to Late Pleistocene	338	2.5%	27	0.2%	62	2.8%	38	2.5%	5	0.3%
Pre-Quaternary	405	3.0%	216	1.6%	47	2.2%	36	2.3%	2	0.1%

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