Seismic Vulnerability Assessment

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3 Seismic Vulnerability Assessment

3.1 Introduction

The project area is in an area of high seismic vulnerability, so all of the transportation assets are at risk from ground shaking and liquefaction of unconsolidated soils. In a sea level rise (SLR) scenario, rising groundwater levels could lead to an increased likelihood of liquefaction and lateral spreading, magnifying the impact of an earthquake. Through a review of the available geographic information system (GIS) information from the California Department of Conservation, U.S. Geological Survey (USGS), and Association of Bay Area Governments (ABAG), this chapter qualitatively analyzes the impact of high seismic vulnerability and how this, coupled with rising seas, might affect the resilience of existing shoreline protection systems and selected transportation assets. As part of the process, the project team met with ABAG and USGS to discuss what issues should be covered and to collect data and GIS resources. Current seismic hazards are reviewed in Section 3.2, and seismic vulnerability from direct inundation and indirect groundwater rise is described in Section 3.3. This process is described in Figure 3.1 below:

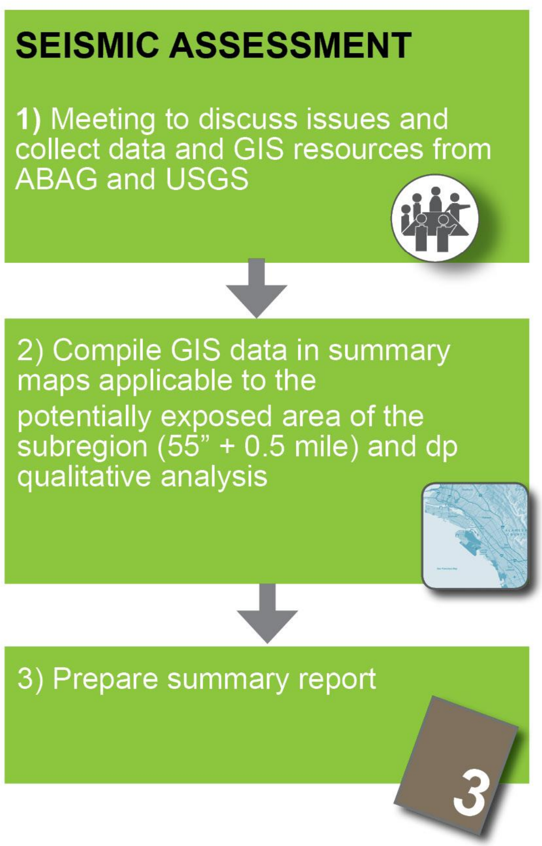

Figure 3.1 Seismic Vulnerability Assessment Process

3.2 Current Geotechnical/Seismic Hazard Conditions

This section qualitatively evaluates the seismic vulnerability of the identified transportation and shoreline assets relative to potential SLR. In order to address seismic vulnerability and assess potential risk to the transportation and shoreline assets, the current primary geotechnical and seismic hazard conditions in the project area are summarized below.

3.2.1 SOFT/WEAK SOILS/FILL

In comparing the historical baylands and modern baylands maps (Figure 3.2 and Figure 3.3), along with other documented San Francisco Bay fill maps (Hitchcock et al. 2008), and overlaying the maximum (55-inch) inundation area, it is evident that a majority of the project area has zones of bay fill that was placed at various times over the past century and a half. Importantly, a majority of this bay filling occurred prior to the 1960s, before much stricter controls and engineering criteria were imposed on subsequent bay filling. Also note that some of the easternmost fringes of the maximum (55-inch) inundation area extend beyond documented fill areas, particularly in the Union City area in southern Alameda County.

Since the mid-1800s, hundreds of millions of cubic yards of fill materials have been placed into San Francisco Bay to reclaim marshland, tidal land, and submerged land. Urbanization was allowed to extend into the bay through the incremental placement of artificial fill on bay mud and natural drainage channel deposits. The predominant native marine deposits beneath the bay fills include the younger bay mud overlying the older bay mud. The history of bay filling is complex from the standpoint of variation in material type and placement methods. A recent report on mapping of artificial fills in the bay indicates that methods of fill placement and types of materials used over the past century directly correlate with the progressive bayward growth of the bay shoreline (Hitchcock et al. 2008). The mapping report indicates that the historical progression of fill evolved from dumping sand from the bay, to hydraulic filling using sand from the bay to modern engineered fill construction. Sources of fill used included local soil and quarry rock during early reclamation, building debris dumped after the 1906 earthquake, and dredged sand during construction of much of Treasure Island and Alameda.

In general, what underlies bay fills is predominantly relatively weak clay materials that increase in strength with depth and degree of consolidation. The majority of bay fills, being placed prior to the 1960s, had little engineering and controls. In many instances, the limited, more recently engineered fills with improved construction standards overlie the older, less controlled fill. Therefore, with the exception of specific improved sites or locations with only recent filling, prevalent unconsolidated, poorly controlled fills overlying soft native soil materials create generally weak soil conditions in the bay fringe areas of the project area. Engineering and construction of transportation and other facilities in these areas have to compensate for these often less than desirable foundation conditions.

3.2.2 GROUND SHAKING POTENTIAL

The shaking severity levels map, Figure 3.4, shows that a majority of the SLR area is identified with a violent shaking severity rating. The only exceptions are a few small locations at the most inland portion of Union City in southern Alameda County, which are out of the bay fill area. These areas are mapped with a strong shaking severity rating. Locations generally expected to experience the greatest severity of earthquake shaking are those with thick soil deposits and fill (including, in particular, weak bay mud

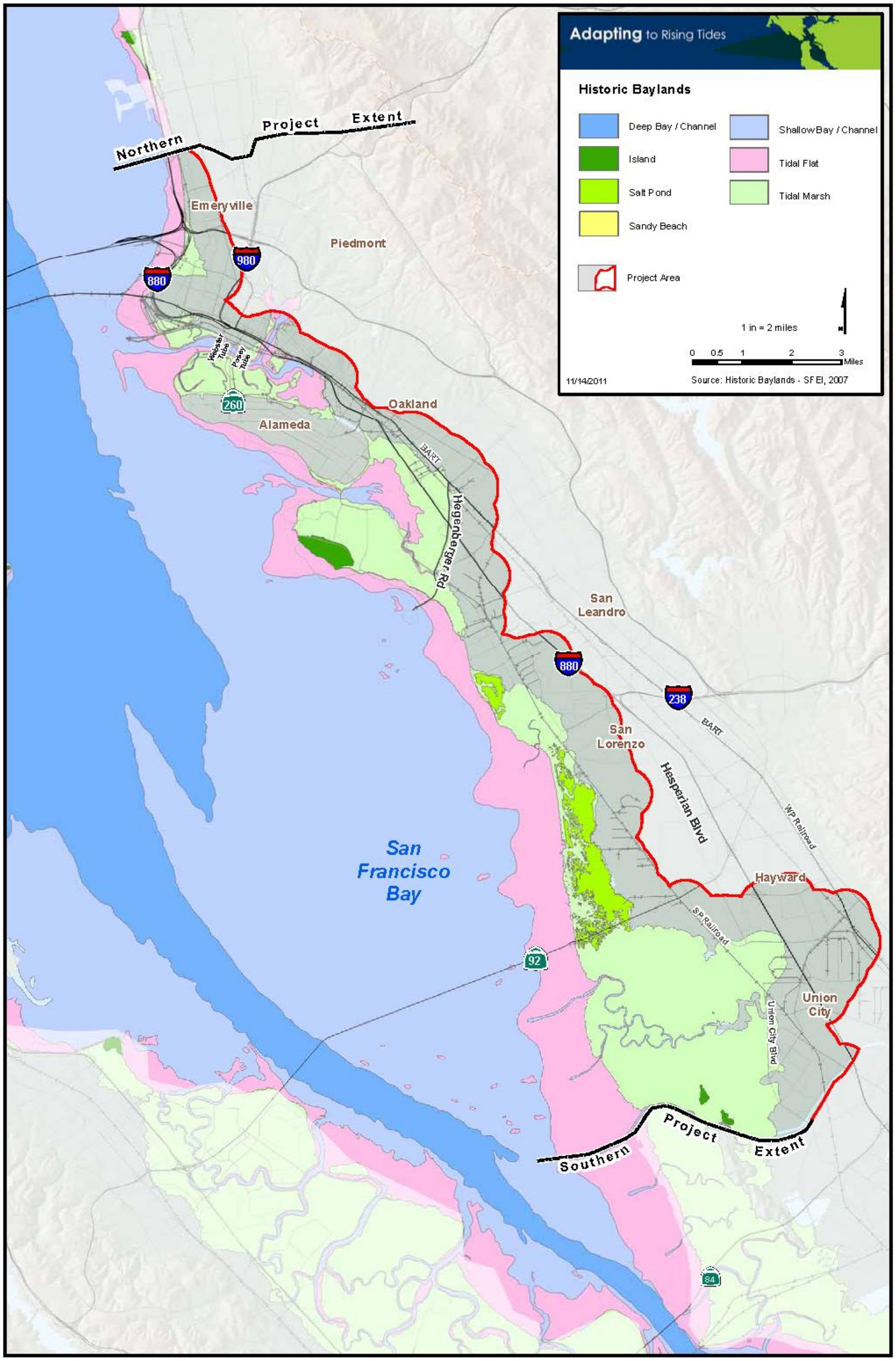

Figure 3.2 Historical Baylands

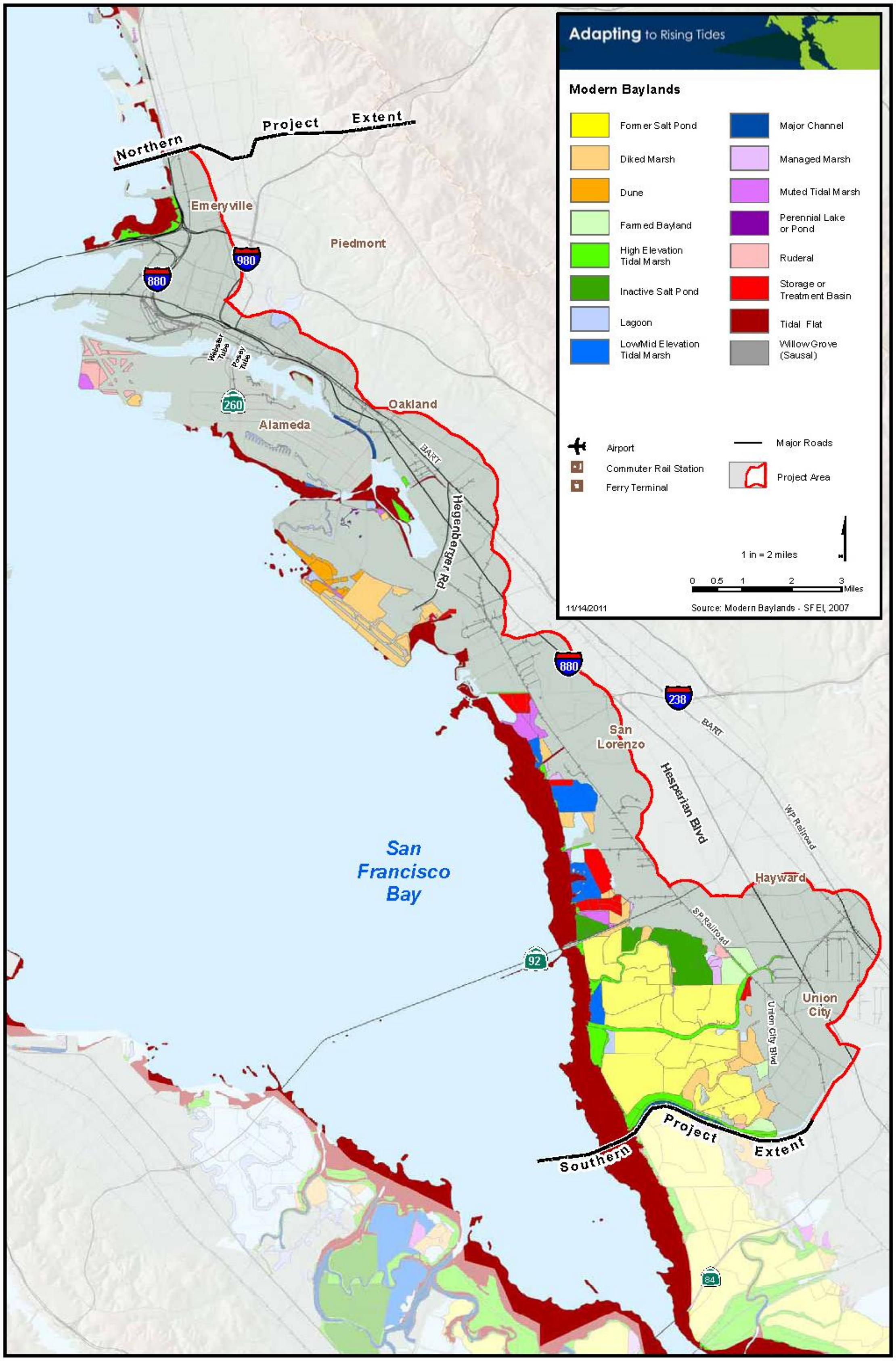

Figure 3.3 Modern Baylands

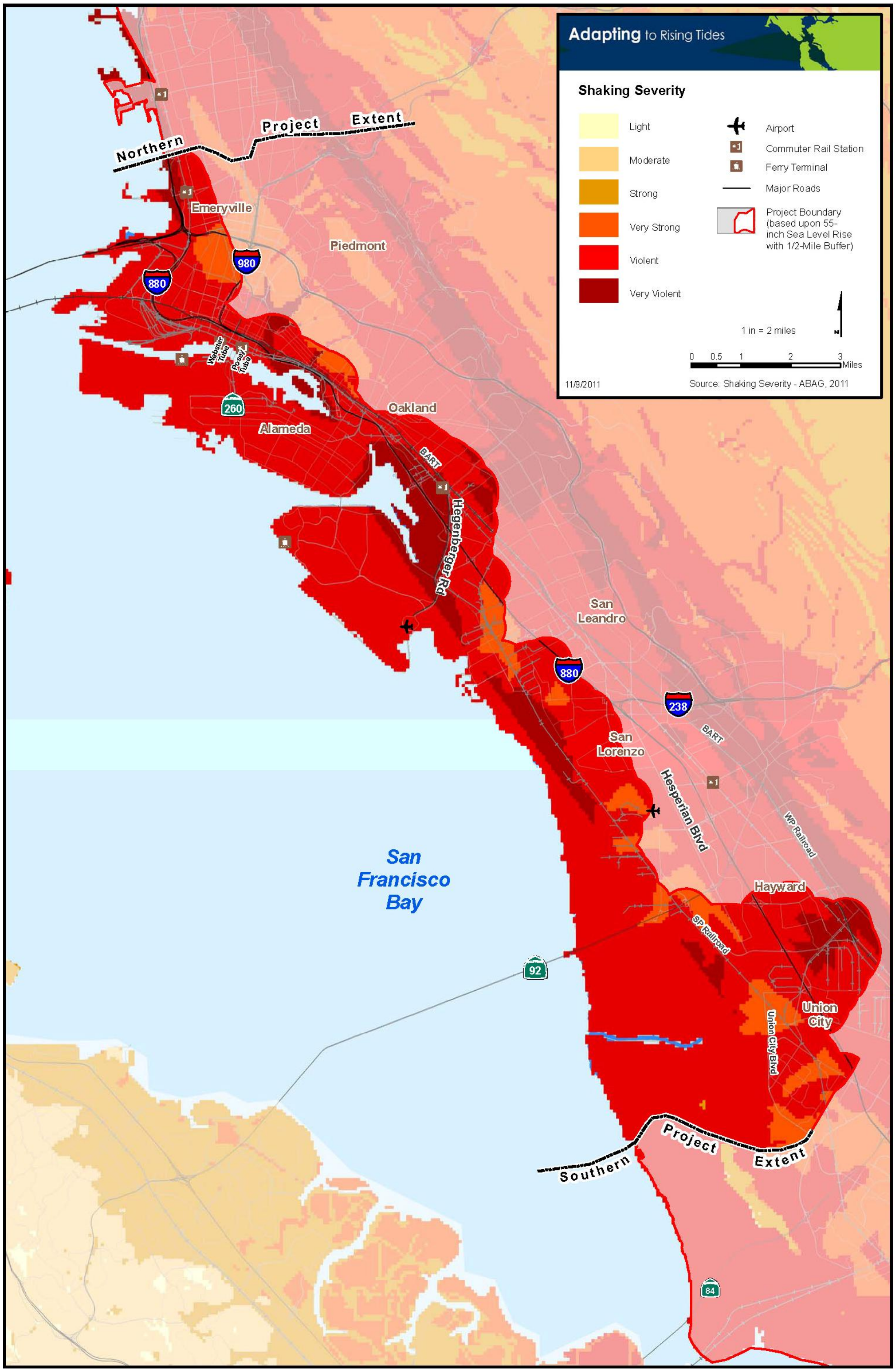

Figure 3.4 Shaking Severity

materials), which can amplify ground shaking to the surface. Structures less compatible with these ground motions require compensation in their engineering and construction.

However, of primary importance to this study is any amplification of seismic vulnerability caused by SLR. This may occur in the form of increased local ground motion at locations that see an increase in liquefaction potential due to rising ground water as a result of SLR. However, it is assumed to be most prevalent in regards to the direct effect of liquefaction and associated lateral spreading. The potential adverse effects of lateral spreading on transportation structures will be further discussed in section 3.3 Seismic Vulnerability From SLR Direct Inundation And Indirect Groundwater Rise.

3.2.3 LIQUEFACTION POTENTIAL

The liquefaction susceptibility map, Figure 3.5, shows that the northern portion of the project area is identified with a very high liquefaction susceptibility rating. In particular, the Emeryville, Oakland, and Alameda waterfront and Oakland International Airport fill areas are believed to have sandy fills with greater susceptibility to liquefaction. To the south, most of the project area in San Leandro, Hayward, and Union City is identified with a moderate liquefaction susceptibility rating.

Soil liquefaction usually has the greatest potential in clean, loose, saturated, uniformly graded silt and fine sand deposits. Liquefaction susceptibility increases as a function of less fine material content in sand/gravel materials, lower density, and greater degree of saturation. The liquefaction phenomenon occurs when the susceptible soils lose their strength with seismic shaking and increased pore water pressure during an earthquake. Coarser, gravelly soils and finer, more cohesive soils, particularly silts and silty clays, can also be vulnerable to liquefaction.

The large, sandy waterfront fills in Emeryville, Oakland, and Alameda were mostly placed after 1906 (Holzer et al. 2006) and were therefore not subjected to shaking from the 1906 earthquake. A lack of awareness of liquefaction as a seismic hazard resulted in these fills typically being placed in a manner similar to that used for many of the pre-1906 fills in San Francisco. Therefore, in general, they can be expected to perform poorly when shaken strongly by future large earthquakes on the major Bay Area faults (Holzer et al. 2006). Although ground shaking from the Loma Prieta earthquake was modest in areas underlain by East Bay fills, liquefaction was widespread with significant damage, including at the Port of Oakland, Oakland International Airport, San Francisco-Oakland Bay Bridge toll plaza, Alameda Naval Air Station, and Bay Farm Island (Holzer et al. 2006). When it comes to development of a specific site for construction of transportation-related or other types of facilities and structures, site-specific investigations will be conducted to establish liquefaction susceptibility and identify associated site improvements needed or the need for a more detailed investigation of liquefaction potential that must accompany the engineering and construction of the project.

3.2.4 GROUNDWATER

Groundwater and soil saturation play a significant role in seismic vulnerability due to their role in establishing conditions that lead to liquefaction caused by earthquake shaking. Relatively high groundwater levels exist in the relatively flat terrain along the bay margins and within the SLR area. This condition in itself presents special circumstances that must be compensated for in the engineering and construction of certain structures. A recent USGS study of the hydrogeology of aquifers beneath the San Leandro and San Lorenzo areas in the central portion of the project area shows groundwater essentially at sea level close to the bay and rising inland, toward the east (Izbicki et al. 2003). The study also acknowledges that groundwater levels near the bay also respond to tidal fluctuation, with associated pressure changes (Izbicki et al. 2003). For the scenario of end of century SLR considered by the pilot

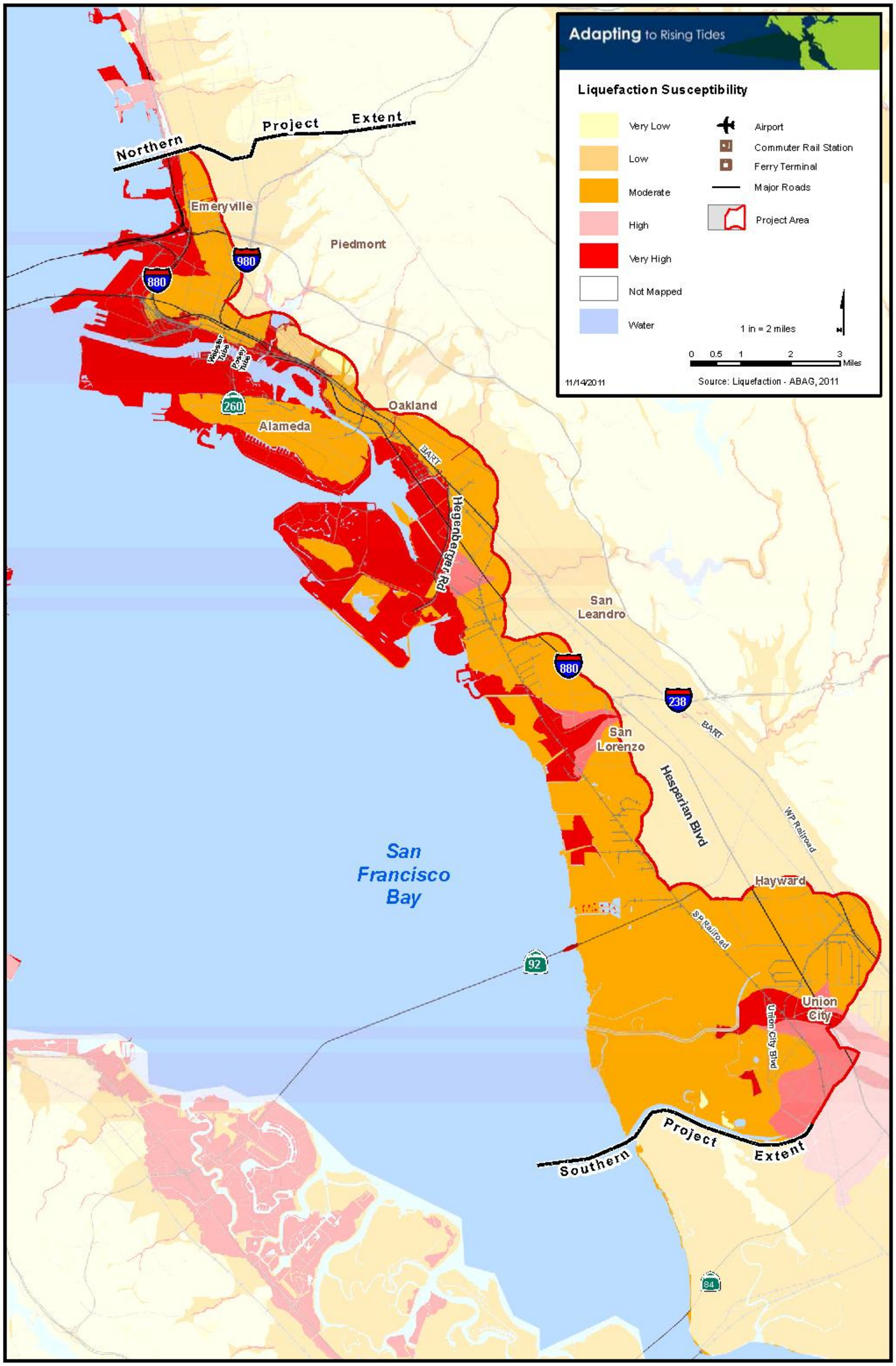

Figure 3.5 Liquefaction Susceptibility

project, it would seem that already high groundwater levels near the bay would rise over the long term essentially in line with the magnitude of the SLR expected.

3.3 Seismic Vulnerability from SLR Direct Inundation and Indirect Groundwater Rise

For the transportation assets being evaluated, the obvious direct effect of rising sea level is inundation. The primary indirect effect on seismic vulnerability of the transportation assets is considered to be the groundwater-level rise associated with the direct effect from increased tidal levels with SLR.

In general, bridges in California built after 1972, following the 1971 Sylmar (LA area) earthquake, were designed to a more modern code, which better addressed the actual seismic demands and detailing requirements. Incremental advancements in seismic design and detailing, especially following the 1987 Whittier Narrows, 1989 Loma Prieta and 1994 Northridge earthquakes, have continued to this day. Beginning in the early 1990s, Caltrans began a more aggressive (phase 2) seismic retrofit program to strengthen vulnerable bridges. Cities, Counties and other agencies also began retrofitting their bridges. The intent of these retrofits is to increase the seismic performance of a bridge to meet a “no collapse” criteria (major damage is acceptable provided the bridge will not collapse). A majority of the road assets in this study were built before the modern codes.

However, of primary importance to this study is any amplification of seismic vulnerability caused by SLR, which is assumed to be most prevalent in regards to liquefaction and associated lateral spreading (tendency of soil layers above liquefiable layers to “flow” downhill). This is particularly pertinent in zones where soils underlying a transportation facility that are in the classification of liquefiable soils but are currently above the water table, become saturated due to the rising ground water associated with SLR.

Although it was standard practice to evaluate the potential for liquefaction during the Phase 2 seismic retrofit program, lateral spreading was typically not accounted for. Caltrans now requires that new transportation structures consider the potential for this effect. Therefore, this study area contains many structures that are currently vulnerable and SLR will result in additional structures becoming vulnerable.

Liquefaction-induced lateral spreading is usually considered to occur just following a seismic event. Once the ground shaking from the earthquake has caused the underlying layer to liquefy, the overlying “crust” loses its resistance to moving down slope. This moving soil can result in tremendous pressure on bridge foundations causing them to fail or displacing them to the point that the bridge deck could collapse.

The above discussion has focused on bridges; however, the study area includes miles of raised roadway on embankment fills. Such embankment fills are even more susceptible to lateral spreading when the overlying soil can spread in two directions. Although, failure of an embankment will not result in as catastrophic damage and potential for loss of life as a bridge failure, such failures can be costly to repair. More importantly, such failure could result in the loss of a critical evacuation/emergency route following the earthquake. Figures 3.6 and 3.7 illustrate the effects of lateral spreading

3.3.1 INCREMENTAL SEISMIC IMPACT/FAILURE RISK TO SHORELINE ASSETS FROM SLR

In the event of SLR, it is obvious that shoreline protection systems, either existing or new, would be required to mitigate the effects of inundation. The inundation maps in Chapter 6 show that the shoreline assets would protect the transportation assets to a certain level under the midcentury and end-of-century SLR scenarios. This protection is provided by a range of shoreline assets, shown in Chapter 2, from

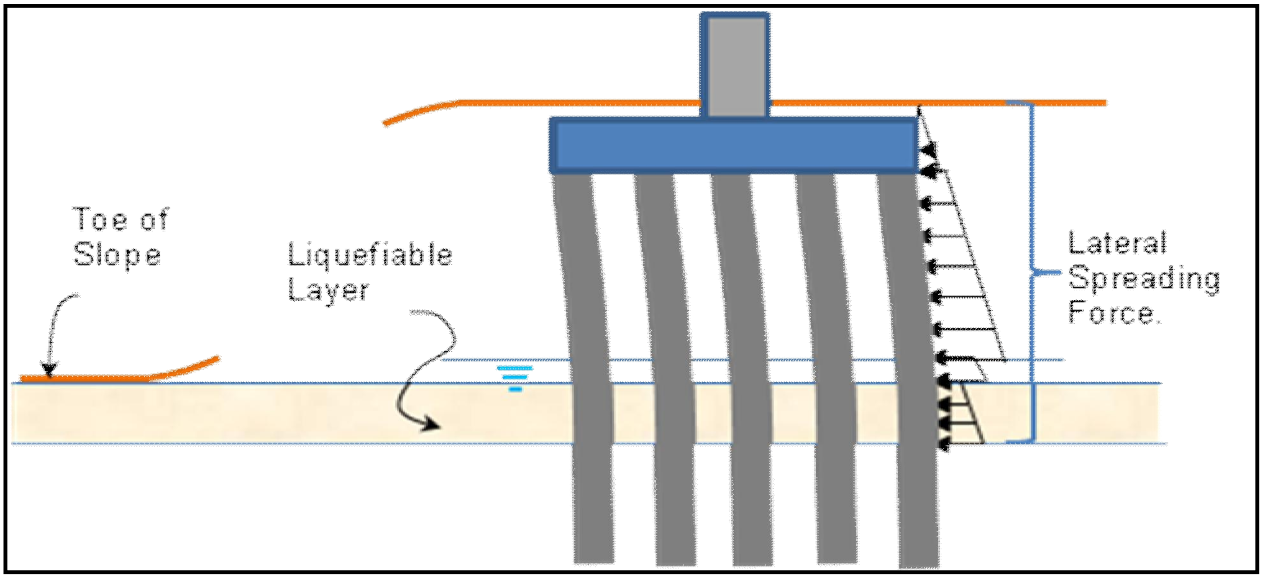

Figure 3.6 Force on Foundation Due to Lateral Spreading

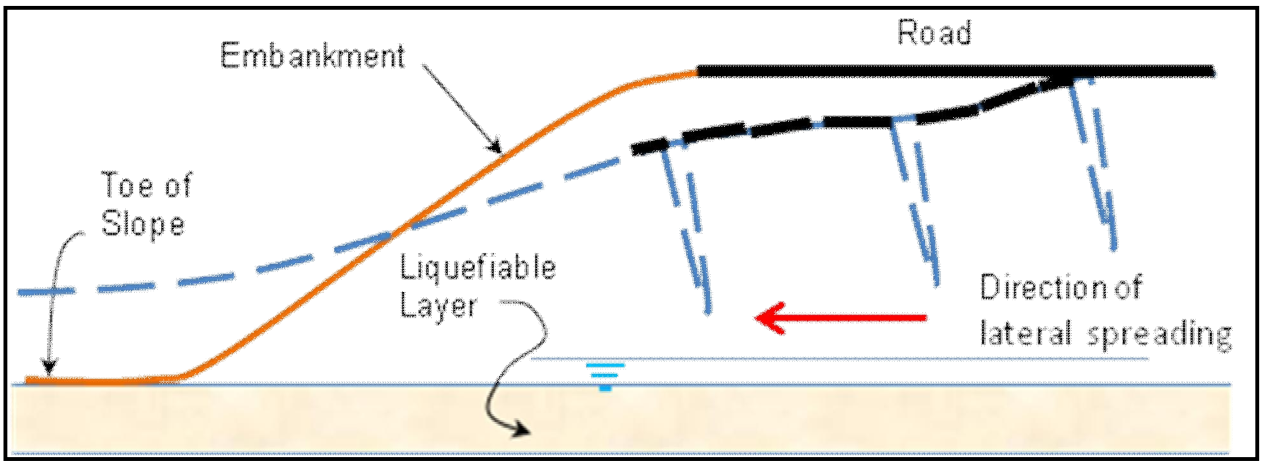

Figure 3.7 Slope Failure Due to Lateral Spreading

engineered structures, such as levees, flood walls, and revetments, to natural beaches and wetlands. However, regardless of the existing type and location of shoreline protection, the inundation mapping for the maximum 55 inches scenario with the most severe flood and wave conditions considered, indicates that nearly all the shoreline assets would be inundated or submerged.

It is assumed that any new shoreline protection installed to protect against SLR and inundation would be engineered and constructed to current standards and minimum regulatory requirements and thus would likely adequately protect against failure and resulting inundation as a result of a seismic event. However, any new loading or adverse conditions imposed, such as from SLR, would at a minimum reduce the level of protection or safety factor against failure, up to creating a failure condition. These more marginal situations under seismic conditions for shoreline protection, specifically resulting from SLR, are presented below:

- **Reduced stability** for levees, dikes, walls, and other water retention structures would be one of the most direct effects of SLR on these engineered shoreline assets. Increased water level loading against the structure reduces the level of stability by a combination of increased driving force of the higher water pressure and possible decreased resisting force with increased buoyancy of the restraining mass. Without a counteracting enhancement of the shoreline protection structure cross section for increased stability, the incremental increased tidal loading from SLR would correspondingly reduce the structure safety factor for static and seismic stability.

- **Increased liquefaction potential** would be expected in cases where shoreline assets rest on or contain potentially liquefiable materials that, with SLR, would be subjected to an increased degree of saturation and higher pore pressures or would be introduced to groundwater and saturation. This would result in previously nonliquefiable materials becoming susceptible to the phenomenon. The result of increased liquefaction potential, as described above, would be reduced stability, with loss of material strength in the susceptible materials due to seismic shaking.
- **Increased lateral spreading potential** would be expected in cases where shoreline assets with geometry that allows lateral translation, which would already be subject to compromise due to liquefaction during earthquakes, would be subject to increased lateral forces associated with higher retained water levels. This would apply to, for example, levees, bulkheads, revetments, and other shoreline protection features with slopes or retaining walls. Lateral spreading is one of several types of ground deformation, others including seismic settlement and bearing capacity failure, that can result from liquefaction and associated material strength loss. With the added adverse forces from SLR on shoreline assets, they would be more vulnerable to damage from lateral spreading as liquefaction will have already led to instability and ground deformation.

3.3.2 INCREMENTAL SEISMIC IMPACT/FAILURE RISK TO TRANSPORTATION ASSETS FROM SLR

Aside from the obvious unacceptable effect on transportation assets from inundation, the seismic vulnerability of and potential failure risk to transportation assets associated with SLR-caused groundwater-level increase revolves around liquefaction potential and the associated resultant adverse conditions it creates. As discussed earlier, the bay margins within the SLR area, which contain the materials most susceptible to liquefaction, often have the shallowest groundwater conditions.

The transportation assets being evaluated that fall within both the SLR area and the high to very high liquefaction susceptibility mapped areas would generally be considered the most vulnerable to increased seismic impact associated with the indirect groundwater rise effect. Thus, most vulnerable would be structures in the SLR areas of the Emeryville, Oakland, and Alameda waterfront and Oakland International Airport fill areas. Less vulnerable are assets in the southern Alameda County SLR areas. The liquefaction-oriented conditions resulting from seismic events, exacerbated by higher groundwater levels, specifically resulting from SLR, are discussed below:

- **Increased liquefaction potential** under the indirect SLR effect of groundwater-level rise would be expected where additional and shallower zones of liquefaction-susceptible materials would be subjected to saturation. A recent liquefaction potential study for various types of surficial geologic units, including alluvial fan deposits in the San Francisco Bay region and sandy artificial fills along the Oakland waterfront, acknowledges that the severity of liquefaction is considered proportional to a number of factors, including cumulative thickness of liquefied layers and proximity of liquefied layers to the ground surface (Holzer et al. 2011). The study developed liquefaction probability curves for the various types of surficial geologic units considered, as a function of earthquake magnitude and peak ground acceleration. It also developed these curves for different water table depths to demonstrate the effect of depth to groundwater. For the alluvial fan and sandy artificial fill cases directly applicable to the SLR study area, the curves generally represent an increase in liquefaction probability on the order of 1.5–3 times higher, for a water table depth at about 5 feet, compared to a water table condition at a depth of about 15 feet (Holzer et al. 2011). Therefore, based on this study, the incremental increased adverse effect of liquefaction due to groundwater-level rise appears quite significant.

- **Increased lateral spreading potential** would be expected to go hand in hand with the increased liquefaction potential from the indirect groundwater-level rise effect in situations where lack of confinement or sloping geometry would allow lateral translation upon liquefaction and strength loss. The increased lateral forces imposed on various types of transportation asset and their foundations can be significant, and the incremental increased forces imposed by the additional indirect groundwater-level rise effect exacerbating the lateral spreading potential could very likely exceed the original structural design loading limitations.

3.4 Recommended Refinements to the FHWA Conceptual Model

A seismic vulnerability assessment is not part of the conceptual FHWA risk assessment model given that it is very specific to bay area geology. Therefore the lessons learnt and recommendations identified below are not specific to the model per se, but may be of use for other projects also in an area of high seismic vulnerability.

3.4.1 LESSONS LEARNED

DATA COLLECTION

Compared to the detailed work establishing the transportation and shoreline assets and mapping the various SLR and other conditions, the scope of the seismic vulnerability assessment was very limited and qualitative in nature. The scope did not include identifying the seismic vulnerability of various specific categories and types of transportation and shoreline assets. The assessment was quite broad and generalized, which seemed somewhat inconsistent with the level of detail for the rest of the assessment work.

DATA AVAILABILITY

Some additional background data for existing groundwater levels in the study area would have been helpful to address the indirect effect on seismic vulnerability associated with anticipated groundwater-level rise with SLR.

3.4.2 RECOMMENDATIONS FOR FUTURE APPLICATIONS

For a more focused and effective evaluation, it would be a more streamlined process to assess the seismic vulnerability once the initial asset identification and mapping had been completed.

3.5 References

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