3.9 GEOLOGY AND SOILS

NSTI is located in the seismically active San Francisco Bay Area, which is characterized by numerous active faults and historic earthquakes. The following description includes regional, vicinity, and underlying geologic features at NSTI. The principal geologic features and formations at NSTI are discussed in this section in the context of the regional geologic setting.

3.9.1 Regional Geology and Seismicity

NSTI is located within the Coast Ranges Geomorphic Province. Landforms within the region are influenced by geologically young processes, such as active uplift of mountains, rapid erosion of streams, active transform faulting within the San Andreas Fault system, and large fluctuations in sea level brought on by Pleistocene (Ice Age) glaciation.

Treasure Island was constructed in 1936 and 1937 with engineered fill placed on a sandy shoal, located immediately north of Yerba Buena Island. Treasure Island is nearly flat, with interior elevations ranging from about 3.7 to 11.7 feet (1.1 to 3.6 meters [m]) NGVD and with a perimeter dike as high as approximately 13.2 feet (4 m) NGVD. (NGVD is the National Geodetic Vertical Datum of 1929, which is the elevation datum used on U.S. Geological Survey topographic maps.)

Yerba Buena Island is a peak in the bedrock surface that underlies San Francisco Bay. To the east of Yerba Buena Island is a deep erosional trough developed in the Franciscan bedrock surface that extends beneath Alameda Island and the Oakland Airport. As a result, the top of the bedrock extends from an elevation of about 338 feet (103 m) NGVD on Yerba Buena Island to about -1,000 feet (-305 m) NGVD beneath Oakland Airport (US NSF 1992).

Geology in the Vicinity of NSTI

East of the San Andreas Fault, the Bay Area is underlain by marine cherts, sandstone, and volcanic rock belonging to the Franciscan Formation. The region that is now San Francisco Bay was above sea level until about a million years ago. At that time, a combination of basin subsidence and rising sea levels led to sediment deposition in the valleys that had been eroded in the Franciscan bedrock surface. Yerba Buena Island may have been uplifted relative to the surrounding land by faulting along an early offshoot of the Hayward Fault. This offshoot, called the Coyote Shear, is believed to have caused the uplift of the Coyote Hills in Fremont. A deep trough formed adjacent to the Coyote Shear zone extends along the East Bay shore from Emeryville to south of the Oakland Airport. Sediments collected in this trough as streams emptied into the basin.

The first sediments deposited on the Franciscan bedrock surface belong to the Alameda Formation, which spans several cycles of glacial advance and retreat between 700,000 and 135,000 years ago. During this period, sea level was as much as 350 feet (107 m) lower than present (US NSF 1992). The Alameda Formation is about 100 feet (30.5 m) thick on the north, east, and south sides of Yerba Buena Island and increases to over 900 feet (274 m) thick where it fills the trough in the Franciscan bedrock surface beneath Oakland Airport.

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The top of the Alameda Formation is an erosional surface caused by downcutting streams. The surface of the Alameda Formation shows evidence of an ancient channel that may have drained to the Pacific Ocean along the southwest side of San Bruno Mountain. Later, the channel changed direction and drained through the Golden Gate via the east side of Yerba Buena Island. Ultimately the channel moved to its current position west of Yerba Buena Island (US NSF 1992).

Around 115,000 years ago, the climate changed dramatically as the huge glaciers covering the interior melted and sea levels rose high enough to inundate the San Francisco basin. The marine silt and clay sediments that were deposited on the surface of the Alameda Formation at this time are known as the Old Bay Mud, and more recently as the Yerba Buena Mud. The thickness of the Yerba Buena Mud ranges from less than 50 feet (15 m) on the west side of NSTI to about 125 feet (38 m) east of NSTI (US NSF 1992). The top of the Yerba Buena Mud is less than 100 feet (30.5 m) below sea level.

The top of the Yerba Buena Mud is an erosional surface created between about 90,000 and 11,000 years ago when sea levels were lower. Coarser, nonmarine sediments, including silts and sands, were deposited in a variety of estuarine, alluvial, and shoreline dune environments during this period. The classification of these units is not well established. In general, the basin deposits have been lumped together as the San Antonio Formation, which includes the Posey and Merritt sand members that form local aquifers. By the end of the Wisconsin glacial age, a number of deeply incised channels had been eroded in the surface of the San Antonio Formation, including Temescal Creek, San Antonio Creek, San Leandro Creek, and San Lorenzo Creek. Temescal Creek flowed around the south side of Yerba Buena Island from what is now Emeryville, joining the north-flowing main drainage channel of the South Bay.

At the end of the Wisconsin Age, sea levels rose again to approximately existing levels. During this period, the Younger Bay Mud (or Bay Mud) was deposited in the now inundated incised stream channels. Figure 3-15 shows an interpretive east-west cross section of the geology beneath Treasure Island.

Seismicity

NSTI is located within the San Andreas Fault system, which is approximately 44 miles (71 kilometers [km]) wide in the Bay Area (USGS 1990a). The principal active faults include the San Andreas, San Gregorio, Hayward, Rogers Creek, West Napa, Calaveras, Concord, and Green Valley faults (California Division of Mines and Geology 1982), as shown on Figure 3-16. The last major earthquake to affect the Bay Area was the Loma Prieta earthquake in October 1989. The epicenter of this earthquake was approximately 59 and 61 miles (95 and 98 km) south of Yerba Buena Island and Treasure Island, respectively. An active fault is defined by the California Division of Mines and Geology (CDMG) as a fault that has "had surface displacement within Holocene time (about the last 11,000 years)" (CDMG 1992a). In general, it is believed that future earthquakes are more likely to occur on recently active faults than on faults that have not been recently active.

In California, special restrictions apply to construction within "fault-rupture hazard zones," as defined by CDMG under the Alquist-Priolo Earthquake Fault Zoning Act (Cal. Pub. Res. Code § 2621), to prevent structures for human occupancy being built across the traces of active faults.

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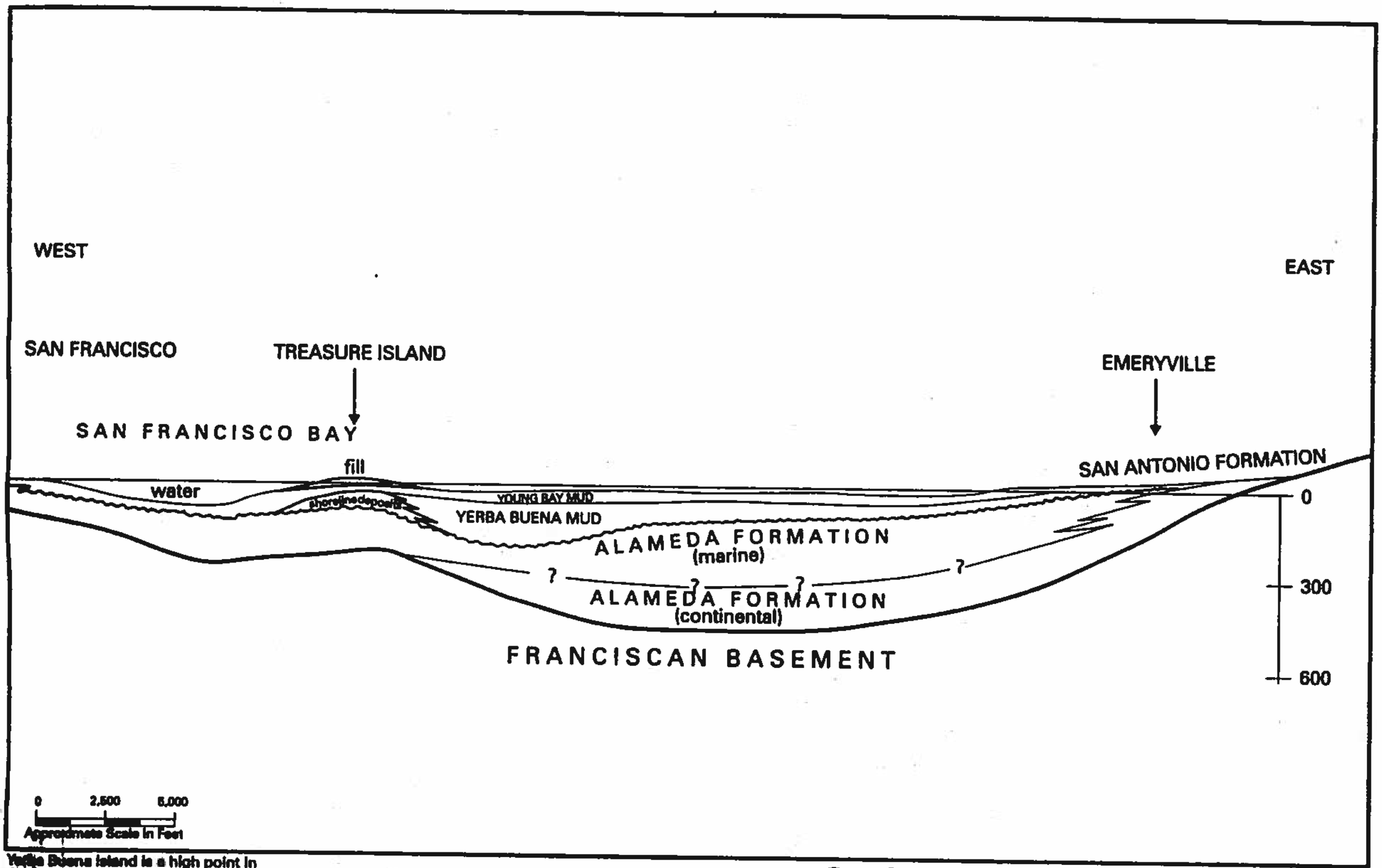

Yerba Buena Island is a high point in the Franciscan formation, which slopes to more than 300 feet beneath Treasure Island. The line of this cross-section passes north of Yerba Buena Island.

Geologic Cross Section from West to East Beneath Treasure Island

Treasure Island, California

Source: Rogers and Figuers 1992

Figure 3-15

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Treasure Island is in an area of liquefaction potential and has been designated a Seismic Hazards Studies Zone (SHSZ) by CDMG (CDMG 1997). No active faults have been identified at NSTI, and NSTI is not in an Alquist-Priolo Earthquake Fault Zone. NSTI is approximately 7 miles (11 km) west of the northern segment of the Hayward Fault and about 18 miles (29 km) east of the San Andreas Fault (CDMG 1994).

The last major earthquake along the Hayward Fault occurred in 1868 (130 years ago) and had an estimated Richter magnitude of 6.8 (CDMG 1992b). It is estimated that the recurrence interval for an earthquake of that size is about 130 ± 60 years (CDMG 1992c). The last major earthquakes on the San Francisco segment of the San Andreas Fault were the 1906 San Francisco earthquake, with an estimated Richter magnitude of 8.3 (USGS 1990b), and the 1989 Loma Prieta earthquake, with an estimated Richter magnitude of 7.1 (USGS 2003).

The probability of one or more large earthquakes (Richter magnitude 7.0 or greater) occurring on the San Andreas, Hayward, or Rogers Creek faults has been estimated to be greater than 67 percent for the 30-year period from 1990 to 2020 (USGS 1990c). The estimated individual probabilities of magnitude 7.0 or greater earthquakes for the same period on either the northern segment of the Hayward Fault or the San Francisco Peninsula segment of the San Andreas Fault were estimated to be 27 percent and 23 percent, respectively.

3.9.2 Geology Underlying NSTI

Treasure Island

Treasure Island is connected to Yerba Buena Island by an engineered causeway constructed on a former sand spit. Treasure Island was engineered by placing over 29 million cubic yards (22 million cubic m [m³]) of fill from various sources (CDMG 1969a). The fill was placed on Yerba Buena Shoals, a submerged area of about 735 acres (298 hectares [ha]), between February 1936 and July 1937. The shoals varied in elevation from -2 feet (-0.6 m) to -26 feet (-8 m) mean lower low waterline (MLLW). About 8 million cubic yards (6 million m³) of the original fill subsequently was lost to erosion, settlement, and drift of fine material during placement (DON 1990c).

The unconsolidated deposits that constitute and underlie Treasure Island can be divided into four broad categories based on their engineering characteristics—fill, native shoal sand, recent bay sediments, and older bay sediments (USGS 1994). The fill was derived from hydraulic and clamshell dredging and was placed within a retaining dike built of rock. Filling commenced February 11, 1936, and was completed July 2, 1937, except for refill operations from August 1 to 24, 1937 (CDMG 1969a). The retaining dike was placed in two to four stages on a prepared bed of coarse sand placed over the shoal. The retaining dike was later covered with riprap from elevation -6 to +14 feet (-2 to +4 m) MLLW (USGS 1994). Of the 29 million cubic yards (22 million m³) of artificial fill placed on Treasure Island, 1.3 million cubic yards (0.99 million m³) (less than 0.5 percent) was described as "heavy sand," consisting of coarse and well-graded sand and gravel from Presidio, Alcatraz, and Knox Shoals. The remaining material was predominantly sand, but much finer-grained, which was transported to the island by pipeline from nearby dredging grounds. Beneath the artificial fill are sand and Bay Mud deposits that formed the Yerba Buena Shoals.

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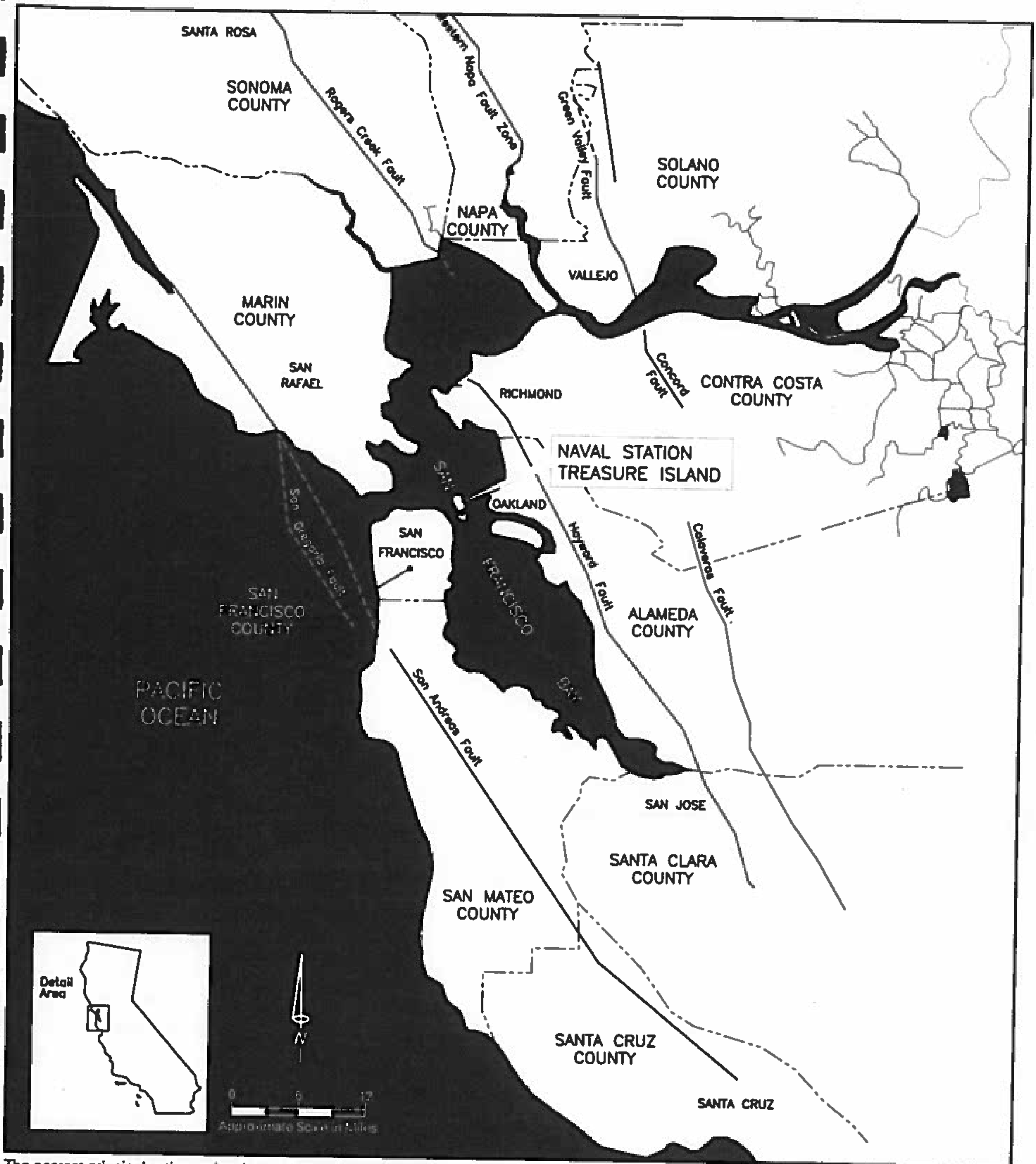

The nearest principal active regional faults to Treasure and Yerba Buena Islands are the San Andreas and Hayward Faults.

Legend:

- ——— Active fault
- - - - - Active fault, concealed
- —·—·— County Lines

Principal Regional Active Faults

Bay Area, California

Source: Wallace 1990

Figure 3-16

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Yerba Buena Island

Yerba Buena Island consists predominantly of consolidated sandstone and shale of the Franciscan Formation. Slopes on Yerba Buena Island range from approximately 5 to 75 percent (Figure 3-17) (DON 1986). The Franciscan Formation is overlain in some areas by thin sand deposits belonging to the Pleistocene Colma Formation (USGS 1974) or is derived from the underlying Franciscan sandstone (USGS 1957). Only a small area has been filled, on the northeast tip of the island beneath the SFOBB (USGS 1975b; USGS 1957).

3.9.3 Soils

Treasure Island

Soils on Treasure Island and the extreme northeastern tip of Yerba Buena Island, covering zero to 2 percent slopes, are classified as Urban Land-Orthents complex. Urban Land includes those areas that are more than 85 percent covered by asphalt, concrete, or structures. Underlying these areas are reclaimed soil, gravel, broken concrete, Bay Mud, and other materials that extend to depths of -2 to -26 feet (-0.6 to -8 m). The main characteristics of these soils are subsidence, corrosivity (due to the shallow tidally influenced water table), and highly variable soil properties (USDA 1991; DON 1986).

Yerba Buena Island

Soils on Yerba Buena Island range from fine sandy loam to gravely loam, 10 to 40 inches (25 to 102 cm) deep. The natural soils consist of a complex of Candlestick, Kron, and Buriburi soils. These are generally coarse, loose soils, which reflect the underlying Franciscan sandstone bedrock. The permeability of these soils is moderately low. Stormwater runoff is rapid, and soil erosion potential is high. Candlestick soil is a sandy loam that is very susceptible to failure on steep slopes. The Kron soil, also a sandy loam, is the shallowest of the three subunits, with a depth of 10 to 20 inches (25 to 51 cm) to bedrock. The Buriburi subunit is a gravelly loam, with a depth of 20 to 40 inches (51 to 102 cm) to bedrock.

The soil covering the moderately steep to steep (5 to 75 percent) slopes of north-central Yerba Buena Island are classified as Orthents, Cut and Fill-Urban Land complex. The original soil structure was modified by cutting and filling (Orthents) and is covered by buildings or pavement (Urban Land). On Yerba Buena Island the properties of this soil are expected to be very similar to the Candlestick-Kron-Buriburi complex from which the soil was derived. Limitations to development tend to be steepness of slopes and high erosion (USDA 1991; DON 1986).

3.9.4 Geologic Hazards at NSTI

Figure 3-17 shows geologic hazards at NSTI, including those that would occur in a major seismic event. These hazards consist of areas of fill and areas subject to liquefaction, settlement, lateral spreading, and slope and dike instability. Each of these potential hazards is described briefly below.

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Ground Shaking

The Mercalli intensity scale is used to describe the severity of an earthquake and rates earthquake damage based on anticipated damage levels ranging from I to XII (e.g., an intensity of I means that the earthquake is not felt, whereas an intensity of XII is a condition where large rock masses are displaced, objects are thrown into the air, and damage is nearly total). Earthquake intensity depends on many factors, including the distance from the origin of the earthquake and the nature of the geologic materials at the location where the earthquake is felt. Generally, bedrock shakes the least because seismic waves travel quickly and efficiently through these materials. Loose water-saturated materials shake more violently because seismic waves are slowed down and are amplified in these materials.

Damage to structures depends not only on the intensity and duration of an earthquake but also on how structures are built, the direction of travel of seismic waves, the orientation of the supporting elements of the structure relative to the direction of seismic wave travel, and the underlying materials (i.e., reclaimed soil, cement, and bedrock).

ABAG has prepared a series of maps projecting the intensity of ground shaking in geologic materials throughout the Bay Area (ABAG 1995a). According to these maps, the fill materials at NSTI are the type of materials that typically increase seismic shaking. The most damaging earthquake at NSTI would be one originating on the northern portion of the Hayward Fault (ABAG 1995a). Such an earthquake, with a Richter magnitude of 7.1, could produce ground shaking on NSTI with an intensity of IX on the Mercalli scale (ABAG 1995a). By comparison, ABAG assigned a Mercalli intensity of VIII to ground shaking on NSTI during the October 17, 1989, Loma Prieta earthquake.

The Loma Prieta earthquake resulted in property damage throughout the greater Bay Area, including Santa Cruz, approximately 65 miles (105 km) south of San Francisco. The 1989 damage in San Francisco was not evenly distributed through the city. Most of the severe property damage occurred in areas built on unengineered artificial fill in the Marina and South of Market districts where the nature of the soils resulted in liquefaction, severe ground shaking, and fire. Bay Area transportation systems were also disrupted, particularly by the collapse of the Cypress Freeway in the West Oakland neighborhood in the City of Oakland and a portion of the SFOBB (San Francisco 1996b).

During the Loma Prieta earthquake, damage varied widely on Treasure Island. Types of damage observed included lateral spreading, slope failure, pavement collapse and cracking, and dike settlement. Liquefaction was pervasive in the interior of Treasure Island, evidenced by numerous large sand boils. Settlement of up to 12 inches (30.5 cm) occurred, causing numerous pipe breaks and ponding water at the surface (USGS 1994). There were no fires.

There is a 67 percent probability that one or more earthquakes of magnitude 7.0 or greater on a nearby portion of the Hayward or San Andreas Faults will occur by 2010 (USGS 1990c). The USGS (1994) predicted that a magnitude 7.0 earthquake on the Hayward Fault would produce a peak bedrock acceleration of about 0.45 times the acceleration of gravity (g) on Yerba Buena Island, or about 7.5 times the acceleration observed during the Loma Prieta earthquake. Even though Treasure Island is underlain by fill, the peak acceleration in a large nearby earthquake

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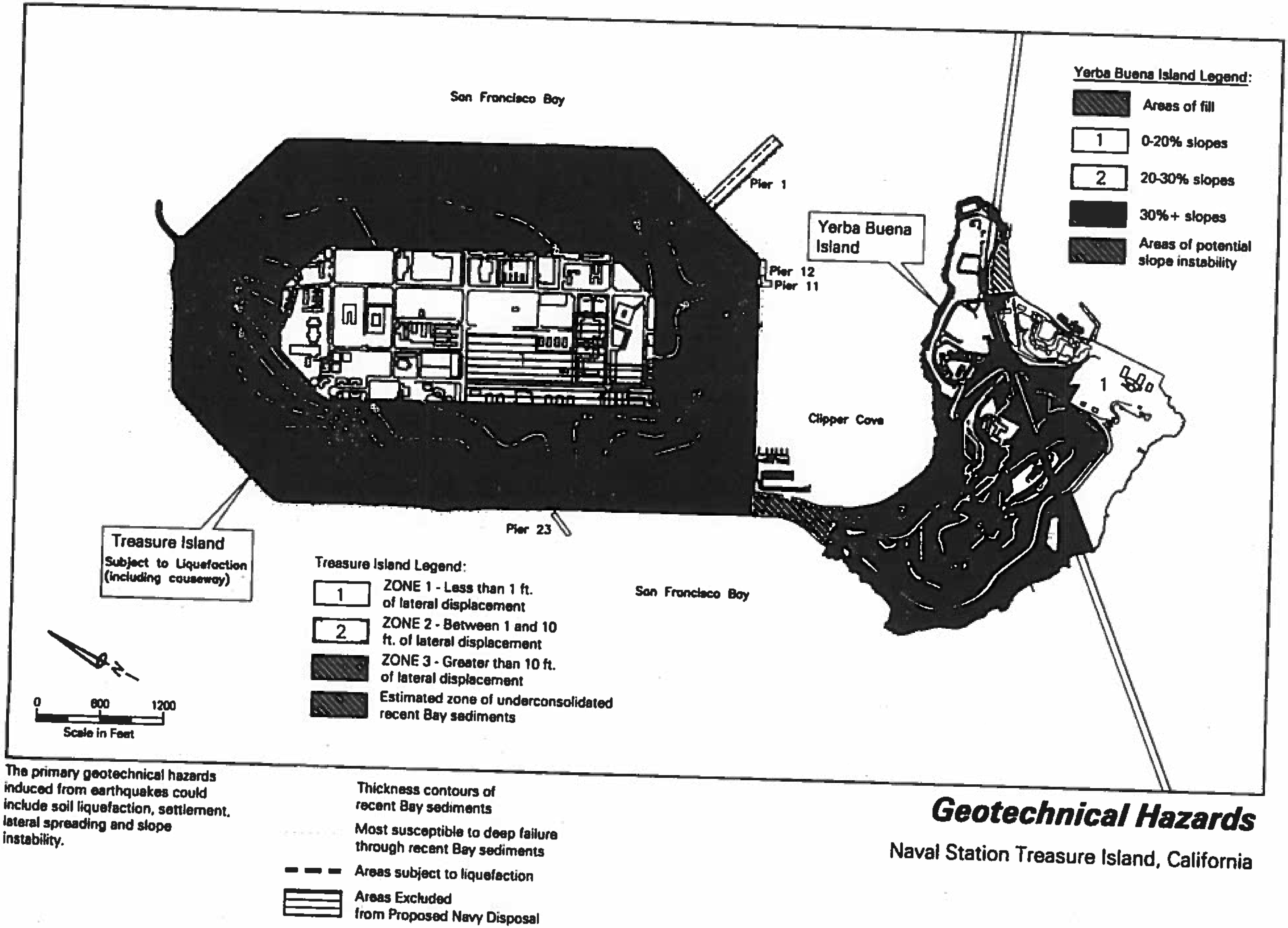

The primary geotechnical hazards induced from earthquakes could include soil liquefaction, settlement, lateral spreading and slope instability.

Source: CCSF 1996e

Geotechnical Hazards

Naval Station Treasure Island, California

Figure 3-17

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would be about the same on both Yerba Buena Island and Treasure Island, because the seismic response of fill is not linear (USGS 1994).

In addition to ground shaking, several types of ground failure can be triggered by earthquakes. These secondary seismic effects include liquefaction, settlement, and lateral spreading, and in areas with steep slopes, earthquakes may trigger landslides.

Liquefaction Potential

A major cause of damage to structures during earthquakes is soil liquefaction, which occurs when loose, water-saturated soils (generally fine-grained sand) are subjected to strong seismic ground motions of significant duration.

Treasure Island has been designated a Seismic Hazards Studies Zone (SHSZ) by CDMG because of its high liquefaction potential (CDMG 1997). The San Francisco General Plan Community Safety Element, Map 4, indicates Treasure Island, along with portions of the San Francisco shoreline perimeter, as an area of liquefaction potential (see Figure 3-18) (San Francisco 1996b). Liquefaction was observed in the Marina and South of Market districts (San Francisco 1996b), as well as throughout Treasure Island, during the Loma Prieta earthquake (DON 1990d).

The materials most susceptible to liquefaction are the sand fill below the water table and the underlying shoal sands. The Treasure Island water table typically occurs at a depth of about 5 to 8 feet (1.5 to 2.5 m) below the ground surface. No damage was observed during the Loma Prieta earthquake in an area on the southeast corner of Treasure Island that previously had been compacted to reduce liquefaction hazards (by a method called "vibroflotation"). This suggests that the liquefaction potential of sediments underlying Treasure Island could be reduced by this method or other appropriate site preparation.

Settlement

Settlement is the gradual downward movement of an engineered structure due to compaction of the unconsolidated material below the foundation (USGS 1979). Bay Mud frequently is associated with settlement problems in the San Francisco Bay Area because of its extremely low shear strength (CDMG 1969b). It has been estimated that for an underlying Bay Mud thickness of greater than 60 feet (18 m), about 35 percent of the ultimate settlement would take place during the first 10 years (CDMG 1969a). Due to the relatively old age of the fill across much of Treasure Island, most of the settlement for the current loading already has occurred. Adding new fill or substantially modifying the current loading would initiate a new cycle of settlement.

Seismic shaking can accelerate the rate of settlement, allowing liquefied sediments to reach a greater degree of compaction than before the shaking. In 1990, after the Loma Prieta earthquake, a Navy study to evaluate the seismic stability of NSTI's perimeter dikes estimated that a relatively uniform seismically induced settlement of 1 to 2 feet (0.3 to 0.6 m) would occur across Treasure Island after a large earthquake (DON 1990c).

Differential or uneven settlement results from spatial variations in the uniformity or thickness of the fill and underlying uncompacted sediments. Differential settlement is of particular

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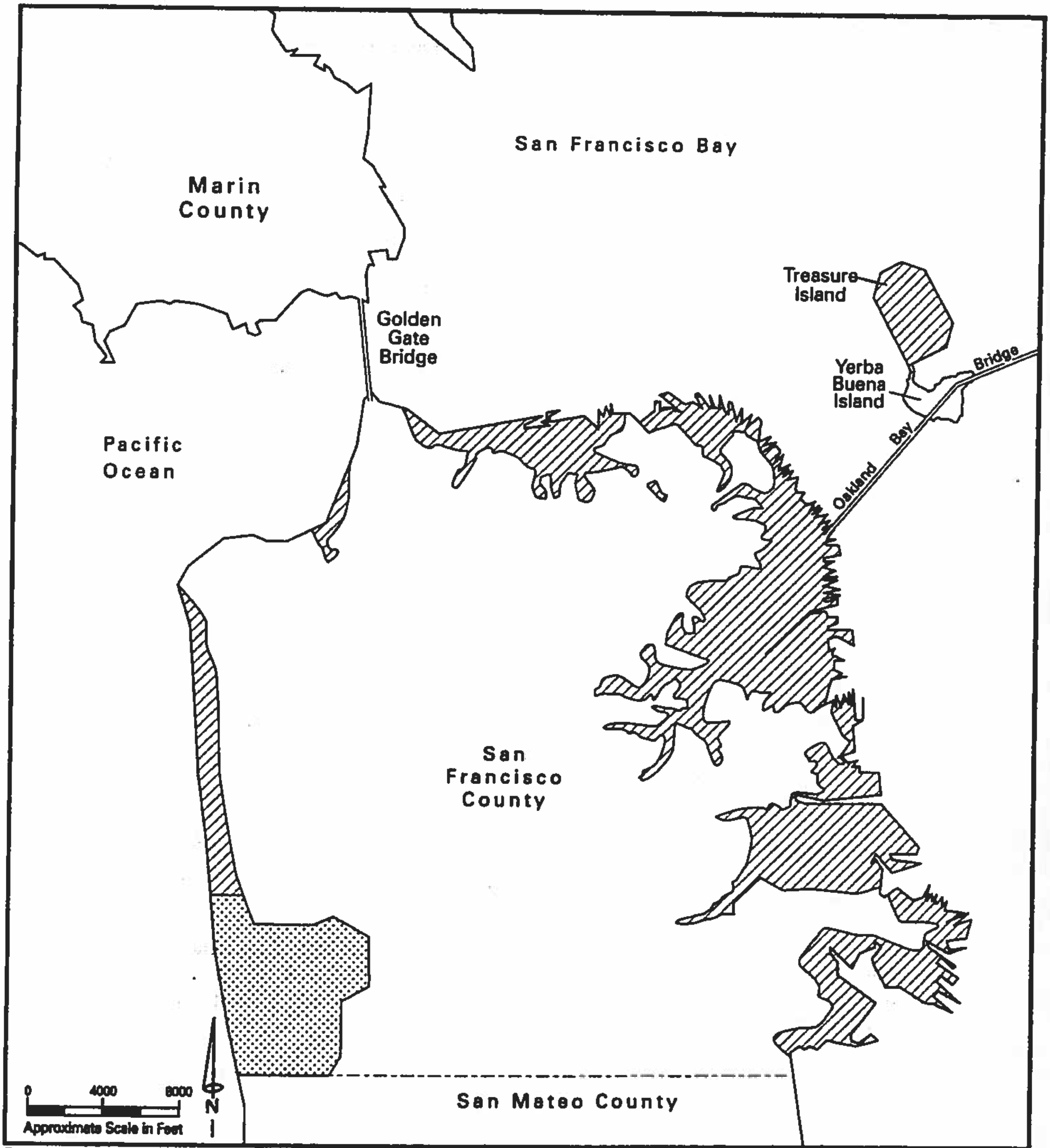

Treasure Island has been designated a seismic hazard zone by the California Division of Mines and Geology because of its high liquefaction potential.

LEGEND:

- Area of liquefaction potential
- Area of probable liquefaction potential

Seismic Hazards Study Zones - Areas of Liquefaction Potential

Bay Area, California

Source: CCSF 1996b

Figure 3-18

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concern to structures because of the potential for floors, foundations, pavement, or other distributed loads to break or buckle rather than to settle uniformly.

Lateral Spreading

Lateral spreading is the horizontal component of soil movement in the direction of an open (i.e., unsupported) slope face that typically results from liquefaction of a supporting soil layer due to an earthquake. Lateral spreading also occurs due to slope failure that is not caused by earthquakes. Cracks in a nearly horizontal or gently sloping ground surface are a common visual indicator of lateral spreading.

Lateral spreading accompanying liquefaction is a major seismic hazard for Treasure Island (DON 1990e). It has been estimated that lateral displacements in the vicinity of the Treasure Island perimeter dikes may be more than 10 feet (3 m) within the first 500 feet (152 m) from the perimeter for a magnitude 8.0 earthquake on the San Andreas Fault and on the order of 4 feet (1 m) for a magnitude 7.0 earthquake on the Hayward Fault (DON 1990e; San Francisco 1995b). The displacements would extend inland, probably significantly more than the 500 feet (152 m) observed in the Loma Prieta earthquake, and would be exposed as horizontal cracks ranging in size from less than an inch (2.5 cm) to a few feet (0.6 m). Vertical sliding of a fourth to a half the magnitude of the horizontal movements also would occur. Vertical sliding is considered more damaging to structures than the more uniform liquefaction-induced settlement.

Slope Stability

Slope stability depends on a combination of factors, including rainfall, geology, slope steepness, orientation, vegetation cover, seismicity, and development. Slope failure could occur from landslides, debris flows and avalanches, creep, earthflow, or erosion. Catastrophic slope failure in susceptible areas may be triggered by seismic events, rainfall, undercutting of slopes by construction activities, and overloading of unstable deposits.

Figure 3-19 shows the locations of landslide deposits on Yerba Buena Island (USGS 1975a). In addition, the San Francisco General Plan Community Safety Element (Map 5) shows areas of potential landslide hazard on Yerba Buena Island. Landslide deposits are susceptible to continuing failure. Landslide deposits occur at the base of steep slopes around the margin of Yerba Buena Island, mostly on the south side. There is one landslide area on the north side. The island interior is underlain by bedrock with thin soil, which is less susceptible to slope failure.

Dike Stability

Treasure Island contains approximately 15,800 feet (4,816 m) of perimeter stone dike that varies in elevation from 7.7 to 13.8 feet (2.3 to 4.2 m) NGVD. The perimeter dike performs several essential functions—it protects the island interior from flooding, it resists shore erosion, and it retains the fill material that composes the island. The island and the dike were constructed concurrently in 1936 and 1937. Portions of the dike were repaired between 1983 and 1985. This increased the height of the slope north of the entry gate to 54 feet (16.5 m). Repairs consisted of placing rock in this area.

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The stability of the perimeter dike at Treasure Island was evaluated by the Navy following the 1989 Loma Prieta earthquake (DON 1990c). It was found that in most locations around the island perimeter, less than 6 inches (15 cm) of lateral (bayward) movement occurred in response to this earthquake. Settlements near the dike were generally less than 12 inches (30.5 cm). Small lateral spreading cracks were observed more than 500 feet (152 m) inland from the perimeter dike on the east side of the island (DON 1990c).

Figure 3-20 shows four cross sections of the perimeter dike (DON 1990c). Cross sections F-F' and I-I', which are the most typical, show that the dikes are constructed on potentially liquefiable material. Cross section C-C' shows where offshore material was removed by dredging or erosion and was repaired with rock. Section D-D' is the location where the retaining dike was reconstructed on 70 feet (21 m) of sand after the slope failed during the initial construction.

The Navy's 1990 study, incorporated into the 1995 Treadwell and Rollo report, indicated that during a design-level earthquake (Richter magnitude 8.0 on the San Andreas Fault or magnitude 7.0 on the north East Bay segment of the Hayward Fault), the sand fill and shoal materials below the water table would be expected to liquefy, and the existing perimeter dikes and causeway shoreline would be expected to spread laterally toward the Bay. Within 500 feet (152 m) inland of the perimeter dike and along portions of the causeway underlain by sand fill and shoal materials, lateral spread displacements were estimated to be greater than 10 feet (3 m). Movements of this magnitude would cause dike failure. Even if improvements are made to mitigate the hazards associated with liquefaction and lateral spreading, rotational slope failures may still occur through the underlying weak layer of recent Bay sediments. During a design-level earthquake, deep failures that could occur through recent Bay sediments could result in up to 5 feet (1.5 m) of slope movement. The study further concluded that if improvements were performed to increase the stability of the slope against deep failures, lateral displacements could be reduced to less than one foot (DON 1990c; San Francisco 1995b).

3.9.5 Improving Ground Stability

Five foundation soil modification techniques have been used at Treasure Island to reduce soil susceptibility to liquefaction and differential settlement (DON 1990c). These techniques involved some form of densifying the underlying soil, such as installing sand compaction piles, installing nonstructural timber piles, vibro-compaction, and stone columns. Mixing the soil with portland cement to form a foundation of "soilcrete" also has been attempted. Figure 3-21 shows the locations of the 12 buildings and one area at the base of Pier 1 with improved foundations. All structures founded on improved ground or piles reportedly performed reasonably well during the Loma Prieta earthquake, with the exception of Building 461 (San Francisco 1995b).

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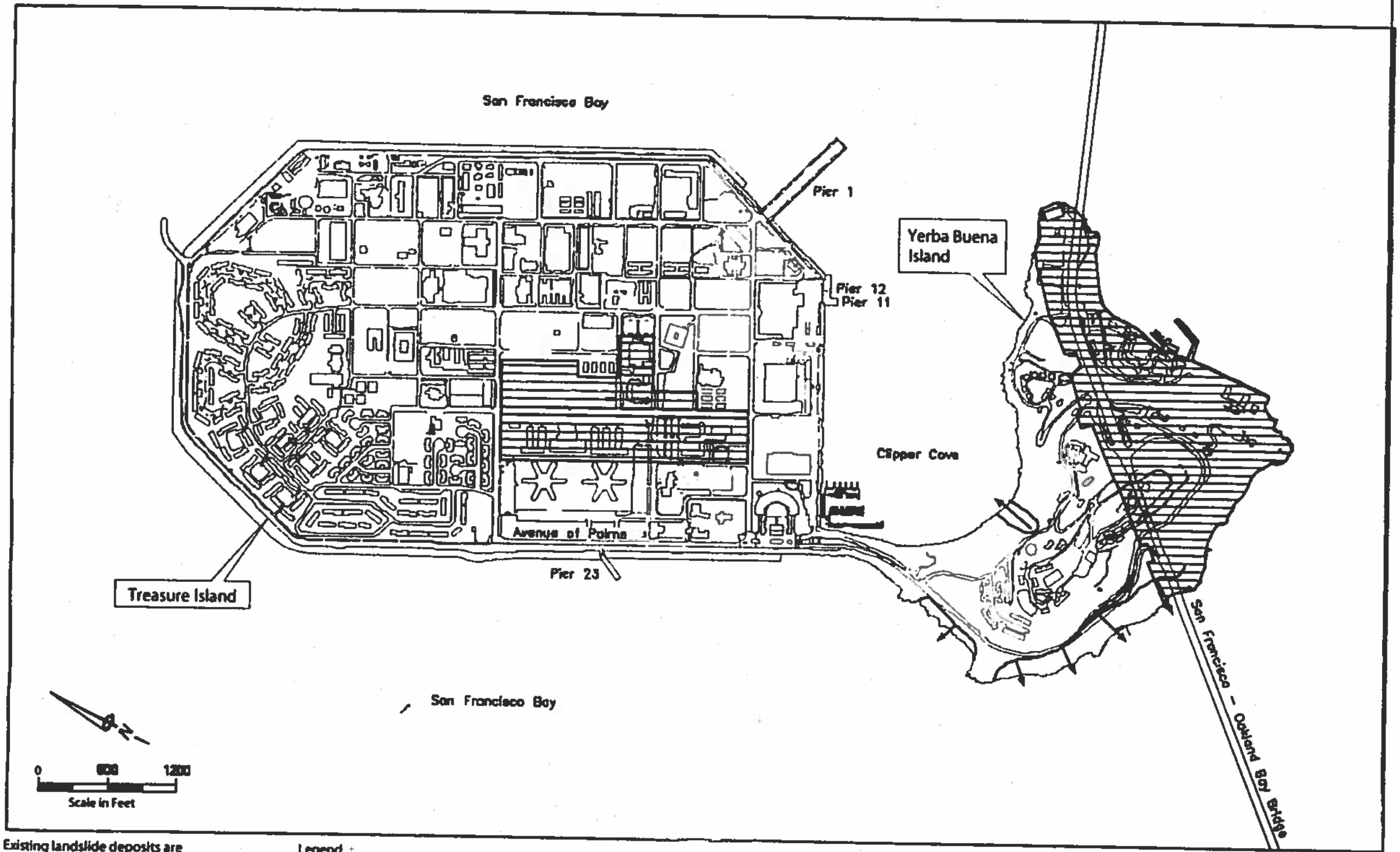

Existing landslide deposits are limited to the margins of Yerba Buena Island.

Legend

Landslide deposit showing direction of movement

Areas Excluded from Proposed Navy Disposal

Landslide Deposits at NSTI

Naval Station Treasure Island, California

Source: Nilsen 1975

Figure 3-19

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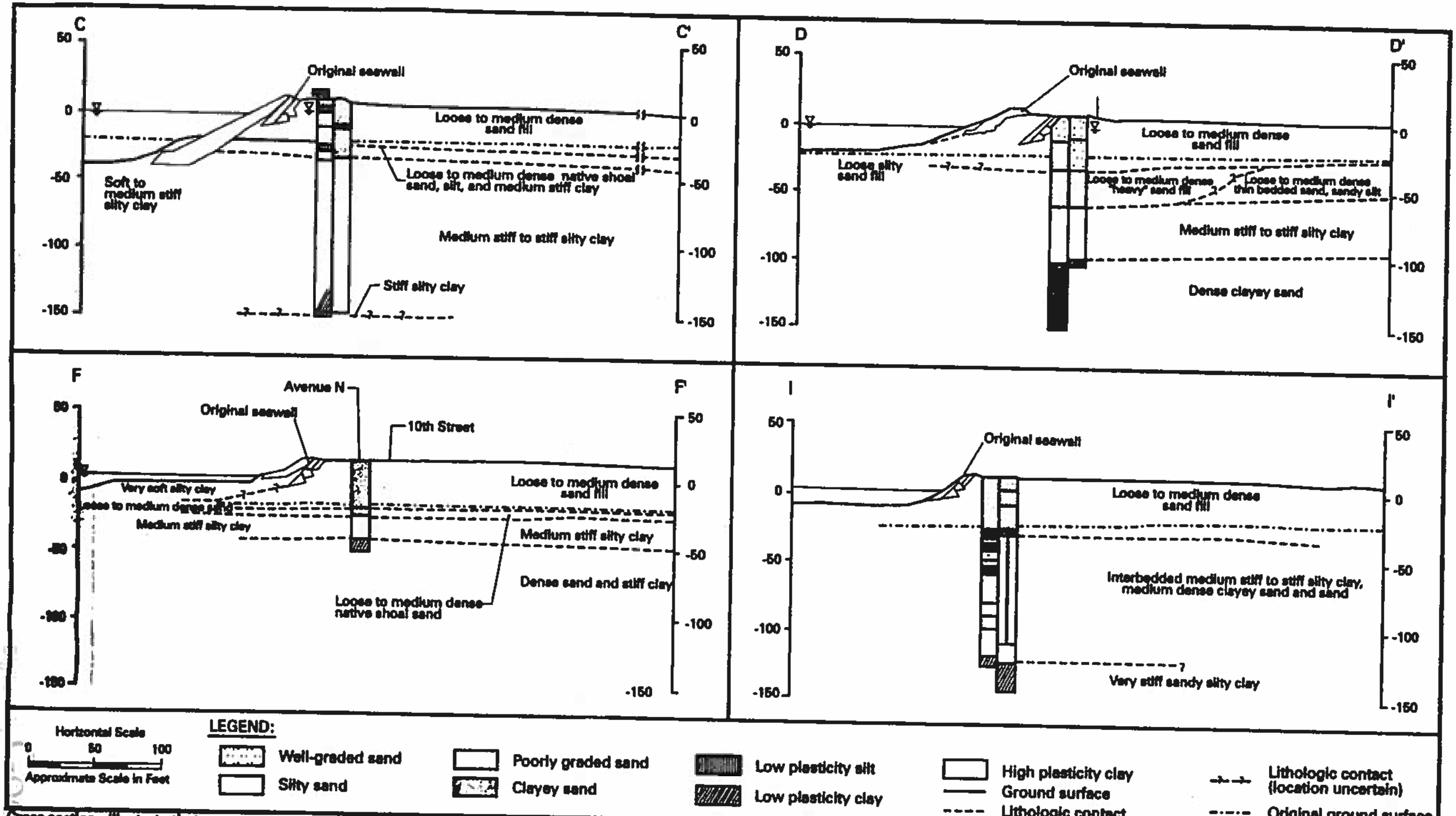
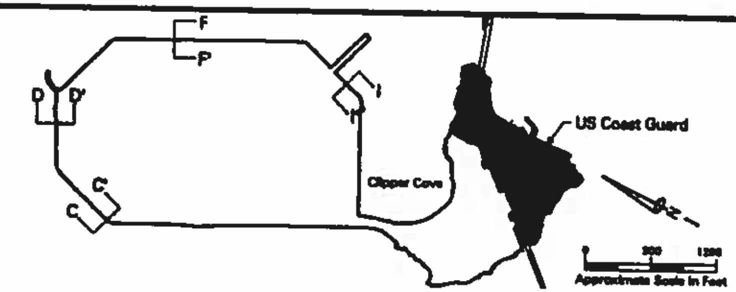


Cross sections illustrate that perimeter dikes are constructed on sand or fill materials.



Representative Cross Sections on Perimeter Dikes at Treasure Island

Treasure Island, California

Source: DON 1990d

Figure 3-20

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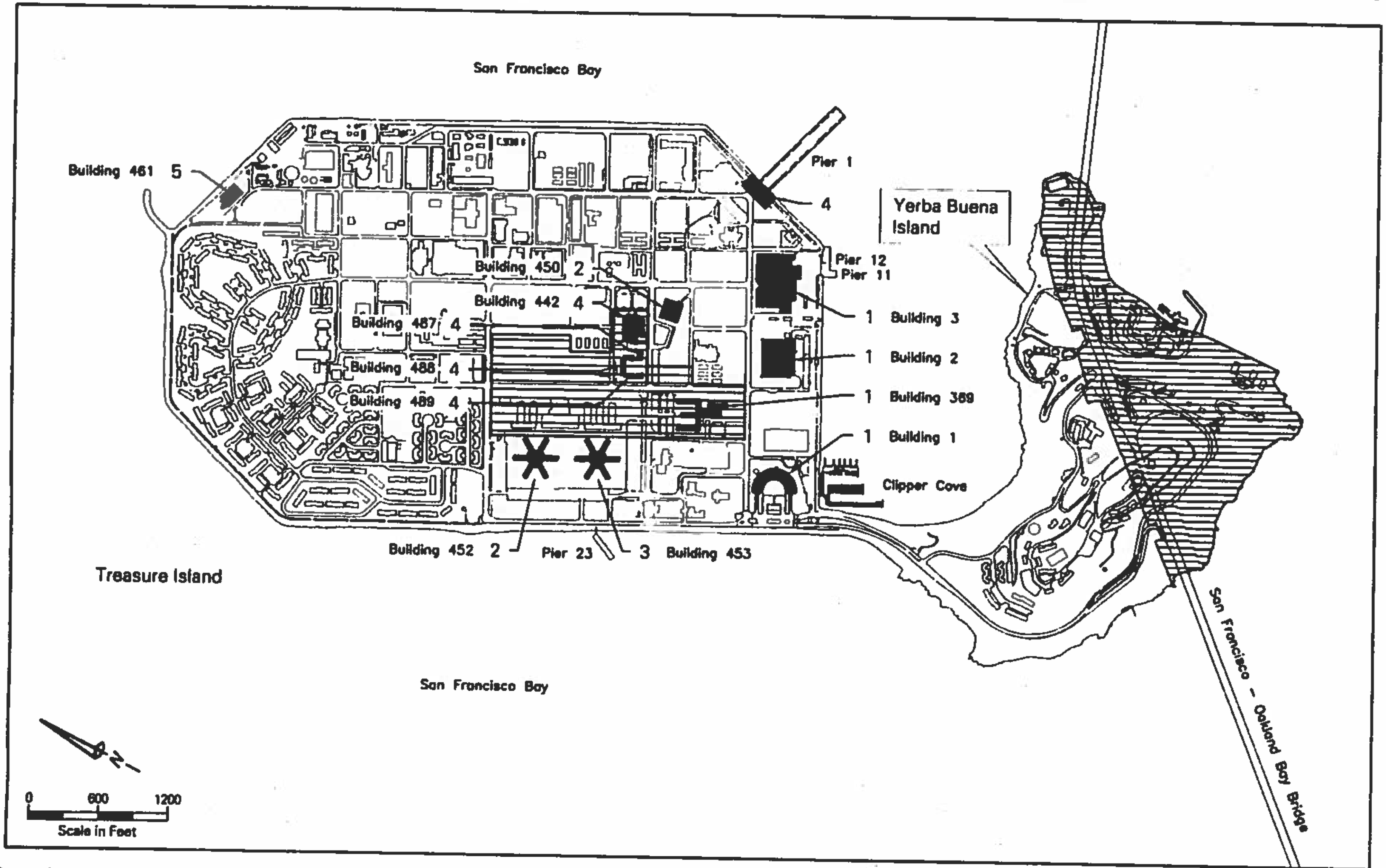

Some of the building sites have been compacted or otherwise prepared to prevent settlement.

Legend:

1 Structure supported by pile foundation
2 Ground improvement by sand compaction piles
3 Ground improvement by nonstructural timber piles
4 Ground improvement by stone columns
5 Structure constructed on pad of soilcrete

Areas Excluded from Proposed Navy Disposal

Buildings with Improved Foundations

Source: DON 1990a

Locations of Buildings with Improved Foundations

Naval Station Treasure Island, California

Figure 3-21

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