Appendix F

Geology

APPENDIX F
GEOLOGY

Stratigraphy

Los Angeles Harbor is located along the southwest margin of the Los Angeles Basin. The basin, approximately 50 miles long and 20 miles wide, slopes gently in a southwesterly direction to the Pacific Ocean. Major drainage for the basin is provided by three intermittent rivers: the Los Angeles, San Gabriel, and Santa Ana rivers. The harbor is located adjacent to the east side of the Palos Verdes Hills. These hills represent a structural block elevated along the Palos Verdes Fault (see Section 3.1.1.1).

Unconsolidated and semi-consolidated Quaternary marine and nonmarine sediments fill the basin. These deposits are underlain by volcanic rocks and marine sedimentary rocks of early Pleistocene, Pliocene, and Miocene age. Metamorphic rocks of the Catalina Schist (possibly Jurassic to late Cretaceous age) comprise the basement complex. These rocks and sediments are discussed in detail in the *Deep Draft Navigation Improvements for Los Angeles and Long Beach Harbors, Final EIS/EIR* (USACE and LAHD, 1992), and summarized below, beginning with the oldest rocks (Jurassic) and concluding with the youngest sediments (Quaternary). Rocks and sediments exposed at the surface are graphically represented on Figure F-1.

The Catalina Schist (possibly Jurassic to late Cretaceous) is thought to underlie most of southern California (Platt, 1976). In certain areas, the Catalina Schist is overlain by as much as 20,000 feet of Miocene and younger sedimentary and volcanic rocks (Yerkes et al., 1965). In the Palos Verdes Hills area, the metamorphic basement is overlain by the Miocene Monterey Formation.

In the harbor area, the Pliocene is represented by the Repetto and Pico Formations. The lower Pliocene Repetto Formation, comprised primarily of massive siltstone, ranges in thickness from 1,000 to 4,000 feet. Sedimentary rocks of the upper Pliocene Pico Formation, which lie unconformably over the Repetto Formation, are composed primarily of siltstone and sandstone, reaching a maximum thickness of about 1,000 feet in the harbor area (Woodring et al., 1946; Yerkes et al., 1965).

Marine gravels, sands, silts, and clays comprise the overlying Pleistocene San Pedro Formation, and are about 1,000 feet thick. Unnamed upper Pleistocene marine deposits unconformably overlie the San Pedro Formation. These deposits, which consist of shallow marine sands and silts, reach a maximum thickness of 150 to 250 feet.

Recent deposits in the area are composed of sands and gravels of the ancestral Los Angeles River. In the Pleistocene glacial period, during the last major worldwide drop in sea level, the ancestral Los Angeles River incised into upper Pleistocene marine deposits, cutting to a depth of 180 feet (Zielbauer et al., 1962). As the sea level rose with the end of the glacial period, fluvial sediments filled this incised trench. Coarse sands and gravels compose the basal portion of this fill, while the upper portion is composed of fine sands, silts and clays. These trench-filling sediments are known as the Gaspur aquifer.

The Los Angeles Harbor was constructed in San Pedro Bay, an estuary of the Los Angeles River. The original nearshore environment of the bay has been completely altered from its predevelopment physiography. Rattlesnake Island, an offshore bar, protected the bay's tidal marshes. Alteration of the bay began in the 1800s. Through a program of dredging, landfilling, and channelization of the Los Angeles River, the harbor was gradually developed into its present configuration. Rattlesnake Island was modified to form Terminal Island. The project site is located on the east side of the West Channel area.

Faulting and Seismicity

Alquist-Priolo Special Studies Zones Act (1972)

In 1972, the California Legislature enacted the Alquist-Priolo Special Studies Zones Act (Chapter 7.5, Division 2, California Public Resources Code) to provide for public safety by restricting development near or over the surface traces of active faults. The act provides for the approval of projects by cities and counties, exemptions for altering and adding to existing structures, and the disclosure of hazards by property sellers and their agents. This legislation provides guidelines to determine fault activity status based on the age of the youngest geologic unit offset by the fault. For zoning purposes, an active fault is defined as one that offsets Holocene deposits (less than 11,000 years old) and can be sufficiently defined by a trained geologist. A potentially active fault is one that has offset Quaternary rocks (less than 3 million years old), and an inactive fault is one that offsets Pliocene or older rocks (greater than 3 million years old).

Seismicity of the Region

Southern California is historically a seismically active region. Most of the earthquake epicenters in the Los Angeles area occur along the San Andreas, San Jacinto, Whittier-Elsinore, and Newport-Inglewood faults, all of which are elements of the San Andreas fault system. This pattern of seismicity reflects the distribution of right-parallel strike-slip faults that delineate the active boundary between the Pacific (oceanic) plate and the North American (continental) plate (Ziony and Yerkes, 1985).

Based on the historic record, it is highly probable that the Los Angeles Harbor area will be affected by future regional earthquakes. Present evidence indicates that in the future, damaging earthquakes will occur on or near recognized Quaternary faults that show evidence of geologically recent activity (Ziony and Yerkes, 1985). Table F-1 lists those faults that have the potential to impact the harbor area. Listed in the table are the maximum credible and maximum probable magnitudes (M) predicted from rupture on the listed faults. These values are from the commonly used Richter scale of earthquake magnitudes, a logarithmic scale where each whole number increase in magnitude represents a tenfold increase in earthquake size.

Faults

Faults are fractures or lines of weakness in the earth's crust, along which rocks on one side of the fault are offset relative to the same rocks on the other side of the fault. Sudden movement along

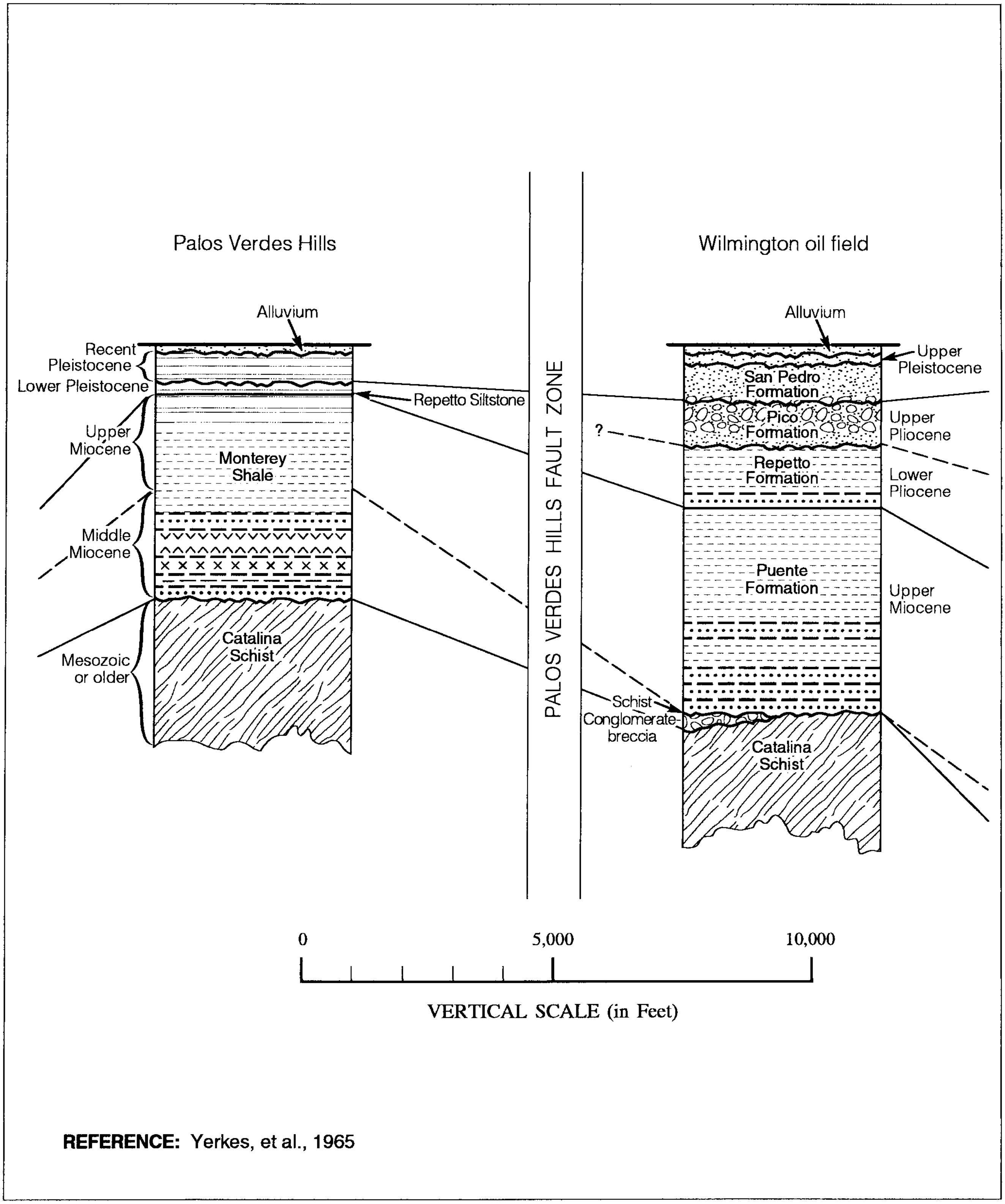


Figure F-1. Typical Geologic Sections for Palos Verdes and Wilmington

Table F-1

SEISMIC PARAMETERS

Potential Causative Fault/Fault Zone	Closest Distance from Fault to Site	Length of Fault/ Fault Zone [1]	Maximum Magnitude of Historic Earthquakes [1]	Approx. Date of Most Recent Surface Rupture	MAXIMUM CREDIBLE EVENT [5]: Maximum Credible Earthquake Magnitude [1, 5]	MAXIMUM CREDIBLE EVENT [5]: Recurrence Interval of Major Earthquake (Years)	MAXIMUM PROBABLE EARTHQUAKE (DESIGN EARTHQUAKE) [10]: Magnitude [1]	Peak Horiz. Ground Accel. at Site (g) [11,12]	Predominant Period (in Bedrock) at Site (sec.) [14]	Duration of Strong Shaking at Site (sec.)
San Andreas	89 km 55 mi	1,000+ km 622 mi	7.9 (1857) 6.0 (1948)	Historic 1857 & 1948	8.5	65-270 [1,7]	8.0	0.13 [13]	0.58	60
San Jacinto	86 km 53 mi	300 km 186 mi	6.8 (1899) 6.0 (1923) 6.6 (1942) 6.5 (1968)	Historic 1899 & 1968	7.5	Approx. 30-150	7.0	0.03	0.42	32
Whittier-Elsinore	32 km 20 mi	240 km 149 mi	6.0 (1910) [3] 5.5 (1938)	Historic [3] Post-1660	7.0	Approx. 500-700 [8,9]	6.5	0.08	0.28	21
Sierra Madre/ San Fernando	48 km 30 mi	80 km 50 mi	6.6 (1971) 6.0 (1991)	Historic 1971 & 1991	7.5	Approx. 1,000-10,000 (Sierra Madre) and 100-300 (San Fernando) [1,7]	6.5	0.07	0.33	23
Newport-Inglewood	8 km 5 mi	73 km 45 mi	6.2 (1933)	Historic [4] 1933	7.0	Approx. 1,500 [8,9]	6.5	0.27	0.28	18
Palos Verdes Hills [2]	0 km 0 mi	70 km 40 mi	None known	Holocene (?)	7.0	2,000-8,000	6.5	0.43	0.28	17
Elysian Park [15]	20 km 33 mi	N/A[16]	5.9 (1987)	N/A	6.5-7.5	unknown	No data	No data	No data	No data

Notes:
1. After Ziony and Yerkes 1985. Earthquakes and magnitudes reported as moment (M) magnitudes except where otherwise noted.
2. Dames & Moore and MESA-2 1983.
3. After Rockwell et al. 1986.
4. After Guptill and Heath 1981.
5. Estimate of the largest earthquake that can reasonably be expected to occur on a given fault.
6. Estimate for a given point along a fault.
7. Recurrence interval based on documented evidence of faulting in sediments of known age.
8. Recurrence interval based on estimated fault slip rate.
9. After Wesnousky 1986.
10. Estimate of the largest earthquake that has a reasonable probability of occurring during the 50-100 year design lifetime of most structures.
11. After Joyner and Fumal 1985.
12. For an event occurring within approximately 32 kilometers (20 miles) of the site, the repeatable high ground acceleration, taken as 65 percent of the instrumented peak acceleration, may be more applicable for design analysis (Ploessel and Slosson 1974).
13. After Schnable and Seed 1973.
14. After Seed et al. 1969.
15. Engineering-Science, 1992.
16. Not applicable -- fault has no surface expression.

one of these faults results in an earthquake. Several major faults are present within 100 miles of the harbor. Numerous smaller faults are located throughout the Los Angeles Basin, some within a few miles of or passing through the harbor. Many of these faults are considered active and capable of generating large damaging earthquakes. These faults are shown in Figure F-2 and discussed below. Tables F-2, F-3 and F-4 list characteristics and ground motion parameters for these faults. Some of these faults also form groundwater barriers in the harbor area.

An earthquake is classified by the amount of energy released, which is quantified using the Richter scale. Earthquakes of Richter magnitude (M) 6.0 to 6.9 are classified as "moderate," M 7.0 to 7.9 are classified as "major," and M 8.0 and larger are classified as "great" (LAHD, 1993). This scale is logarithmic, where each whole number increase in Richter magnitude (M) represents a tenfold increase in the wave amplitude generated by an earthquake, which is a representation of an earthquake's size. Additionally, for each full point increase in Richter magnitude, the corresponding amount of energy released is 31.6 times greater. Another measure of earthquake intensity is the Modified Mercalli scale. It is based on damage sustained by man-made structures constructed prior to building code revisions that were prompted by the 1933 Long Beach earthquake.

Seismic activity of a fault is determined from the study of past earthquakes associated with that fault. The California Mining and Geology Board has defined an active fault as one which has had "displacement within Holocene time" (within the last 11,000 years). A Potentially Active Fault is one which has not been proven by direct evidence to have either moved or not moved within Holocene time. An inactive Fault is any fault that has been proven by direct evidence not to have moved within Holocene time. Historical records and geologic data indicate that the faults described below are considered active and capable of generating earthquakes that could affect the harbor area. At least two of these faults, the San Andreas and Newport-Inglewood faults, have the potential to cause severe damage in the harbor. Seismicity of these and other faults in the area is summarized on Tables F-3 and F-4, and is discussed below. Historical records indicate extensive seismic activity in the Los Angeles region, particularly with respect to the harbor area (see Figure F-3). Large historic earthquakes recorded in the Los Angeles region are listed on Table F-5 and are summarized below (after LAHD, 1996).

San Andreas Fault Zone

The San Andreas Fault Zone is located approximately 55 miles from the project site. The San Andreas Fault System, comprised of the San Andreas Fault Zone and other major fault zones, is considered the boundary between two major crustal plates (Pacific and North American) that are moving in opposite directions. This motion has been responsible for numerous historic earthquakes along the entire length of the fault, including several major and two great earthquakes.

Physical evidence of historic earthquakes that have occurred along the San Andreas Fault since 260 a.d. is preserved in the sediments at Pallett Creek, about 16 miles southeast of Palmdale. Twelve significantly large earthquakes, including the 1857 Fort Tejon earthquake, are recorded in the sediments at this site. The "San Juan Capistrano" earthquake of December 8, 1812, estimated at M 7.0, is considered one of these twelve events (Sieh et al., 1989). At least 5 of the earthquakes were similar in magnitude to the 1857 event (Ziony and Yerkes, 1985).

Based on earlier studies of the occurrence of these twelve earthquakes, the average recurrence interval for a major (M 7.0-7.9) or great (M 8.0+) earthquake in the area was estimated at 145 years (Ziony and Yerkes, 1985). Recent studies by Sieh et al. (1989), have refined earlier data. Sieh et al. (1989) now estimate the average recurrence interval for a major or great earthquake in the area at 132 years.

There is a high probability that southern California will experience another great earthquake similar in magnitude to the 1857 event during the remainder of this century or early in the next century. Such an event would be capable of generating strong or intense ground motion in the Los Angeles Harbor area (Davis et al., 1982). There is a 44 percent probability of a M 7.5 event occurring along the Mojave Desert or San Bernardino Mountain segments of the San Andreas Fault Zone in southern California during the next 30 years (Ward and Page, 1990). Computer models (Evernden and Thomson, 1985; Davis, 1982) of a seismic event similar to the 1857 earthquake indicate that the harbor area will experience Modified Mercalli intensities of VII to VIII. The San Andreas Fault has been zoned for special studies under the Alquist-Priolo Act (Hart, 1988).

San Jacinto Fault Zone

The San Jacinto Fault Zone, about 55 miles from the harbor, is a northwest trending series of right-lateral faults. The San Jacinto Fault Zone is currently considered the primary active branch of the San Andreas Fault System in this area (Iacopi, 1973). It may be the most active fault in southern California, producing numerous small to moderately large historic earthquakes (Allen, 1965). This fault has been zoned for special studies under the Alquist-Priolo Act.

The high level of seismic activity exhibited by the San Jacinto Fault Zone indicates continuous releases of strain along this zone. As a result, the probability of a major (M 7.0 to 7.9) or great (M 8.0+) earthquake occurring on the San Jacinto Fault Zone is very low. Small to moderate earthquakes will continue to result from movement along this zone, but compared to the seismic risk from other faults in the region, the San Jacinto Fault Zone is not considered a primary seismic hazard to the harbor area. However, a large earthquake along this zone could generate strong ground motion in the harbor and pipeline area.

Newport-Inglewood Structural Zone

The Newport-Inglewood structural zone, located about 5 miles from the project site, is zoned for special studies under the Alquist-Priolo Act. This zone poses one of the greatest seismic hazards to Los Angeles (Toppozada et al., 1988 and 1989). Because it is located within the greater Los Angeles metropolitan area, a major earthquake along this zone would produce intense ground motion and result in more damage and loss of life in Los Angeles than a M 8.0 earthquake on the San Andreas Fault (Toppozada et al., 1988 and 1989).

Table F-2

MAXIMUM PROBABLE AND CREDIBLE EARTHQUAKES, LOS ANGELES HARBOR AREA

Fault Zone	*Approximate Distance from Site (mile)*	*Estimated Total Fault Length (mile)*	*Maximum Magnitude of Historical Earthquakes (Richter)*	*Probable Maximum Rupture Length for Maximum Earthquake (mile)*	*Corresponding Range of Maximum Earthquake Magnitudes (Richter)*	*Maximum Probable Earthquake Magnitude (Richter)*	*Maximum Credible Earthquake Magnitude (Richter)*
Palos Verdes	<1	12	not known	6 or less	5.0 - 6.0	5.0	6.0
Newport-Inglewood	5	55	6.3 (1933)	27 or less	6.6 - 7.6	6.6	7.6
Whittier	21	64	3.2 (1971)	30 or less	6.8 - 7.7	6.8	7.7
Elsinore	25	110	5.5 (1938)	55 or less	7.2 - 8.0	7.2	8.0
San Jacinto	50	190	7.1 (1940)	95 or less	7.5 - 8.2	7.5	8.2
San Andreas	53	700+	8.3+(est.) (1857)	200 or less	7.7 - 8.4	7.7	8.4
Sierra Madre-San Fernando	27	65	6.4 (1971)	30 or less	6.6 - 7.7	6.6	7.7

Sources: LAHD (1988); Frank & Associates (1992).

Table F-3

ESTIMATED GROUND AND BEDROCK MOTION CHARACTERISTICS FOR MAXIMUM PROBABLE EARTHQUAKES LOS ANGELES HARBOR AREA

Fault Zone	*Distance from Site (miles)*	*Estimated Magnitude (Richter)*	*Estimated Maximum Bed Rock Acceleration at site (g)*	*Estimated Repeatable High Ground Acceleration at site (g)*	*Predominant Period of Bed Rock Motion (seconds)*	*Probable Duration of Strong Shaking (seconds)*
Palos Verdes	<1	5.0	0.56	0.36	0.25	16
Newport-Inglewood	5	6.6	0.65	0.42	0.30	25
Whittier	21	6.8	0.21	0.14	0.35	29
Elsinore	25	7.2	0.20	0.13	0.35	37
San Jacinto	50	7.5	0.10	0.07	0.45	45
San Andreas	53	7.7	0.10	0.07	0.50	52
Sierra Madre-San Fernando	27	6.6	0.12	0.08	0.30	25

Sources: LAHD (1988); Frank & Associates (1992).

Table F-4

EXPECTED GROUND MOTION PARAMETERS, LOS ANGELES HARBOR AREA

Fault	*Slip Rate (inch/yr)*	*Length (miles)*	RECURRENCE INTERVALS AT A POINT ON FAULT (YEARS) *M 6*	*M 7*	*M 8*	RECURRENCE INTERVALS OVER LENGTH OF FAULT (YEARS) *M 6*	*M 7*	*M 8*
Northwest Trend Right-Slip								
San Andreas (southern segment)	1.18	310	10	40	200	3-1	3-10	40-100[a]
San Jacinto	0.12	190	100[a]	400[a]	2,000	4-100[a]	40-100[a]	400-1,000
Whittier-Elsinore-Agua Caliente-Laguna Salada	0.03	170	300	2,000	6,000	20-90	200-900	3,000-9,000
Northeast Trend Left-Slip								
Big Pine	0.08	40	100	600[a]	3,000	20-100	300-1,000[a]	3,000-10,000
Garlock	0.31	155	30	200	600	2-10	30-90	300-900
Reverse and Thrust								
White Wolf	0.02	33	1,000	2,000[a]	4,000	200-900	1,000-5,000[a]	8,000-25,000
Sierra Madre-San Fernando	0.31	65	100[a]	300[a]	800	30-100	100-600[a]	800-2,000

Note: a. Most likely, based on historical records.

Source: Lamar et al. 1973.

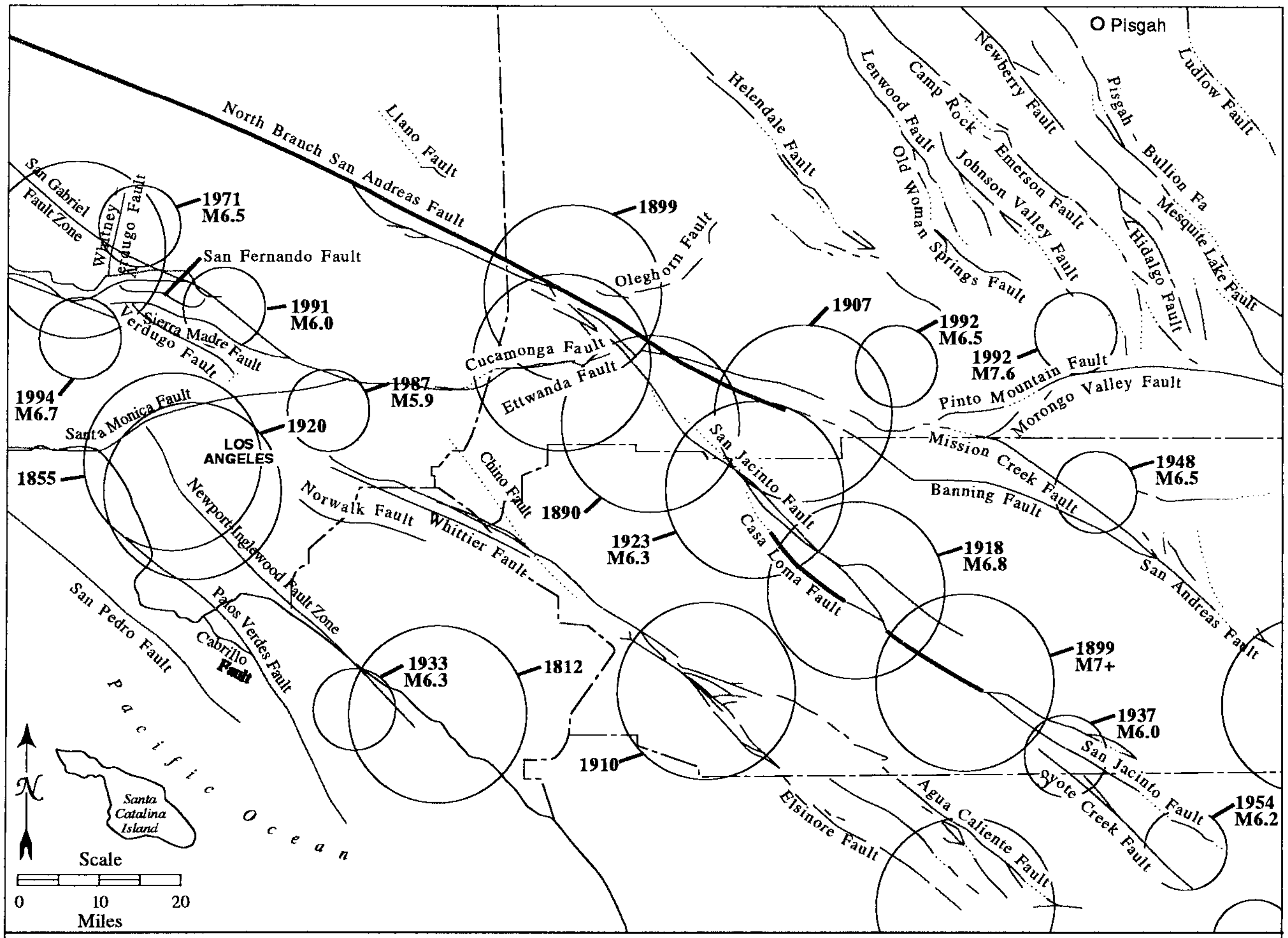
Table F-5

LARGE EARTHQUAKES RECORDED IN THE LOS ANGELES HARBOR AREA

Date	Magnitude	Fault
17 Jan 1994	6.7	Northridge (unnamed subsurface fault)
28 Jun 1992	7.6	Landers (Camp Rock-Emerson; Johnson Valley; Homestead Valley)
28 June 1992	6.5	Big Bear (unnamed subsurface fault)
1 Oct 1987	5.9	Elysian Park Fault
9 Feb 1971	6.4	San Fernando-Sunland Fault
21 Jul 1952	7.7	White Wolf Fault
1 Jul 1941	5.9	Undetermined Fault in Santa Barbara Channel
10 Mar 1933	6.3	Newport Inglewood Fault Zone
4 Nov 1927	7.5	Undetermined Fault offshore Point Arguello
29 Jun 1925	6.3	Undetermined Fault in Santa Barbara Channel
23 Jul 1923	6.3	Claremont Fault (San Jacinto Fault Zone)
21 Apr 1918	6.8	Claremont Fault (San Jacinto Fault Zone)
23 Oct 1916	6.0*	Tejon Pass area (San Andreas Fault Zone, suspected)
25 Dec 1899	6.6*	Claremont Fault (San Jacinto Fault Zone)
4 Apr 1893	6.0*	San Fernando-Santa Susana Fault
9 Jan 1857	8.3+*	San Andreas Fault Zone
8 Dec 1812	7.0*	San Andreas Fault Zone (Newport-Inglewood Fault Zone also suspected)
21 Dec 1812	7.1*	Undetermined Fault in Santa Barbara Channel
28 Jul 1769	6.75*	San Fernando-Santa Susana Fault (suspected)

Notes: * Estimated magnitude.
+ Or greater.

Source: Engineering-Science, Inc.



MAJOR EARTHQUAKES AND RECENTLY ACTIVE FAULTS IN THE SOUTHERN CALIFORNIA REGION

ACTIVE FAULTS

Total length of fault zone that breaks Holocene deposits or that has had seismic activity

Fault segment with surface rupture during an historic earthquake, or with a seismic fault creep.

O Holocene volcanic activity (Amboy, Pisgah, Cerro Prieto and Salton Buttes)

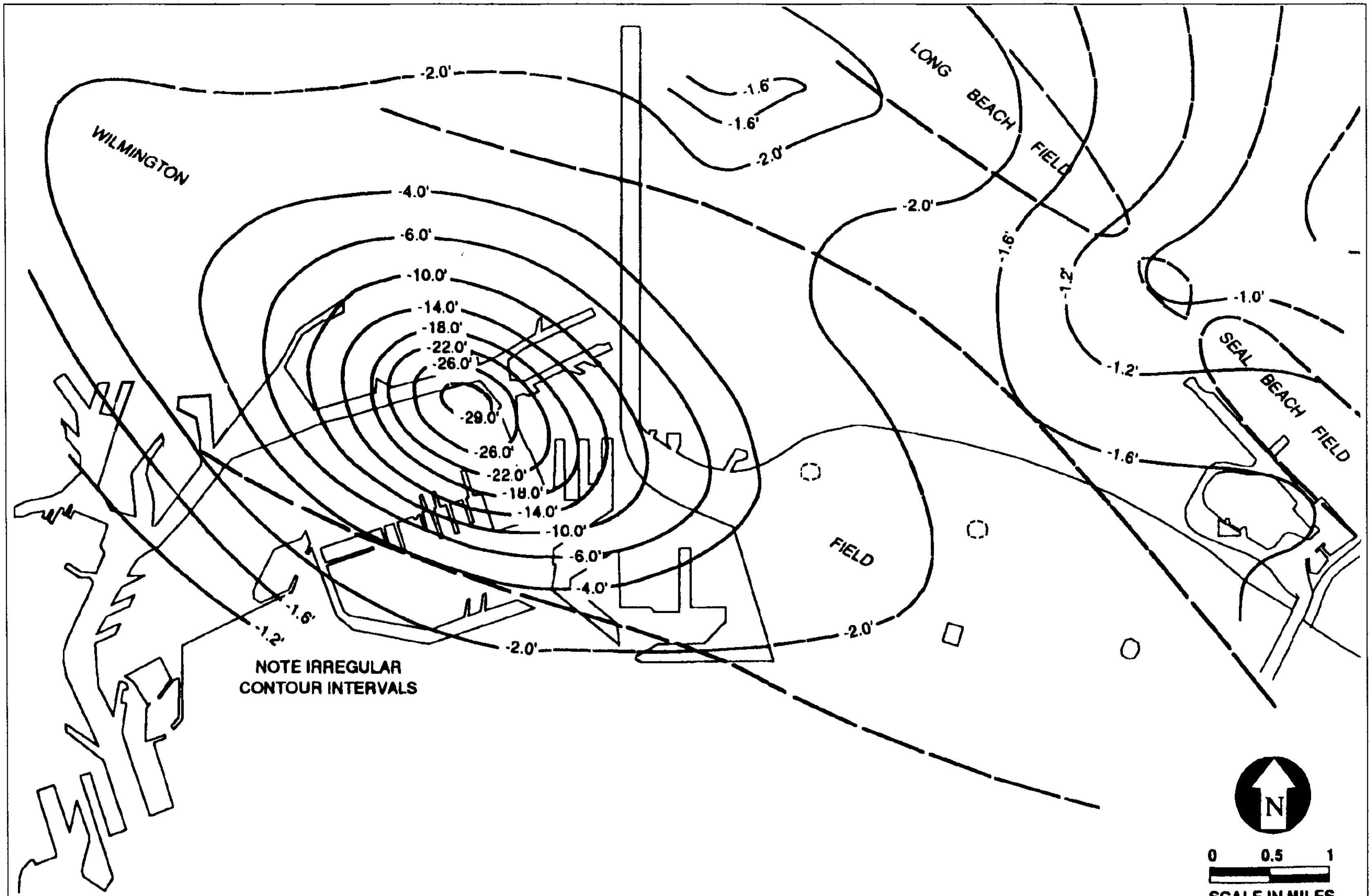
EARTHQUAKE LOCATIONS

1899 M7+ — Approximate epicentral area of earthquakes that occurred 1769-1933. Magnitudes not recorded by instruments prior to 1906 were estimated from damage reports assigned on intensity VII (Modified Mercali scale) or greater; this is roughly equivalent to Richter M6.0. 31 moderate earthquakes, 7 major and one great earthquake (1857) were reported in the 164-year period 1769-1933.

1952 M7.7 — Earthquake epicenters since 1933, plotted from improved instruments. 29 moderate and three major earthquakes were recorded in the 40-year period 1933-1973.

Source: SAIC, from Moran et. al. 1973.

Figure F-2. Regional Fault Map



Source: Allen (1973)

Figure F-3. Cumulative Subsidence 1928-1970, Wilmington and Nearby Oil Fields

The Newport-Inglewood fault zone consists of a series of northwest trending fault segments and folds, extending from Beverly Hills southeast to Newport Bay. Various fault segments of the Newport-Inglewood fault zone have a history of moderate to high seismic activity. The largest instrumentally recorded event was the 1933 Long Beach earthquake. It occurred on the offshore portion of the fault zone and registered a Richter magnitude of 6.3. A maximum credible earthquake of M 7 has been assigned to this fault zone (Ziony and Yerkes, 1985).

The impact of a large or major future earthquake along the Newport-Inglewood structural zone has been studied extensively (Barrows, 1974; Evernden and Thomson, 1985; Toppozada et al., 1988 and 1989). A large or major earthquake along this fault zone would produce intense ground motion in the harbor area (Toppozada et al., 1988). Computer modeling of hypothetical M 6.5 (Evernden and Thomson, 1985) and M 7.0 (Toppozada et al., 1988 and 1989) earthquakes along the northern portion of the Newport-Inglewood Fault indicates the generation of Modified Mercalli intensities of VIII+ to IX at the harbor, causing extensive damage to harbor and pipeline facilities.

Palos Verdes Fault Zone

The Palos Verdes Fault Zone lies along the northeast margin of the Palos Verdes Hills and passes through the Los Angeles Harbor. It is inferred that this fault crosses within about 0.5 mile east of the site, however, the exact location of the fault is not well-defined. As illustrated in Figure F-1, several authors have extended the fault trace across the harbor area resulting in the fault being about 1.5 miles of the project site. In general, the main shear of this fault zone has been projected beneath West Basin and the Vincent Thomas Bridge, extending to the southeast, and exiting the harbor near Angel's Gate (U.S. Army Corps of Engineers, 1985). Offshore, the Palos Verdes Fault Zone is about 0.5 mile wide, and as much as 6,500 feet of vertical offset has been observed (Ziony et al., 1974).
Geologic evidence suggests that the main portion of the Palos Verdes Fault zone extends approximately 40 miles (64 km) from Redondo Beach, southeast through Los Angeles Harbor (Dames & Moore, 1977). Within Los Angeles Harbor, the fault zone is approximately 0.6 to 0.9 mile (1 to 1.5 km) wide and includes at least five prominent fault segments. Predicted segments of the fault cross Terminal Island and pass offshore at its west end, near Reservation Point and Fish Harbor (MESA-2, 1983), directly underneath part of Pier 300 and 400. The activity of this fault zone is the subject of differing professional opinion. According to Dames & Moore and MESA-2 (1983), two of these fault segments show evidence of Holocene activity further offshore. However, recent work by the U.S. Geological Survey (LAHD, 1993b) has resulted in some doubt as to whether the Palos Verdes Fault has caused, or is capable of causing, surface rupture. Other studies by Darrow and Fischer (1983) and Fischer (1987), based on geophysical evidence, have inferred that some surface rupture during late Holocene has occurred along offshore segments of this fault (USACE and LAHD, 1992).

The Cabrillo Fault, part of the Palos Verdes Fault Zone, is located approximately 1,640 feet southwest of the San Pedro breakwater. It marks a zone of disruption up to 1,640 feet wide, which extends over 6 miles long (U.S. Army Corps of Engineers, 1990). Late Pleistocene activity has been inferred for the onshore portion of the Cabrillo Fault, while offshore activity has been estimated to be of late Holocene Age (U.S. Army Corps of Engineers, 1990).

Although historically no damaging earthquakes are known to have been associated with this fault, it should be considered a potential source of both strong ground motion and ground surface rupture. No damaging historic earthquakes are associated with the Palos Verdes Fault, but minor seismic activity has been measured near offshore segments of this fault (Real et al., 1978). Offshore geophysical data reveal abundant evidence that fault segments cut across Holocene sediments and displace the seafloor, indicating recent activity (Darrow and Fischer, 1983; Fischer, 1987). Based on offshore seismic reflection data, it has been inferred that two to five moderate earthquakes caused surface rupture along this fault zone during the late Holocene (Fischer, 1987).

Although the Palos Verdes Fault has not been designated "active" under the Alquist-Priolo Act, this fault should be considered a potential source for strong ground motion, and possible surface rupture, in the harbor and pipeline areas. Wesnousky (1986) assigns a maximum credible earthquake of M 7 to the Palos Verdes Fault zone. However, Teng and Henyey (1975) estimate that the probability of a M 6 seismic event along the fault over a given 100-year period is low. According to Rockwell et al. (1987), the seismic slip potential for the fault is estimated to be about the same as that for the Newport-Inglewood fault (i.e., a known active fault) because both are receiving equal amounts of stress.

Whittier-Elsinore Fault Zone

The Whittier-Elsinore Fault Zone, located approximately 20 miles from the harbor which parallels the San Jacinto Fault, is a zone of moderate seismic activity, producing numerous earthquakes of M 4, and a few M 5 earthquakes. These faults have been zoned for special studies under the Alquist-Priolo Act.

The probability of this fault zone generating a major earthquake during the life of the project is extremely low (Lamar et al., 1973). Preliminary evidence suggests that the magnitude 5.3, October 4, 1987, aftershock of the October 1, 1987 (M 5.9), Whittier Narrows earthquake may have occurred on the northernmost portion of the Whittier fault. A maximum credible earthquake of M 7 has been proposed for the Whittier-Elsinore fault (Ziony and Yerkes, 1985). Although the impact on harbor facilities from earthquakes along this fault zone is considered low relative to other faults discussed in this section, this fault is capable of generating moderate ground motion in the harbor and pipeline area.

Faults of the Transverse Ranges

Unlike most major features in California, which trend northwest-southeast, mountains and valleys of the Transverse Ranges trend predominantly east-west. North and south of the Transverse Ranges, the San Andreas fault has a long, straight south-southeasterly trend, but as it enters the Transverse Ranges, it swings more eastward to form a "great bend." The part of California on the southwest side of the San Andreas fault, along with the adjacent floor of the Pacific Ocean, are moving northwest relative to the parts of California on the northeast side of the fault and the rest of North America. Because of the "great bend," these two major structural blocks are, in part, moving toward each other in this area, causing strong north-south compression over a fairly large region. This compression is relieved, in part, by both vertical and lateral movement along other east-west trending faults. Vertical movement is responsible for uplift of the mountainous terrain in the Transverse Ranges.

The Frontal Fault System and the Santa Susana-San Fernando-Sierra Madre Fault System, as well as their offshore extensions, are two of the major east-west trending fault zones within the Transverse Ranges. Based on the 1927 Point Arguello (M 7.5) and 1952 Kern County (M 7.7) earthquakes, Ziony and Yerkes (1985) suggest the possibility of a M 7.7 earthquake within the Transverse Ranges.

Malibu-Santa Monica-Hollywood-Raymond Hill Fault System

The Malibu-Santa Monica-Hollywood-Raymond Hill Fault System, known as the Frontal Fault System, is comprised of several individual faults located within 24 miles of the harbor area. Faults within the Frontal Fault System have been active during Quaternary, and probably during the Holocene (Hill et al., 1979; Weber et al., 1980). Holocene displacement has been documented for the Raymond Hill Fault, and has also been inferred for the Hollywood Fault (Ziony and Jones, 1989).

This fault system is considered active (Jennings, 1975), and capable of generating damaging earthquakes. The Raymond Hill fault has been zoned for special studies under the Alquist-Priolo Act. Major earthquakes along this system could generate strong ground motions in the harbor and in the area of the proposed pipeline.

Santa Susana-San Fernando-Sierra Madre Fault System

The Santa Susana-San Fernando-Sierra Madre Fault System, located within 30 miles of the harbor area, is comprised of a series of independent, arc-shaped fault segments. This fault system is active and capable of generating moderate to major earthquakes with associated strong or intense ground motions in the area. Approximately 7 feet (2 m) of uplift occurred along the westward extension of this fault during the 1971 San Fernando earthquake (Crook et al., 1978). A more recent earthquake of M 6.0 occurred on June 28, 1991 that has been attributed to movement on this fault. A maximum credible earthquake of M 7.5 has been proposed for this fault (Ziony and Yerkes, 1985). The San Fernando Fault has been zoned for special studies under the Alquist-Priolo Act. Strong ground motions in the harbor could result from a large earthquake along this fault system, and could cause extensive damage to harbor and pipeline facilities.

Elysian Park and Torrance-Wilmington Faults

It has been inferred that potentially destructive, deeply buried faults underlie the Los Angeles Basin. These low-angle reverse or thrust faults include the Elysian Park and Torrance-Wilmington faults (Kerr, 1988). Little is known about either of these faults. Their existence is inferred from the clustering of data from deep earthquakes along two trends.

The Elysian Park Fault, the better known of these two faults, lies within 20 miles of the harbor. It follows a line of hills extending from Whittier through Montebello, Elysian Park, the Cahuenga and Sepulveda passes, to Malibu and Point Dume (Reich, 1989).

The Torrance-Wilmington Fault follows the Newport-Inglewood structural zone offshore from Newport Beach to Long Beach, crosses beneath the harbor and the Palos Verdes Hills, extends into Santa Monica Bay, and merges with the Elysian Park Fault near Malibu.

The newly proposed Torrance-Wilmington fault (Hauksson and Saldivar, 1989) underlies the harbor area. Although information is still too preliminary to be able to quantify the specifics of this potential fault system, it appears to be active and responsible for many small to moderate earthquakes within Santa Monica Bay and the Los Angeles Basin. The existence of this fault is inferred from clustering of data from deep earthquakes along a certain trend. The proposed fault could be interacting with the Palos Verdes Fault at depth. Therefore, it should not of itself cause surface rupture, but only strong ground shaking in an earthquake. This type of fault is known as a low-angle thrust or reverse fault, meaning it has a very shallow fault plane.

Elysian Park and Torrance-Wilmington Faults are believed capable of generating earthquakes of M 6.5 to 7.5. The probability of such an earthquake occurring is unknown. An earthquake of this magnitude on either fault would generate intense ground motions in the harbor area. A major earthquake along the Torrance-Wilmington Fault could produce damage equivalent to, or greater than, damage projected for a M 7.0 earthquake generated by the Newport-Inglewood Fault.

Insufficient data are available to allow calculation of parameters associated with faults tabulated on Tables F-2, F-3 and F-4. Because most of the motions generated by an earthquake on a thrust fault occur on the upper plate (Oakeshott, 1975), local peak horizontal ground accelerations experienced during a major (M 7.0) earthquake on either of these faults could easily exceed 1.0 g. [It is common practice to refer to ground accelerations relative to a known acceleration, i.e., gravity (g) or 9.8 m/s^2.] Groundshaking would be intense and of long duration. Typically, engineered structures are not designed to withstand such large ground accelerations, and may not be able to withstand long durations of intense groundshaking. The design standards set by the Uniform Building Codes require that structures built in Seismic Zone IV (most of southern California) be constructed to withstand accelerations of 0.44 g. Groundshaking would be intensified where underlying sediments are water saturated.

Effects of Earthquakes

The principal damaging effects of earthquakes consist of strong ground motion, fault displacement, liquefaction, and tsunamis.

Effects of Strong Ground Motion

The intensity of ground shaking at a specific location depends on several factors, including earthquake magnitude, distance from the source (epicenter), and site response characteristics, particularly near-surface geologic materials. Table F-1 lists the generalized seismic parameters for the project area. These were estimated using empirical relationships between the listed parameters with distance from the causative fault and earthquake magnitude, associated with a maximum probable earthquake on the causative fault. These parameters are used in the design of earthquake-resistant structures and include peak horizontal ground acceleration, predominant period, and duration of strong ground motion.

Ground shaking generally causes the most widespread effects, not only because it can propagate considerable distances from an earthquake source, but also because it can trigger secondary effects. These secondary effects include liquefaction and slope failure, with resultant structural damage to buildings and foundations. The effects of ground shaking are often greatest on young, water-saturated sediments. Within the Los Angeles Harbor, the existing hydraulically placed landfills consist predominantly of loose to medium-dense, water-saturated sands and silts.

Fault Displacement

Based on the location of the Palos Verdes Fault in Los Angeles Harbor and possible evidence of Holocene activity along this zone, there is a potential for surface fault rupture in this area. However, as discussed previously in this section there are differing opinions among experts as to the recency of activity along this fault. There is no accurate predictive measure available to assess potential surface fault rupture on this fault.

The potential maximum surface displacement during future earthquakes on this fault zone can be estimated from empirical relationships between earthquake magnitude, length of surface rupture, and amount of surface displacement along faults. Based on an assumed Richter magnitude 6.5 to 7.0 event, the estimated potential maximum surface displacement is 3 to 7 feet (1 to 2 m), should it occur.

Liquefaction

Strong ground motions generated by earthquakes cause various types of ground failures, including liquefaction. Liquefaction is most likely when cohesionless, granular sediments are water saturated to within 50 feet or less of the surface. Unconsolidated silts, sands, and silty sands are most susceptible to liquefaction. Soil liquefaction is a phenomenon in which the ground loses its strength or stiffness when ground shaking associated with an earthquake induces large excess pore water pressures, causing the soil to liquefy. While almost any saturated granular soil can develop increased pore water pressures when shaken, these excess pore water pressures can lead to liquefaction if the intensity and duration of earthquake shaking are great enough. Among the recent earthquakes that were great enough to cause liquefaction were the Loma Prieta earthquake in 1989, the Mexico City earthquake in 1985, the Central Japan Sea earthquake in 1983, the San Fernando earthquake in 1971, the 1964 Alaska earthquake, and the Niigata (Japan) earthquake in 1964. Structures particularly vulnerable to liquefaction during these earthquakes were buildings with shallow foundations, railways, highways, bridges, buried structures, dams, canals, retaining walls, port structures, utility poles, and towers. Shaking intensity decreases approximately one intensity unit with an increase in depth to groundwater from 0 to 30 feet (Evernden and Thomson, 1985).

Subsidence

Subsidence in the Los Angeles-Long Beach Harbor area was first observed in 1928. It has affected the majority of the harbor area to varying degrees. Based on extensive studies by the City of Long Beach and the California Division of Oil and Gas, it has been determined that most of the subsidence shown in Figure F-4 is the result of oil and gas production from the Wilmington Oil Field, following its discovery in 1936. Water injection operations to repressurize the field and increase oil recovery were initiated in the early 1950s. Now regulated by the Division of Oil and Gas, this practice has effectively mitigated the subsidence from oil extraction activities.

Tsunamis and Seiches

A tsunami is an ocean wave generated by the rapid displacement of a large volume of seawater as a result of either submarine vertical faulting or large-scale submarine landslides. These ocean waves, also known as seismic sea waves, may travel thousands of miles, reach heights over 40 feet, and cause extensive damage to unprotected coastal areas. Based on the Safety Element of the Los Angeles County General Plan (Leighton and Associates, 1990), the project site lies within the modeled inundation area for a tsunami with a 500-year recurrence interval.

During historic times, coastal California has experienced numerous tsunamis of both local and distant origin. Crescent City in northern California received extensive damage from a tsunami generated by the 1964 Alaska earthquake (M 8.6). Waves in Los Angeles following this event reached up to 3 feet (1 m) in height (McCulloch, 1985). Los Angeles and Long Beach Harbors sustained minor damage (USACE and LAHD, 1992). The most damaging tsunami in southern California occurred after the 1960 Chilean earthquake (M 8.8 to 8.9) when 5-foot (1.5 m) waves were documented in Los Angeles harbor (McCulloch, 1985). Locally, the 1927 Point Arguello earthquake generated a tsunami of 6.5 feet in the Los Angeles region (Ziony and Yerkes, 1985).

A seiche is an oscillatory wave in an enclosed body of water, such as a harbor, lake, reservoir or water tank. They are produced by high winds, earthquakes, or atmospheric changes, and can result in structural damage and/or flooding hazards. Tsunamis and storm surges may cause seiches in the harbor that can cause extensive damage or erosion. Most of the damage to boats and harbor facilities caused by the tsunami associated with the 1960 Chilean earthquake resulted from seiche movements within the Cerritos Channel.