of these passenger terminals were accessible for observation, whereas the office buildings were not; no damage to the interiors of the passenger terminals was observed at the time of our reconnaissance. The soil settlements alongside pile-supported buildings that otherwise performed well during the earthquake were larger at buildings located in the waterfront areas (i.e., areas of lateral, as well as, vertical movement of the soils).

3.6.3 Parking Structure at Pier 4 of Shinko Piers

An interesting example of liquefaction-induced building damage at the port was a two-story parking structure at Pier 4 of the Shinko Piers. This structure is located just to the north of the south end of Pier 4 (see Fig. 3-29) where liquefaction of the fills caused lateral movement of the quay walls, substantial ground settlement, and lateral movement of the north support of the Kobe Ohashi Bridge (as discussed further below). The parking structure was founded on piles and pile caps interconnected by grade beams. Liquefaction of the fills beneath the structure led to extensive settlement (exceeding 2 m at some locations) of the pavement between the grade-beam/pile-cap supports (Figs. 3-30a through c). In addition, approach ramps leading from the roadway just north of the bridge into the parking structure were severely damaged (Figs. 3-29 and 3-30d and e). No significant damage to the aboveground structural elements of the parking structure was observed, suggesting that its pile foundation probably performed effectively (although the piles themselves were not accessible for observation during our reconnaissance).

3.7 Seismic Performance of Supporting Lifelines and Tanks

3.7.1 Highway Bridges

Highway bridges that service the Port of Kobe area also experienced damage that inhibited post-earthquake repair and reconstruction efforts at the port. Examples of this damage are described below:

0 **Kobe Ohashi Bridge.** This steel arch bridge that links Port Island to Pier 4 of the Shinko Piers and the City of Kobe experienced damage in the form of about 0.6 meters of horizontal movement of the base of its north column support relative to its pile cap support (Fig. 3-31). Liquefaction and extensive movement of the underlying soils was the major contributor to this observed damage. In addition, the earthquake damaged the north approach to the Kobe Ohashi Bridge, which extends along Pier 4 and is a reinforced concrete elevated viaduct with two-column bents. This approach suffered extensive column damage, due to inadequate shear reinforcement in the presence of strong ground shaking (Fig. 3-32). Both the Kobe Ohashi Bridge and its north approach were open to limited automobile traffic at the time of our reconnaissance.

0 **Maya Ohashi Bridge and the Dai-ni Maya Ohashi Bridge.** These two parallel adjacent bridges connect the western portion of the Maya Piers at Pier 1 to the eastern part of the Shinko Pier near Pier 8. Both bridges were damaged and closed to traffic during our
reconnaissance. The Dai-ni Maya Ohashi Bridge suffered damage to its foundations, its columns (fracture of transverse reinforcement of columns and buckling of longitudinal column reinforcement), and its beam-column joints. Extensive soil movement at the base of the bridge columns was undoubtedly a significant contributor to this damage, in addition to ground shaking (Fig. 3-33). The Maya Ohashi Bridge is a cable-stayed structure which shifted off of its seats at the top of the piers (Fig. 3-34). Despite the movement of the main bridge deck, the support cables appeared to have retained most, if not all, of their tension.

0 Nadahama Ohashi Bridge. This bridge connects the northeast corner of the Maya Piers to the mainland. It appeared to be undamaged despite considerable liquefaction-induced soil deformation around the foundation.

0 Hanshin Expressway Bridge (Osaka Bay Route). This new steel arch bridge, which connects Rokko Island to the mainland, suffered a bearing failure due to excessive substructure movements (Fig. 3-35). This led to a racking of the arch and a buckling of the top cross framing. In addition to large inertia forces due to strong shaking, the bridge substructure was subjected to liquefaction-induced ground displacements (Fig. 3-35d). The results of detailed surveys of the bridge piers will indicate if the foundations have undergone permanent deformation, and will also yield important information on the interaction of this large pile-supported structure with its surrounding liquefied soils.

3.7.2 Rail System Damage

In addition to highway bridge damage along the Kobe Port, railroad bridges near the port also suffered damage (see Chapter 2). Information on the impact of this damage on the post-earthquake recovery of the Kobe Port is expected to become available in the months to come.

3.7.3 Utility Lifelines

As a result of the massive soil movement at the port, underground water, wastewater, and natural gas pipelines in the area were severely damaged. This damage had not yet been repaired at the time of our visit; as a result, service of these utility lifelines had not yet been restored, and there was no indication that these utility services would be restored in the immediate future. Power and telephone communication were operating at the port during our reconnaissance. Damage to these utilities was reportedly restored throughout the Kobe area (including the port) within a few days after the earthquake. Examples of damaged water lines at the Port of Kobe are shown in Figure 3-36.

3.7.4 Tanks

During our Kobe Port reconnaissance, we were able to carry out limited observations of tanks farms at the Nagata Harbor (western-most portion of the port) and near the entrance to the Fourth Reclamation Area (eastern-most portion of the port). The tanks at Nagata Harbor were observed to have tilted substantially, and minor wall buckling was observed at tanks in the Fourth Reclamation
Area (Fig. 3-37). More widespread damage at tank farms and also at oil and petrochemical terminals at the Kobe Port has been reported by others (e.g., Eskijian, 1995).
<table>
<thead>
<tr>
<th>Pier</th>
<th>Dates of Reclamation</th>
<th>Dates of Construction</th>
<th>Total Length of Waterfront (m)</th>
<th>Total Area (Hectares)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyogo</td>
<td>Prior to 1900</td>
<td>Piers 1-2, 1919-1939</td>
<td>5,100</td>
<td>51</td>
<td>Redevelopment of Piers 2 and 3, 1989-1993</td>
</tr>
<tr>
<td>Takahama Wharf/Naka</td>
<td>Prior to 1900</td>
<td>1900-1920</td>
<td>3,600</td>
<td>34</td>
<td>Redevelopment of piers, 1992-present</td>
</tr>
<tr>
<td>Shinko</td>
<td>Prior to 1900</td>
<td>No. 1-4, 1896-1922</td>
<td>13,700</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No. 4-6, 1919-1939</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No. 7, 1951-1956</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No. 8, 1954-1967</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port Island Stage One</td>
<td>1966-1981</td>
<td>-</td>
<td>-</td>
<td>436</td>
<td></td>
</tr>
<tr>
<td>Port Island Stage Two</td>
<td>1987-1996 (est.)</td>
<td>-</td>
<td>-</td>
<td>390</td>
<td></td>
</tr>
<tr>
<td>Port Island Total</td>
<td>-</td>
<td>-</td>
<td>19,300</td>
<td>826</td>
<td></td>
</tr>
<tr>
<td>Rokko Island</td>
<td>1972-1992</td>
<td>-</td>
<td>12,200</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>Fourth Reclamation Area</td>
<td>1934-1940 (mainland)</td>
<td>1965-1970</td>
<td>3,900</td>
<td>51</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 3-2
GROUND CONDITION AND IMPORTANCE FACTORS USED TO COMPUTE
SEISMIC DESIGN COEFFICIENT FOR PORT FACILITIES IN JAPAN
(KANAI, 1983)

<table>
<thead>
<tr>
<th>Thickness of Quaternary Deposit</th>
<th>Gravel</th>
<th>Sand or Clay</th>
<th>Soft Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5m</td>
<td>1st kind</td>
<td>1st kind</td>
<td>2nd kind</td>
</tr>
<tr>
<td>5-25m</td>
<td>1st kind</td>
<td>2nd kind</td>
<td>3rd kind</td>
</tr>
<tr>
<td>&gt;25m</td>
<td>2nd kind</td>
<td>3rd kind</td>
<td>3rd kind</td>
</tr>
</tbody>
</table>

a) Soil Classifications

<table>
<thead>
<tr>
<th>Classification</th>
<th>1st kind</th>
<th>2nd kind</th>
<th>3rd kind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

b) Ground Condition Factor, G

<table>
<thead>
<tr>
<th>Structure</th>
<th>Characteristics of Structure</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special Class</td>
<td>The structure has significant characteristics described by items (1)-(3) in A class.</td>
<td>1.5</td>
</tr>
<tr>
<td>A Class</td>
<td>(1) If the structure is damaged by an earthquake, a large number of human life and property will possibly be lost. (2) The structure will perform an important role on the reconstruction work of the region after an earthquake. (3) The structure handles a hazardous or a dangerous object, and it is feared that the damage on the structure will cause a great loss of human life or property. (4) If the structure is damaged, economical and social activity of the region will be severely suffered. (5) If the structure is damaged, it is supposed that the repair work of it is considerably difficult.</td>
<td>1.2</td>
</tr>
<tr>
<td>B Class</td>
<td>The structure is other than Special, A and C classes.</td>
<td>1.0</td>
</tr>
<tr>
<td>C Class</td>
<td>The structure is small and easy for repairment, excepting that in Special and A classes.</td>
<td>0.5</td>
</tr>
</tbody>
</table>

c) Importance Factor, I
a) Port Island and Kobe City to North and West

b) Rokko Island and Kobe City to North

FIGURE 3-2
AERIAL VIEWS OF PORT ISLAND AND ROKKO ISLAND
(Port of Kobe, 1994)
FIGURE 3-3
DEVELOPMENT OF KOBE WATERFRONT (1872 TO PRESENT)
(Kashima Construction Company, 1995)
a) General Soil Profile at Port Island (First Stage) (Nakakita and Watanabe, 1981)

b) Grain Size Distribution of Sand Obtained from Liquefaction Features (Kamon et al, 1995)

FIGURE 3-4
SOIL CHARACTERISTICS AT KOBE PORT
a) First Stage

b) Second Stage

FIGURE 3-5
SOIL IMPROVEMENT ON PORT ISLAND
(Fudo Construction Company, 1995)

3-25
FIGURE 3-6
SOIL IMPROVEMENT ON ROKKO ISLAND
(Fudo Construction Company, 1995)
a) Deep Water Section, Naka Pier

b) Shallow Water Section, Sixth Pier of Shinko Piers

FIGURE 3-8
PILE-SUPPORTED CONCRETE CAISSON
QUAY WALLS AT KOBE PORT
(Iwasaki, 1995a)
FIGURE 3-9
HORIZONTAL SEISMIC COEFFICIENTS
USED FOR DESIGN OF PORT FACILITIES IN JAPAN
a) Ranges of Grain Size Distribution Curves for Liquefiable Soils

FIGURE 3-10
ASSESSMENT OF LIQUEFACTION POTENTIAL IN 1989 SEISMIC DESIGN PROCEDURE FOR PORTS IN JAPAN (Iai et al, 1989; Tsuchida 1990)

b) Design Charts
FIGURE 3-11
GROUND MOTIONS RECORDED AT KOBE PORT CONSTRUCTION OFFICE (ON MAINLAND) (DPRI, 1995b)
FIGURE 3-12
DOWNHOLE ARRAY OF ACCELEROMETERS AT PORT ISLAND
(GRI, 1995b)
FIGURE 3-13
HORIZONTAL ACCELEROMGRAMS RECORDED
AT PORT ISLAND DOWNHOLE ARRAY
DURING HYOGO-KEN NANTU EARTHQUAKE
(GRI, 1995b)
FIGURE 3-14
LIQUEFACTION OF FILLS AT KOBE PORT
(Aerial Photos of Port Island from
Kyodo News Agency, 1995 and
Asahi Newspaper Company, 1995b)
FIGURE 3-15
QUAY WALL MOVEMENT AND FILL SETTLEMENT
KOBE PORT
e) Pier 4 at Shinko Piers

f) North Side of Maya Piers
(Yomiuri Shimbun, 1995)

g) Hanky Ferry Terminal

h) Northeast Side of Rokko Island

FIGURE 3-15 (continued)
i) Northeast Side of Rokko Island

j) On Mainland, between Naka Pier and Takahama Wharf

k) On Mainland just North of Pier 4, Shinko Piers

l) Hyogo Pier (Asahi Newspaper Co., 1995b)

FIGURE 3-15 (continued)
FIGURE 3-16
CRANE DAMAGE AT KOBE PORT
e) Damaged Crane Rail at Minami Wharf, Port Island
f) Movement of Crane off of Rail, Rokko Island

g) Crane Repair, Rokko Island
h) Collapsed Support at Pier 7, Shinko Piers

FIGURE 3-16 (continued)
a) Looking North along East Face of Pier 1, at Location of Soil Settlement Adjacent to Steel Cell Caissons

b) Close-up of Soil Movement from a) Above

FIGURE 3-17
SEISMIC PERFORMANCE OF STEEL PLATE CELLULAR BULKHEADS AT PIER 1 OF MAYA PIERS
FIGURE 3-18
MAYA PIERS AND CONTAINER TERMINAL
(Port of Kobe, 1994)
a) Berth A

b) Berth C

FIGURE 3-19
CROSS SECTION OF WATERFRONT RETAINING STRUCTURES AT MAYA PIER 1 (dimensions in meters)
Figure 3-20
Seismic Performance of Waterfront Structures at the Maya Piers

(a) Movement of Quay Wall at North Approach to the Maya Piers (Same Location as Fig. 3-15f)

(b) Damage to Lightly Reinforced Concrete Cylinder Piles Beneath Building in Foreground of a)

(c) Lateral Movement of Caissons at Berth 0.

(d) Area Between Piers 1 and 2
e) Berth E, Pier 1 (Looking Toward Area in d)  

f) Southern End of Pier 1  

g) Southwestern end of Pier 1  

h) View Along West Edge of Pier 1 (Looking North from Berth A)  

FIGURE 3-20 (continued)
i) Minor Quay Wall Damage between Berths B and C

j) Relative Seaward Movement between Berth B (background) and Berth C (foreground)

k) Waterfront at Berth C

l) Interlocking Steel Pipe Piles at Berth C

FIGURE 3-20 (continued)
a) Buckling of Steel Pipe Pile - Fourth Reclamation Area
(Photo Courtesy of Mitsui Construction Company)

b) Fracture of Hollow Concrete Cylinder Pile at Pile Cap - Port Island, Pier 1

FIGURE 3-21
PILE DAMAGE AT KOBE PORT
FIGURE 3-22
GOOD SEISMIC PERFORMANCE OF A PILE-SUPPORTED WHARF (TAKAHAMA WHARF)
FIGURE 3-23
GROUND SETTLEMENT ADJACENT TO PILE SUPPORTED STRUCTURES
a) Connection Failure of Braced Corrugated Metal Warehouse at Naka Wharf, Port Island

b) Door Damage at Building in a)

c) Floor Settlement at Building in a)

d) Damage to Wooden Warehouse, Hyogo Pier

FIGURE 3-24
DAMAGE TO CORRUGATED METAL AND WOODEN BUILDINGS AT KOBE PORT
FIGURE 3-25
POOR PERFORMANCE OF NON-DUCTILE CONCRETE FRAME WAREHOUSE STRUCTURE AT PIERS 8A AND 8B, SHINKO PIERS
FIGURE 3-26
DAMAGE TO NON-DUCTILE CONCRETE FRAME WAREHOUSE STRUCTURE AT PIER 7, SHINKO PIERS
FIGURE 3-27
STRONG MOTION ACCELEROMETER
RECORDED AT PIER 8, SHINKO PIERS
(DPRI, 1995b)
FIGURE 3-28
GOOD SEISMIC PERFORMANCE OF CONCRETE SHEAR WALL STRUCTURE AT PIER 6, SHINKO PIERS
Pier 4 of Shinko Piers

North Approach to Kobe-Ohashi Bridge (Fig. 3-32)

Collapsed Ramp (Fig. 3-30e)

Parking Structure Beneath North Approach (Fig. 3-30)

Kobe-Ohashi Bridge (Fig. 3-31)

Port Island

FIGURE 3-29
AERIAL VIEW OF PIER 4 AND KOBE-OHASHI BRIDGE AFTER EARTHQUAKE
(Mainichi Newspaper Company, 1995)

3-54