6.0 PORT FACILITIES AND COASTAL INFRASTRUCTURE

The main port in Port-au-Prince is operated by the Autorite Portuaire Nationale (APN) and consists of two separate facilities designated as the North Wharf and South Pier. According to data provided by APN, the port handled 978,575 metric tons of cargo in 2005-2006 from 490 ship calls. The port is located slightly north of the main city center of Port-au-Prince and approximately 20 to 25 km from the fault rupture of the 12 January 2010 earthquake (Figure 6.1).

Pre- and post-earthquake aerial images of the port are shown in Figure 6.2, and these images clearly show evidence of liquefaction and lateral spreading, failure of the North Wharf, and collapse of portions of the South Pier. The photo of the port shown in Figure 6.3 (unknown photographer) is circa 1962, and shows one long pier that extends from the main coastal road. This pier is located along the southern margin of the current port (Figure 6.4), which suggests that the present port facility is constructed on fill, likely un-engineered and of unknown origin. Also, from field reconnaissance, it is clear that the fill material extends to the North (to the left and out of view of the photo shown in Figure 6.3), demarcated by dashed lines in Figure 6.4. The port suffered extensive damage during the earthquake (Figure 6.5), inhibiting the delivery of relief supplies to areas affected by the earthquake. Light-colored areas on the ground surface in Figure 6.4 are sand boils/ejecta and can be seen in the eastern half of the container storage yard and behind and between the two warehouses. The locations where large lateral spreading fissures were observed are also shown in Figure 6.5.

Figure 6.1 Location of main port in Port-au-Prince.

Figure 6.2 Pre- and post-earthquake satellite/aerial imagery (top and bottom, respectively) of the port at Port-au-Prince, Haiti (N18.555058°, W72.351144°). Imagery courtesy of Google Earth.

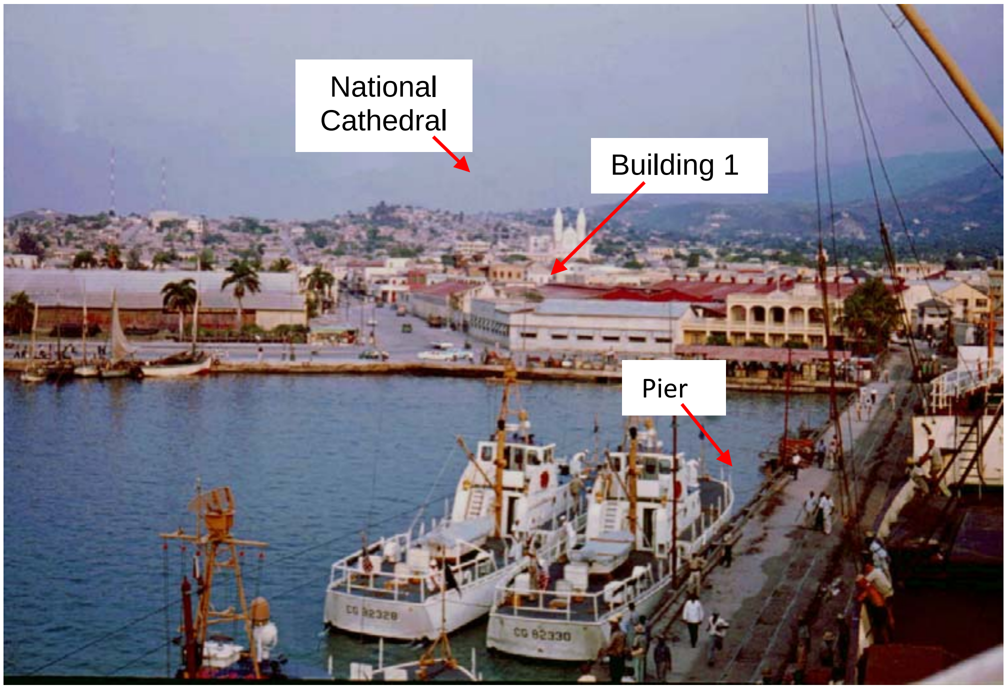


Figure 6.3 Photograph of the port circa 1962 (Source unknown).

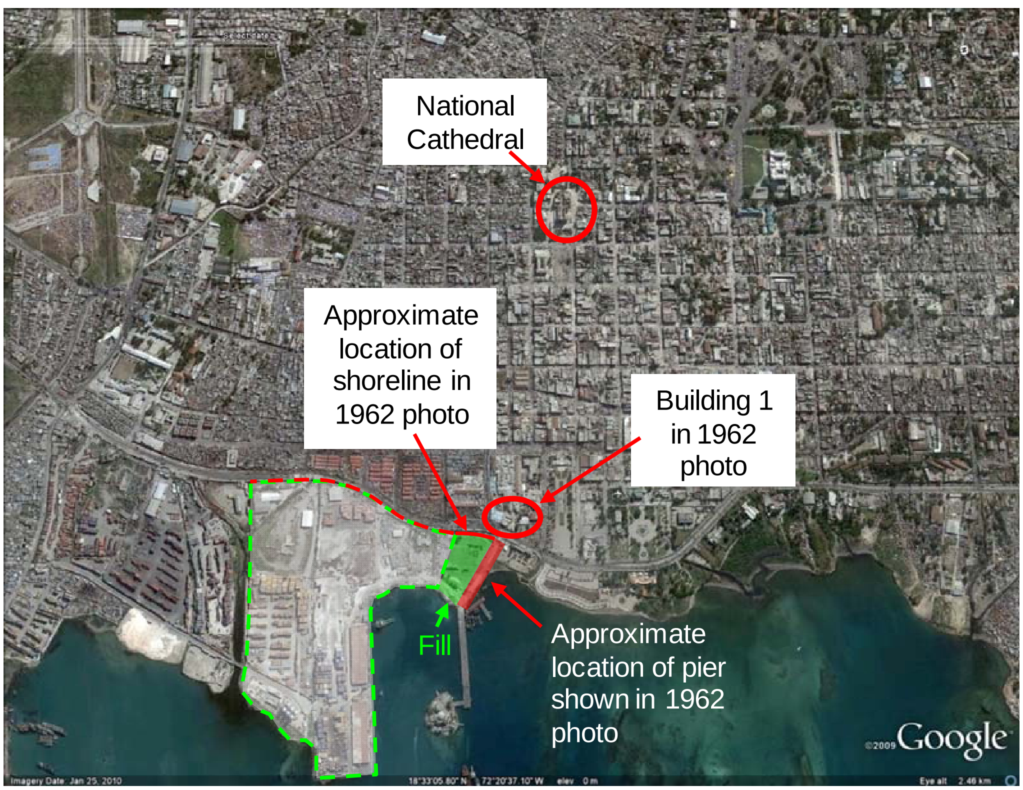


Figure 6.4 Recent aerial image of port, with the landmarks shown in Figure 6.2 annotated. The extent of the fill to the North (left) is unknown and is thus annotated by dashed lines. Imagery courtesy of Google Earth.

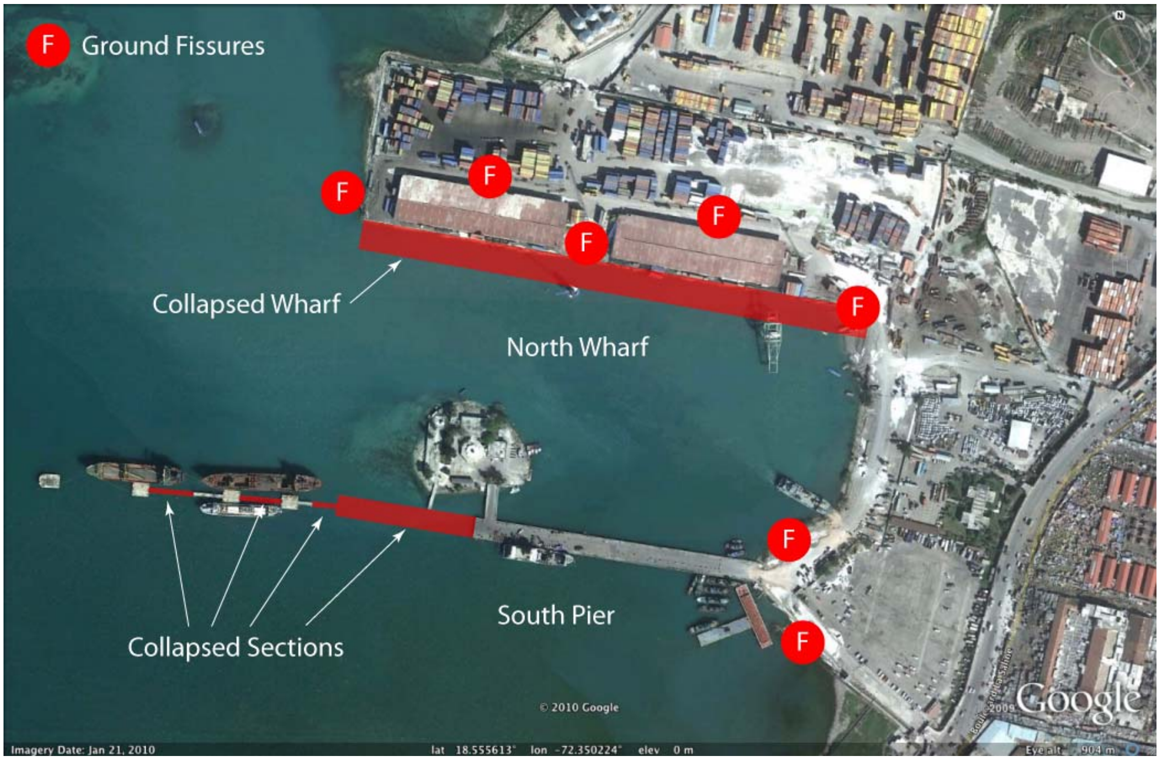


Figure 6.5 Annotated aerial image of Port de Port-au-Prince showing locations of damage due to the earthquake. Imagery courtesy of Google Earth. (N18.555058°, W72.351144°)

The North Wharf consisted of a pile-supported marginal wharf that was approximately 450 m in length and 20 m in width and was likely constructed on un-engineered fill. The water depth is 8 to 10 m. Other information about the construction of the wharf such as when it was constructed and the number and size of piles is unknown at present. Immediately adjacent to the wharf are two steel-frame warehouses, each approximately 150 m by 40 m. Behind the warehouses is a container storage yard with a large number of mostly empty containers stacked two to four high at the time of the earthquake. There are three cranes at the North Wharf, including one 15-m gauge, A-frame container crane and two rubber-tired mobile cranes.

The North Wharf collapsed, most likely due to liquefaction-induced lateral spreading. Numerous surface manifestations of liquefaction and lateral spreading were present in the vicinity of the North Wharf. By the time the GEER Team arrived at the port (G. Rix on 27 January and 2 February for the rest of the team), the US Navy construction teams had already placed fill over large portions of the road that ran adjacent (on the North side) to the warehouses. The Navy construction workers told the GEER Team that the fill was needed because the lateral spread cracks made the road impassable by vehicles. The presence of these cracks was confirmed by post-earthquake satellite/aerial imagery taken between 13 and 21 January, and re-grading had removed them by the time a 25 January image was taken. Nonetheless, numerous manifestations of liquefaction and lateral spreading were untouched at the time of the GEER Team's inspection (Figures 6.6 through 6.11).

Figure 6.6 Lateral spreading adjacent to the collapsed North wharf. Note the crane in the water in the background and the metal warehouses on the right. (N18.55622, W72.34787)

Figure 6.7 Lateral spreading between the two metal warehouses, adjacent to the collapsed North wharf (left). A cumulative total of 89 cm of horizontal movement (determined by crack width) was measured in a zone extending inland approximately 30 m from the post-earthquake shoreline. Post-earthquake imagery indicates lateral spread cracking extended 50 m inland. (N18.556696, W72.34787)

Figure 6.8 Lateral spreading west of the two metal warehouses. Photo taken facing north with the metal warehouses to the right. (N18.557075, W72.352045)

Figure 6.9 Lateral spreading west of the two metal warehouses. Photo taken facing south with the metal warehouses to the left. (N18.557075, W72.352045)

Figure 6.10 Liquefaction and lateral spreading adjacent to the north side of the metal warehouses. Photo on top taken facing west, photo on bottom taken facing east. (N18.556961, W72.349751)

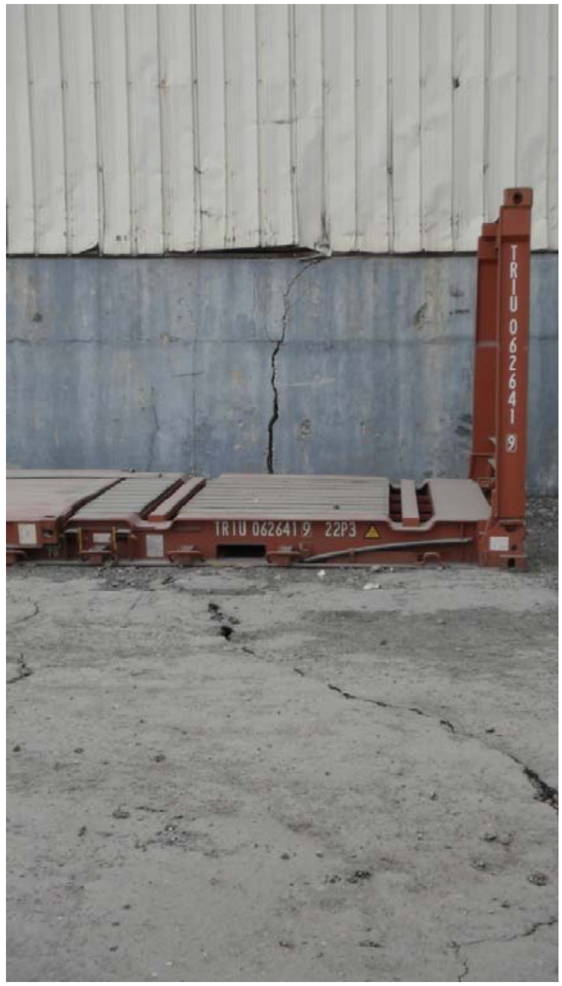


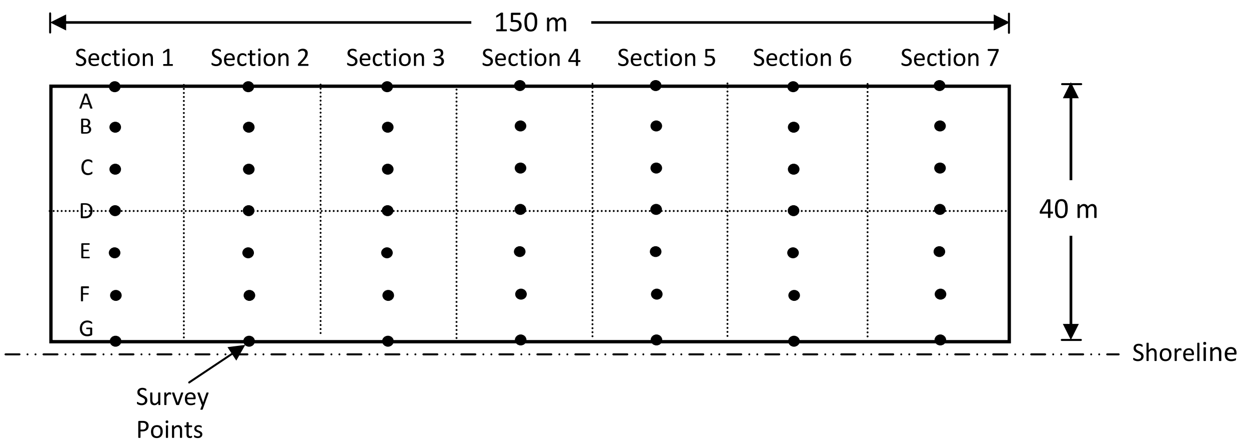
Figure 6.11 Lateral spreading crack extending into the western foundation wall of the west warehouse. Photo taken facing east. (N18.55721, W72.35179)

Two of the three cranes were apparently on the North Wharf at the time of the earthquake and are now partially submerged. Figure 6.12 shows the A-frame container crane in the foreground and a submerged mobile crane in the background. There was no obvious structural damage to the container crane. Interestingly, a photo taken by an unknown photographer (apparently aboard a ship docked at the eastern end of the wharf) immediately after the earthquake (Figure 6.13) shows that the landside legs of the A-frame crane were still above water, with the crane in its most eastwardly position. However, a U.S. Coast Guard photo taken during an overflight of the port at mid-day on January 13, 2010 shows the crane in the same position as in Figure 6.12 (i.e., moved westward about 60 m from its position in Figure 6.13) and with the base of the crane fully submerged. Also, the January 13 photo shows that additional subsidence occurred at the eastern end of North Wharf (i.e., the location of the crane in Figure 6.12). The National Earthquake Information Center reports no fewer than 45 aftershocks ranging from M_w 4.0 to 6.0 following the main shock until 1:54 pm EST on January 13, 2010. This raises the likelihood that a portion of the observed permanent displacements caused by liquefaction occurred as a result of aftershocks. The second mobile crane was parked between the two warehouses and appears to be undamaged.

Figure 6.12 Submerged 15-m gauge container crane (foreground) and mobile crane (background). Photo taken facing west. (N18.55598, W72.348564)

Figure 6.13 Photo taken immediately after the earthquake with the crane in its most eastward position and with the landside legs of the crane above water. Photo taken facing east. Source: unknown (N 18.556056, W72.347981)

The warehouses suffered severe damage as a result of the lateral spreading and settlement, and will likely have to be torn down. As shown in Figure 6.11, lateral spreading cracks running in the East-West direction cut through each warehouse foundation wall. A detailed survey of the relative elevations and lateral movements of the west warehouse slab is shown in Figure 6.14. The interior slab consisted of 14 separate slabs, two abreast and seven long. Due to lateral spreading, the south wall (adjacent to the shoreline) moved approximately 0.7 to 1.4 m laterally towards the shoreline (i.e., the width of the warehouses increased). The relative elevations across the slab are more difficult to interpret because it was clear that the slab was constructed with a significant slope and/or curvature towards the seaward edge. Without knowledge of the relative elevation differences before the earthquake, these movements cannot be converted to relative settlements due to liquefaction. Nonetheless, the relative elevations across the interior were variable, with the some areas almost 1 m lower than others. It appeared that the warehouses were founded on strip footings around their perimeters, which settled significantly. Settlements measured at the inland corners of the warehouses are also shown in Figure 6.14. The west warehouse appears to have settled approximately 15 cm relative to the ground surface, while the east warehouse settled more than 40 cm



	Survey Pt	*Section 1*	*Section 2*	*Section 3*	*Section 4*	*Section 5*	*Section 6*	*Section 7*
Vertical Settlement (cm)	A	0.0	-6.1	27.5	42.7	-7.6	32.0	-4.6
	B	-7.3	-4.3	-2.7	24.7	-14.9	24.7	-5.8
	C	-20.4	-20.4	-25.0	-32.6	-23.5	-43.3	-0.6
	D	-24.4	-18.3	-21.4	-2.7	-13.7	-47.3	0.0
	E	-6.7	-32.6	-8.2	-11.3	-5.2	-23.5	-15.9
	F	-16.5	-25.6	-25.6	-34.8	-19.5	-27.1	-25.3
	G	-48.8	-63.4	-74.7	-79.3	-67.1	?	-58.0
Displacement of south wall towards south (cm)		71.1	94.9	119.9	104.6	141.5	131.8	84.8

** Assumed datum at north edge of Section 1. All data based on survey with hand level with values adjusted to correct for apparent instrument bias*

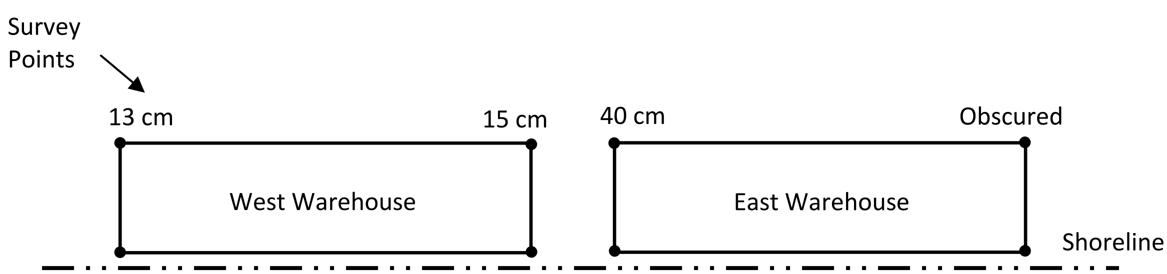


Figure 6.14 Results of a detailed survey of the relative settlements of the west warehouse slab, and the total settlements at the inland corners of the warehouses

The South Pier is a pile-supported structure that was originally 380 m in length and 18 m in width (Figure 6.5). A large bridge and a small pedestrian bridge that are approximately perpendicular to the longitudinal axis of the pier connected the pier to an island where the port security office is located. The western end of the pier was also connected to three dolphins by small pedestrian bridges. All of the bridges were also pile-supported structures. It is believed that an American or British contractor constructed the pier around 1975. The piles supporting the pier are approximately 51-cm square concrete piles on 4.3 to 4.9-m centers and include both vertical and battered piles. The pile bents are 1.5 m deep and 0.9 m wide and the deck is 45 cm thick (Brian Crowder, personal communication).

During the earthquake, the western-most 120 m of the South Pier and portions of the pedestrian bridges linking the dolphins collapsed and are now submerged. One hypothesis is that the abutment of the pier and the large bridge connecting the pier to the island together provided sufficient lateral restraint to prevent this portion of the pier from also collapsing. Nonetheless, the portion of the pier that is still standing was heavily damaged. US Army divers inspected the piles following the earthquake to determine whether the pier could support loads imposed by trucks carrying relief supplies. They found that approximately 40% of the piles were broken, 45% were moderately damaged, and 15% were slightly damaged. Generally, the batter piles were more heavily damaged than the vertical piles. An aftershock on January 26, 2010 may have caused more damage, and the pier remained closed to traffic as of February 1, 2010. Engineers from U.S. Naval Facilities Engineering Command have developed a strategy that they hope will allow them to repair the damaged in about 10 weeks from the start of construction.

In addition to the damage to the piles supporting the South Pier, the abutment also experienced liquefaction-induced lateral and vertical displacements. Approximately 1 m of fill was required to re-level the approach to the pier as shown in Figure 6.15. Also, the piles supporting the small pedestrian bridge connecting the South Pier to the island could be readily observed. Figure 6.16 shows the damage to these piles, including the extensive damage to the landward row of piles.

North of the main port facility along the shoreline, there were six steel grain hopper silos and two storage yards (Figure 6.17). From aerial imagery, it was determined that the grain silos were built sometime between March 2008 and January 2010. As shown in Figure 6.18, lateral spreading occurred behind the silos (westward side), but the silos and their foundation system showed no visible signs of distress (Figures 6.18 and 6.19). The amount of grain in the silos at the time of the earthquake is unknown. Also, the foundation system for the silos is unknown at this time. Extensive lateral spreading occurred in the two storage yards that are just north of the silos (Figures 6.20 through 6.24). Approximately 2.4 m of cumulative lateral displacement was measured at the northern storage yard. A unique feature of these lateral spreads is that the fill is garbage overlain by cobbly soil (Figure 6.24). However, it is believed that sand underlying the garbage fill liquefied and caused the lateral spreading.

Finally, one of the main entrance roads to the port was heavily damaged by liquefaction-induced lateral spreading, as shown in Figure 6.25.

Figure 6.15 Approach to the South Pier immediately after the earthquake (top photo: Source unknown; photo taken facing South-East) and after approximately 1 m of fill was placed (bottom photo: photo taken facing West). (N18.554028, W72.348658)

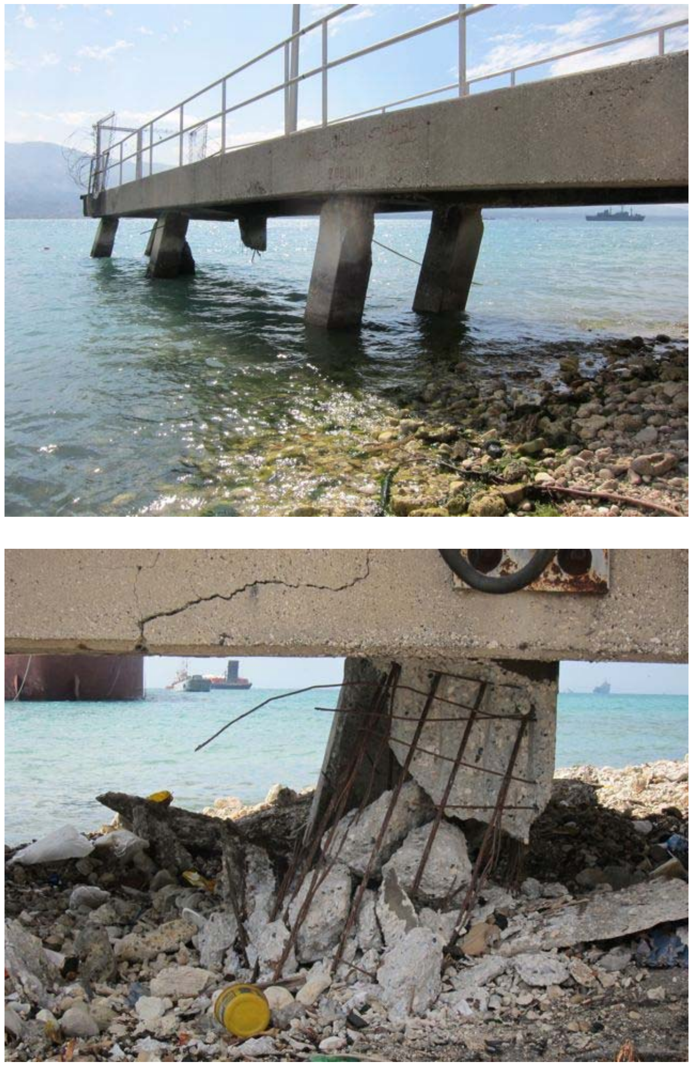
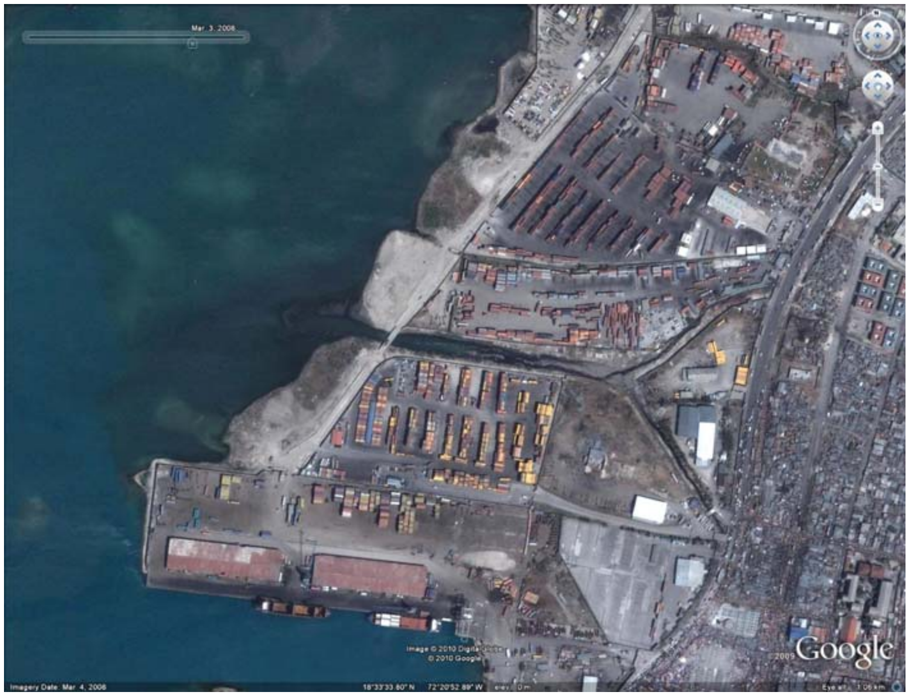


Figure 6.16: (top) Damage to piles supporting the pedestrian bridge connecting the South Pier to the island (photo taken facing South) and (bottom) extensive damage to the landward row of piles (photo taken facing West) (N18.554628, W72.351492)



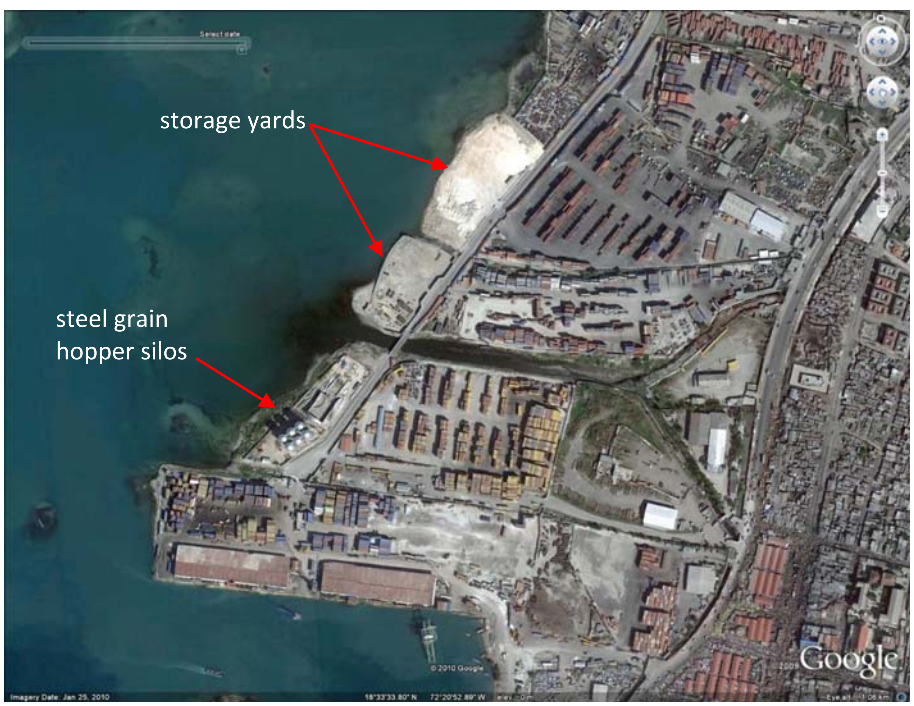


Figure 6.17 Aerial imagery of the northern part of the port facilities before the steel grain hopper silos and storage yards were built (top: image from March 2008) and after (bottom: image from January 2010). Imagery courtesy of Google Earth.)

Figure 6.18 Lateral spreading behind (westward side) steel grain hopper silos. However, the foundation system for the silos showed no visible signs of distress.
Imagery courtesy of Google Earth.

Figure 6.19 Post-earthquake photo of steel grain hopper silos (photo taken facing North). The silos showed no visible signs of distress.
(N18.558431, W72.350350)

Figure 6.20 Lateral spreading in the storage yards in the northern part of the port facility. Imagery courtesy of Google Earth. (18˚33'40.23"N 72˚20'52.33"W)

Figure 6.21 Lateral spreading in the storage yards in the northern part of the port facility. Photo taken facing South. (18˚33'41.39"N 72˚20'52.51"W)

Figure 6.22 Lateral spreading in the storage yards in the northern part of the port facility. Photo taken facing South. (18˚33'41.76"N 72˚20'52.25"W)

Figure 6.23 Lateral spreading in the storage yards in the northern part of the port facility. Lateral spread crack passes through a stone/masonry wall. Photo taken facing South. (Approximate long. and lat. of photo: 18˚33'35.15"N 72˚20'56.18"W)

Figure 6.24 Lateral spreading in the storage yards in the northern part of the port facility. A unique feature of this lateral spread is that the fill is garbage. However, it is believed that the liquefaction of the sand below garbage is the cause of the lateral spreading. Photo taken facing North-East. (Approximate long. and lat. of photo: 18˚33'38.93"N 72˚20'54.89"W)

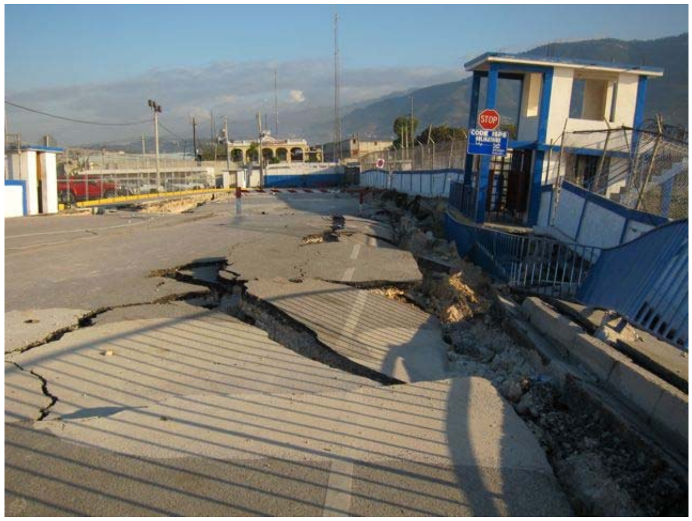


Figure 6.25: Damage to entrance road caused by lateral spreading. Photo taken facing South-East. (Approximate long. and lat. of photo: 18˚33'11.61"N 72˚20'52.50"W)

To identify the depth(s) and thickness(es) of the soil layer(s) that liquefied at the port, Spectral Analysis of Surface Waves (SASW) and Dynamic Cone Penetrometer Test (DCPT) tests were performed at various locations. All the tests were conducted on Monday, February 1, 2010. The test locations are shown in Figure 6.26, with the latitude and longitude coordinates for each provided in Tables 6.1 and 6.2 for the SASW and DCPT, respectively. Photos of the test setups are shown in Figures 6.27 and 6.28.

The SASW and DCPT results are currently being processed. The SASW results will give the shear wave velocity (Vs) profiles at each array location. It is expected that these Vs profiles will extend to an approximate depth of 6 m based on the range of wavelengths/frequencies collected in the field. If a heavier/lower-frequency source had been available, the depth of these profiles could have been extended significantly. The DCPT were performed to depths ranging from 3 to 6 m until refusal. However, from visual inspection of the free face of one of the lateral spread features (Figure 6.29), the soil profile consists of approximately 10 cm of asphalt on top of 28 cm of well-graded gravel (GW) base, which overlays 30 cm of cobbles. The cobbles are underlain by more GW, the thickness of which could not be ascertained. The depth of the water table is controlled by the tide and appeared to average approximately 1.2 m below the ground surface.

Figure 6.26 Spectral Analysis of Surface Waves (SASW) and Dynamic Cone Penetrometer Test (DCPT) locations at the port in Port-au-Prince Haiti. Imagery courtesy of Google Earth. (Approximate long. and lat. of center of image: 18˚33'27.09"N 72˚21'03.51"W)

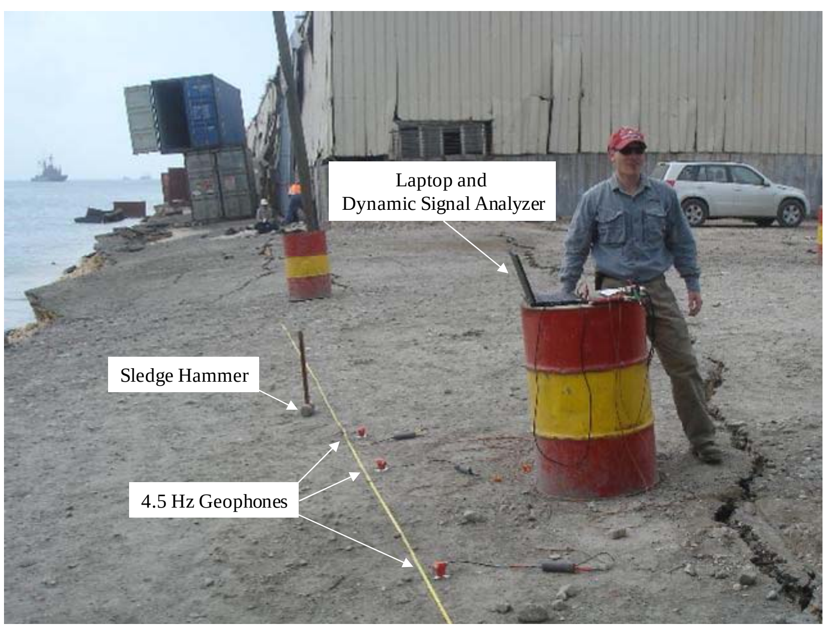


Figure 6.27 Lightweight, dynamic equipment used to conduct SASW testing in Haiti. This photograph was taken at the location of SASW 1, facing West. (N18.556635°, W -72.350202°).

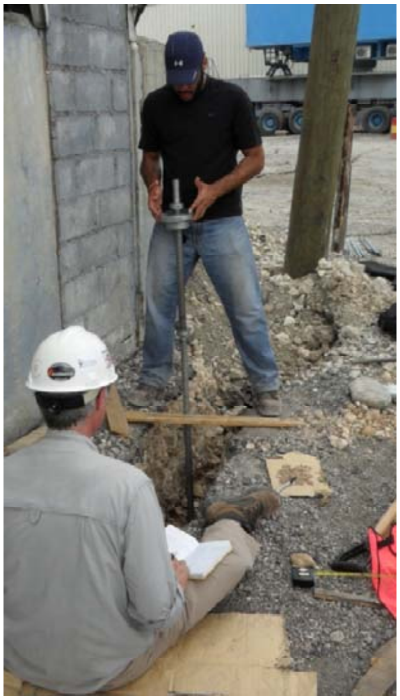


Figure 6.28 Dynamic Cone Penetrometer Test (DCPT). This photograph was taken at the location of DCPT1, facing East. (N18.556681°, W -72.350398°).

Figure 6.29 Near-surface soil layering at the wharf as observed on the free-face of the lateral spread that collapsed the wharf deck. This picture was taken just south of SASW 1 (refer to Figure 6.26), facing East. (N18.556635°, W 72.350202°).

Table 6.1 Spectral Analysis of Surface Waves (SASW) array locations at the port in Port-au-Prince, Haiti

SASW Locations at the Port in Port-au-Prince, Haiti		
Array	Latitude	Longitude
SASW 1	18.556635°	-72.350202°
SASW 2	18.556858°	-72.350238°
SASW 3	18.557468°	-72.350657°
SASW 4	18.558007°	-72.351057°
SASW 5	18.557238°	-72.351896°

Table 6.2 Dynamic Cone Penetrometer Test (DCPT) sounding locations at the port in Port-au-Prince, Haiti

DCPT Locations at the Port in Port-au-Prince, Haiti		
Sounding	Latitude	Longitude
DCPT 1	18.556681°	-72.350398°
DCPT 2	18.556983°	-72.349906°
DCPT 3/4	18.558030°	-72.351066°