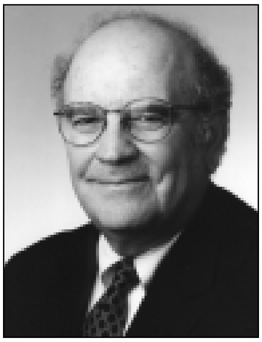
The engineer who oversaw the construction of the World Trade Center "bathtub" describes the recovery efforts.

World Trade Center "Bathtub": From Genesis to Armageddon

George J. Tamaro



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My first experience with "slurry wall" construction[1] was in Italy in 1964 when I was on a work/study assignment for the New York Port Authority. The Chief Engineer of the Port Authority at the time asked that I inspect and report to him on the use of the new technology. In 1967 the Port Authority assigned me to oversee the original construction of the World Trade Center (WTC) slurry walls. From that assignment I moved on to a nine-year career as a contractor constructing slurry walls and a 21-year career as a consulting engineer designing slurry walls around the globe. Back in 1964, I had no idea that my brief assignment in Rome would have a significant effect on my career and interests. This report describes the initial work on the WTC "bathtub" in the late 1960s and the recent work during the recovery.

Genesis

The WTC complex consisted of seven buildings on a 16-acre site in lower Manhattan. The deep basement (bathtub) portion of the site covers a four-city block (980 foot) by two-city block (520 foot) area some 200 feet from the east shore of the Hudson River (Figure 1). The deep basement occupies only about 70 percent of the 16-acre WTC site and is just west of the place

[1] Commonly referred to as diaphragm wall construction in Europe.

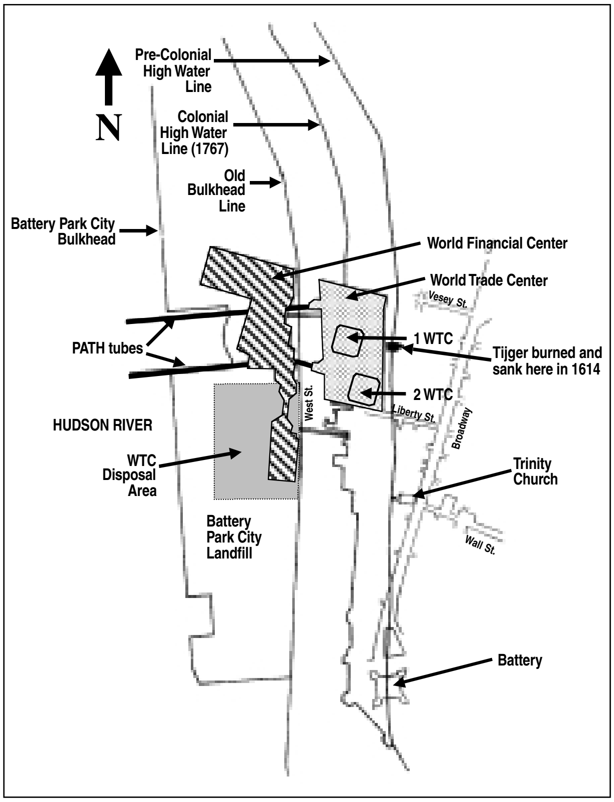

FIGURE 1 Location plan.

where the Dutch landed in 1614. The size and depth of the deep basement and the alignment of the perimeter wall were dictated by several requirements: the construction of a new interstate commuter railroad (PATH) station parallel to the Greenwich Street east wall; support for an operating New York City subway tunnel located just outside the east wall; protection of the entry points of two 100-year old, 17-foot diameter PATH tunnels on the east and west; and the foundation of the twin towers (WTC 1 and WTC 2) on bedrock within the excavation (Figure 2).

The geology of the WTC site varies from east to west. On the east (Greenwich Street), 15 to 30 feet of fill cover as much as 20 feet of glacial outwash sand and silt, below which are 5 to 20 feet of glacial till/decomposed rock. The Manhattan schist bedrock is found at depths of 65 to 80 feet. A knoll of quartzite rock intrudes into the site at the southeast corner. On the west (West Street), the fill is 20 to 35 feet thick and is underlain by 10 to 30 feet of soft organic marine clay (river mud). Below the river mud is a 20-foot thick layer of glacial outwash sand and silt and 5 to 20 feet of glacial till/decomposed rock. Bedrock is found at depths of 55 to 75 feet. Groundwater levels were within several feet of ground surface. The fills were placed into the river during various periods of development and consisted of excavation spoil, demolition debris, marine construction, abandoned vessels, lost cargo, and garbage. A maze of utilities and abandoned structures further complicated the ground conditions.

Two short segments of the West Street wall projected 65 and 90 feet to the west to permit the slurry wall to cross over the PATH tunnels where the tunnel invert was buried in rock; the top half was covered with soil. At that location, the slurry wall concrete could be cast against the top of the cast iron tunnel rings and socketed into rock on both sides of the tunnel, creating a watertight seal at the crossing (Figure 3).

The basement was bounded by a 3,500-foot long, 3-foot thick slurry wall (perimeter wall) constructed from grade and socketed into rock located at depths of as much as 80 feet. In the 1950s, continuous underground walls were constructed using bentonite slurry as a temporary support for slot excavations in difficult soil conditions. Bentonite slurry is only slightly heavier than water. Early on, the Port Authority Engineering Department recognized that this technology would be suitable for construction of a safe, economical deep basement in extremely difficult ground conditions.

The slots at the WTC were eventually filled with reinforcing steel cages that were assembled on site; each cage weighed as much as 22 tons. The cages were concreted, using Tremie methods, to form 158 individual panels. Special jointing details were used to ensure watertight connections of the individual panels that were used to form the perimeter. Each panel was approximately 22 feet long. The slurry wall was installed in a 12-month period ending in 1968.

The next phase of construction required careful staging of the excavation and temporary support of the PATH tubes that traversed the site. To provide lateral support of the wall as the excavation proceeded downward, 1,500 high-strength tendon tieback anchors were installed. Four to six tiers of tieback anchors were installed through sleeves ("trumpets") in the slurry wall, drilled through the soil using steel pipe casing, and then drilled 30 to 35 feet into bedrock. Each anchor was grouted in place, tested, and locked off at 50 percent to 100 percent of the design load. Tieback anchor capacities varied from 100 to 300 tons. About 55 additional anchors were installed to replace anchors that were obstructed during drilling, damaged during installation, or did not reach design capacity during testing.

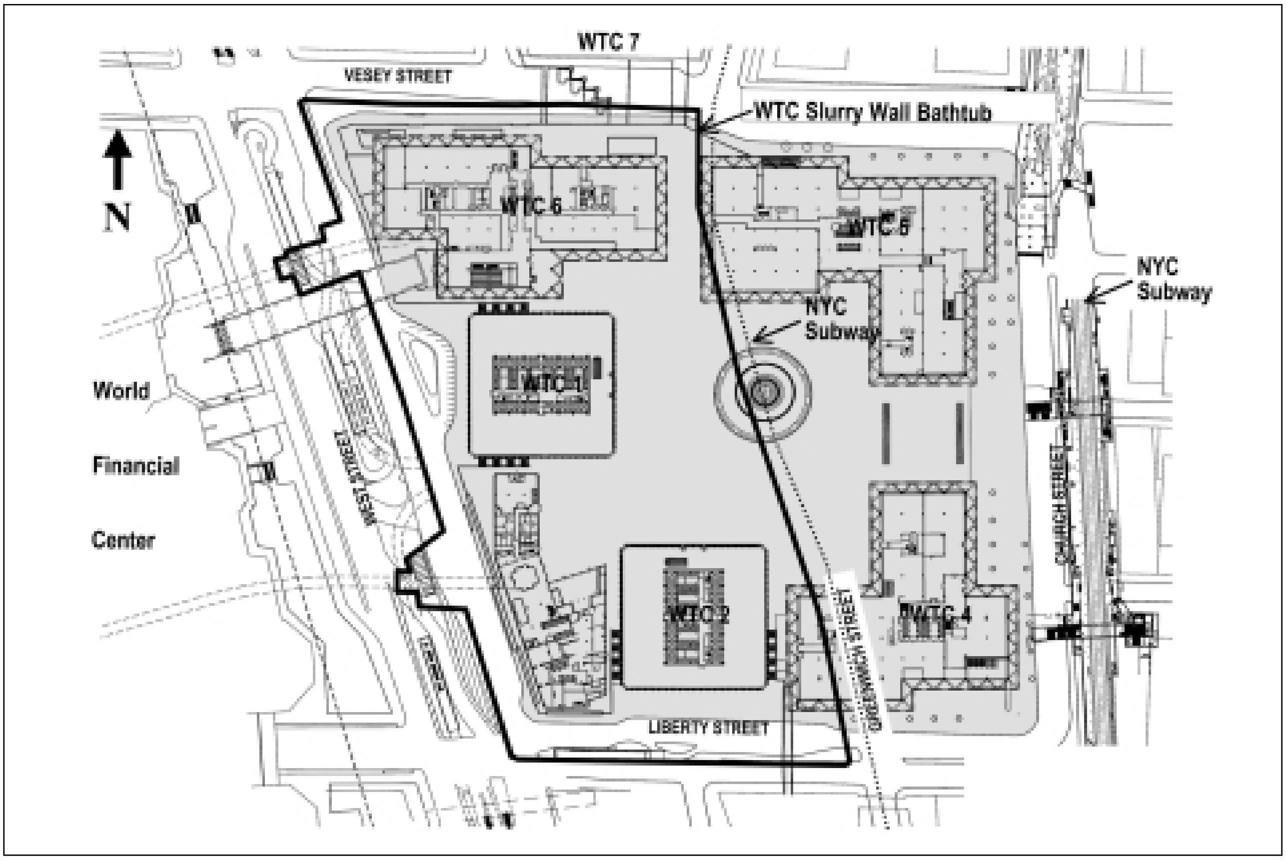

FIGURE 2 WTC site plan.

More than a million cubic yards of excavation spoil was carted to a disposal area across West Street and eventually incorporated into the landfill for Battery Park City. The southernmost building of the World Financial Center is located on that portion of the landfill (Figure 4). The excavation phase required a year. Once the permanent basement floors were capable of supporting the walls, the tieback anchors were detensioned and the sleeves sealed.

The scale of the WTC project was unprecedented. This was only the third time slurry walls were used in the United States and one of the earliest uses of a large number of tieback anchors to such high capacities. The WTC basement was the most challenging foundation construction in New York up to that time and, for that matter, up to the present (Figure 5). The Port Authority exhibited great courage and foresight when it designed and oversaw the construction of the basement structure.

Prelude

In 1993, terrorists detonated a bomb in the WTC basement adjacent to a column of the north tower (WTC 1) causing damage to the floors that were supporting the slurry walls. Fortunately, the walls themselves were not damaged, did not leak, and were able to span across the damaged areas. Visual inspection of the walls in spring 2001 revealed that the walls were in good condition.

Armageddon

On September 11, 2001, terrorists again struck the WTC complex, this time causing the collapse and destruction of the majority of above-grade structures and the partial collapse of the below-grade structures. The limits of the bathtub and the condition of the below-grade structures were not immediately evident in the aftermath of the attack.

Initial Response

Immediately after the collapse, the New York City Department of Design and Construction established a team of engineers and contractors to assist the NYC Fire Department in its search and rescue efforts. One group of engineers, under the direction of Thornton-Tomasetti Engineers (TTE), focused on the inspection of adjacent

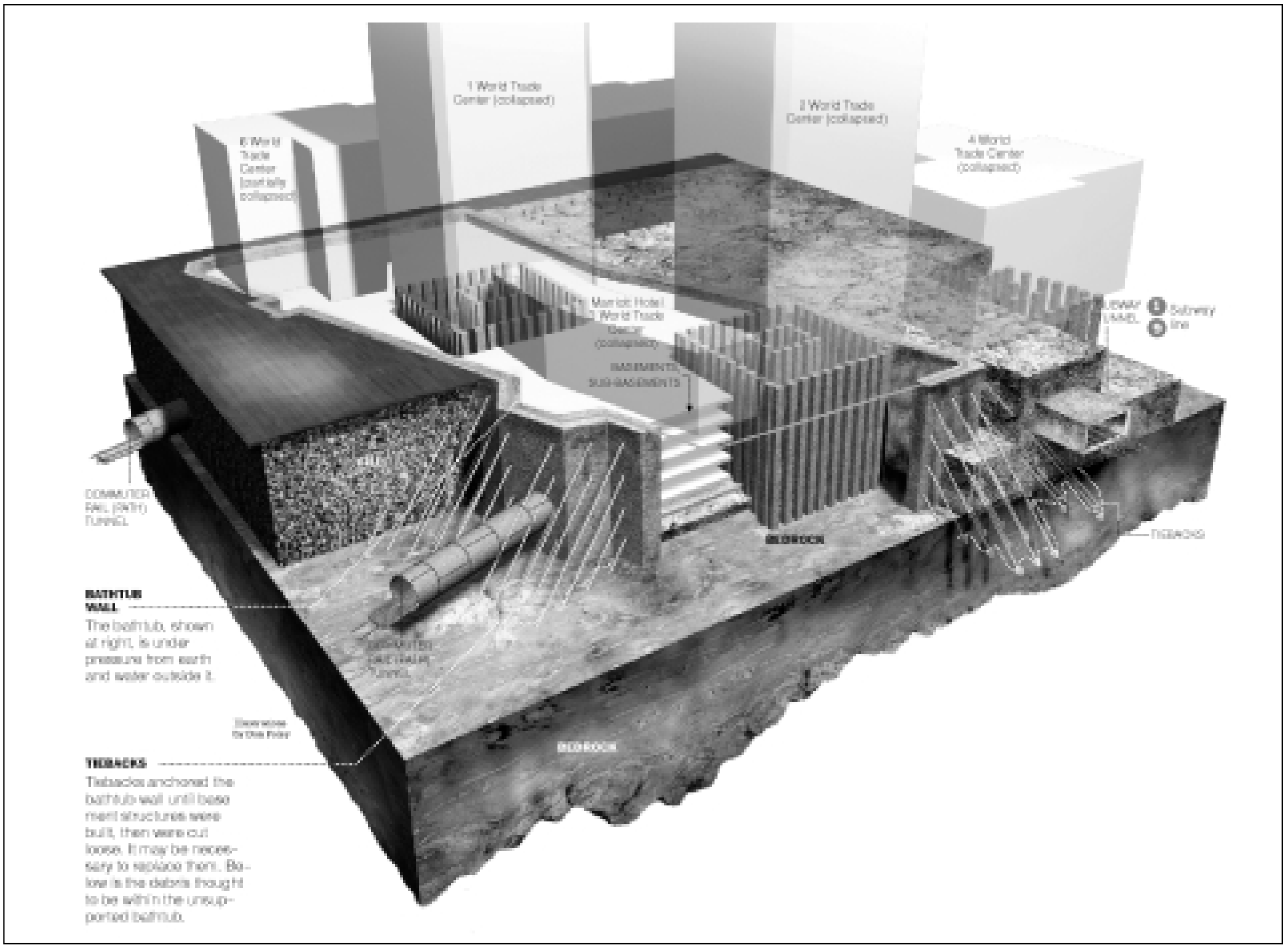

FIGURE 3 Schematic view of slurry wall/PATH crossing at West Street.

buildings while another provided advice on below-grade structures in the WTC complex, the World Financial Center complex located to the west in the Battery Park City landfill, the PATH tubes, and the New York City subway tunnels.

As heavy equipment (e.g., 1,000-ton cranes) began to arrive at the site, it became apparent that ground rules had to be established for the safe use of the equipment outside the confines of the basement, over major utilities, over access stairs to the PATH tubes and ramps, in the streets, and over structural platforms spanning open water. The use of this heavy equipment adjacent to the slurry walls or over the basement structure itself could cause the collapse of the slurry walls or any remaining basement structures. A collapse of the slurry wall would mean inundation from the nearby Hudson River.

As a first step, Mueser Rutledge Consulting Engineers (MRCE) prepared cartoon-like sketches showing the location of below-grade structures outside the slurry wall that could not be traversed by heavy equipment. The locations of four 6-foot diameter water lines were also identified. The Port Authority closed valves for two water intake lines shortly after the incident. The other two discharge water lines could backfeed river water

FIGURE 4 Original PATH tube suspension system.

into the basement during periods of high tide and had to be sealed as soon as possible. The sketches were provided to the Fire Department and the contractors for use in placing rescue, construction, and demolition equipment. Weidlinger Associates subsequently prepared more detailed utility drawings for the contractors.

PATH Tunnels

Concurrent with rescue work in New York, Port Authority engineers were investigating the condition of the PATH tunnels in Jersey City, New Jersey, where the Exchange Place Station, which was at an elevation 5 feet lower than the WTC PATH Station, had served as a sump for fire water, river water, and broken water mains discharging into the bathtub. Inspection indicated that water in the tunnels between New York and New Jersey had completely filled the north tunnel at the midriver low point. Pumps were immediately put into action to keep Exchange Place Station from flooding. As much as 3,000 gallons per minute were pumped from the north tunnel for a 12-hour period each day. Tests of the water were inconclusive as to the source; however, most was believed to come from the vast amounts of water that were poured onto the debris to extinguish continuing fires. Within days, a 16-foot long low-strength concrete plug was placed in each tube as a seal in the event that the bathtub walls were breached and the tunnels fully flooded. The plugs were designed to withstand an 80-foot head of water pressure and will be removed once the slurry walls are fully secured (Figure 6). The Port Authority is currently preparing to remove the plugs in preparation for rehabilitation of the tunnels.

FIGURE 5 Original excavation, WTC 1 steel core started, PATH tubes temporarily supported while new station is constructed along Greenwich Street slurry wall.

FIGURE 6 Current PATH tube plug at Exchange Place Station in Jersey City.

Damage Assessment

MRCE began to compile information on the condition of the slurry walls and the remaining basement structure as soon as below-grade access was possible. Teams of engineers, including MRCE, TTE, and Leslie E. Robertson Associates (LERA), and rescue personnel from FEMA, the U.S. Army Corps of Engineers, the Fire Department, and the Police Department conducted inspections of all accessible below-grade areas. These teams reported on the condition of the slurry wall, the floor slabs, and the debris fields and judged whether the floor slabs and debris could safely support the slurry walls. MRCE compiled this information on damage assessment drawings showing the locations of stable and collapsed floors, as well as the location of dense debris fields. Those diagrams were used by contractors removing the debris to prevent compromising the slurry walls; the drawings were used by MRCE in the design of the slurry wall resupport system. Figure 7 shows a typical example of a damage assessment drawing for one of the basement levels. The drawings showed that remnants of

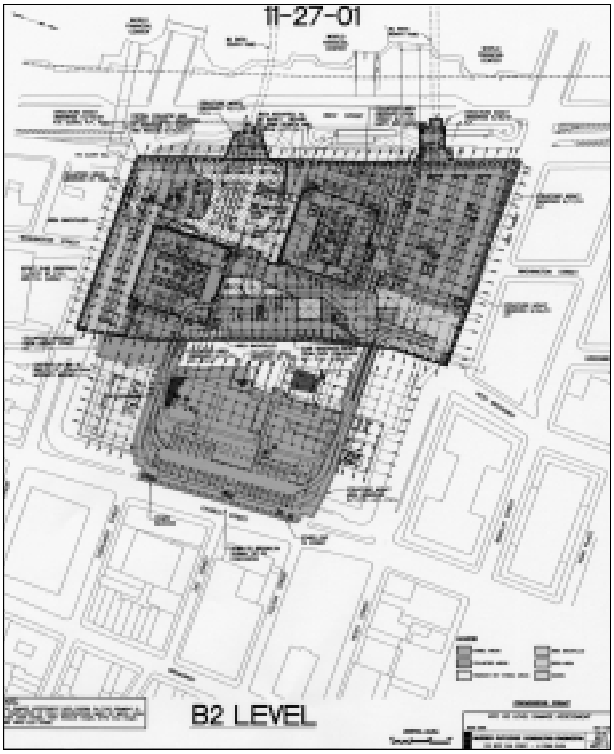

FIGURE 7 Damage assessment drawing for Level B2.

the existing floors continued to support the slurry walls in the northern sector of the site. LERA is currently reassessing the condition of the slabs in the northern sector as a temporary support for the slurry wall and for their possible reuse in a reconstructed basement.

In the center sector, the walls were supported by debris that varied from loose to compact. Along the south wall at Liberty Street, the majority of the wall was unsupported for most of its 60-foot height. Ultimately, tension cracks developed in Liberty Street immediately south of the wall, and the top of the wall moved more than 10 inches toward the site. Backfilling of the south sector began as soon as it became safe to work in the area and the extent of the problem could be determined (Figure 8). Slope inclinometers, survey points, and monitoring wells were used to measure the behavior of the wall and the groundwater levels. Dewatering wells were installed to reduce water pressure on the walls, and instrumentation was installed to measure movements. The instrumentation showed that backfilling had reduced the rate of wall movement to the point that an upper tier of tiebacks could be installed to stabilize the wall. The contractor is currently installing the fourth level of tiebacks at that location in preparation for excavation to track level by March 2002.

FIGURE 8 Backfill operations at Liberty Street.

NYC Transit Tunnels

An inspection of the subway tunnels immediately east of the slurry wall indicated that the south half of the tunnel was either collapsed or had been pierced by a falling structure (Figure 9); the north half was relatively undamaged. Bulkheads were designed at both ends to prevent inundation of an adjacent section of tunnel that was secure and operating. A more easterly subway tunnel was found to be almost undamaged and was returned to service late in October 2001. New York City Transit has prepared contract documents for reconstruction and reopening of the line by October 2002.

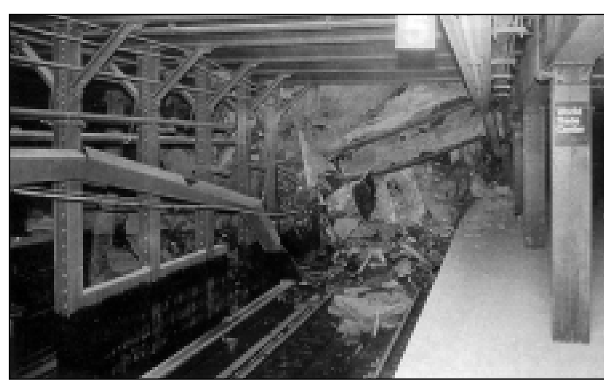

FIGURE 9 Damaged subway tunnel.

Resupport of Slurry Walls

The recovery of bodies, remains, and personal items, debris removal, and the excavation of residue continues under Fire Department and Police Department oversight; when human remains are discovered, work is halted to ensure their dignified removal from the site.

The abandoned “original” tieback tendons were inspected and found to be unsuitable for reuse. Replacement anchors, intended to be permanently corrosion protected are now being installed on the south half of the bathtub; these anchors will be tested to 400 tons and locked off at 300 tons. Because of the uncertainties about the support of the wall by debris and concerns about sudden loading of the wall as a result of the collapse of the lower level floors, tieback capacity of the top two tiers of anchors was set sufficiently high so that the anchor would not fail prior to development of the ultimate moment capacity of the wall.

Tieback work is performed from inside the wall using crawler-mounted drills set on timber mats or from outside the wall using "floating leads" extending over the wall. The floating leads are used where the working surface is unsafe (Figure 10). (Excavating equipment has fallen several floors through the debris on two occasions.)

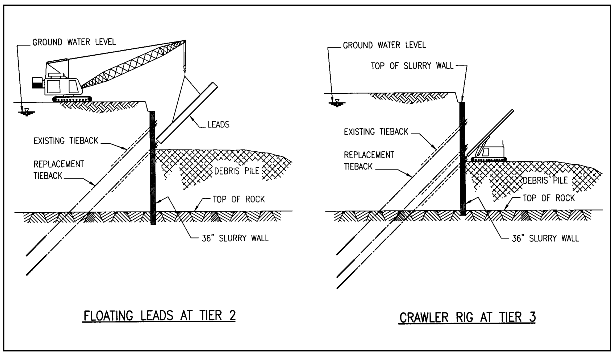

FIGURE 10 Tieback installation with floating leads and crawler rigs.

The current design requires one less tier of anchors at each wall section than was used in the original construction. At several tiers, the replacement tieback anchors will be placed either directly above or below abandoned anchors; at other tiers, the replacement anchors will be remote from abandoned original anchors. The first three tiers of anchors at the south wall were in place, and work had begun on the fourth tier as of January 2002 (Figure 11). First and second tier anchor installation on West and Greenwich Streets is proceeding from south to north as debris is removed and work space becomes available. Tiebacks will also be required

FIGURE 11 Progress along the Liberty Street slurry wall showing the installation of the fourth-tier anchors.

for a segment of the Vesey Street wall where recent demolition has caused the collapse of formerly stable floors. More than half of the first phase anchors will be in place by the end of January 2002.

As of January 2002, the slurry wall was found to be mostly intact, except for minor leaks at a few abandoned tieback seals and the upper portion of two panels at the southeast corner that were crushed by falling debris (Figure 12). The estimated time of removal of all debris is less than one year. The Port Authority has indicated its desire to restore interim PATH service in the area of the former station once the slurry walls are stabilized and the debris removal is completed. Planning for a memorial and commercial and public buildings is under way.

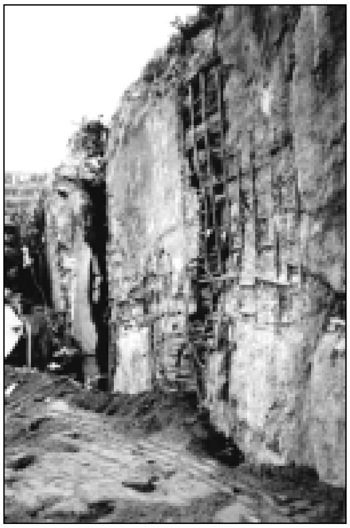

FIGURE 12 Damaged walls at Greenwich Street.