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The World Trade Center “Bathtub”, a Case History

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ABSTRACT

In 1967 the Port Authority of New York and New Jersey (PANYNJ) undertook the construction of the World Trade Center (WTC) diaphragm (slurry) walls, installation of the lateral support system and the excavation of the site, commonly referred to as the "Bathtub". The work took two years to complete. In 2001 the City of New York undertook the re-excavation of the site after the terrorist attacks. The recovery work took eight months to complete. When the World Trade Center Recovery Effort officially concluded on May 30, 2002, reconstruction was already underway. The Port Authority of New York and New Jersey had already completed its plans for the reconstruction of the Port Authority Trans Hudson (PATH) tubes and a temporary station. New York City Transit (NYCT) started the reconstruction of the Interboro Rapid Transit (IRT) 1 and 9 line tunnel in Greenwich Street after having already restored service on the Brooklyn Manhattan Transit (BMT) N and R lines in Church Street. Silverstein Properties started reconstruction of World Trade Center 7 (WTC 7) and the construction of the Consolidated Edison (Con Ed) transformer vaults located within the base of the WTC 7 building. These replacement structures, when combined with other existing structures such as the slurry wall, affect future development of the World Trade Center site. This paper will discuss the original construction of the "Bathtub", the recovery effort, changes at the site since May 2002, conditions which will affect construction in the future and proposals for new construction.

INTRODUCTION

The WTC complex consisted of seven buildings on a 65,000 square meter (16 acre) site in New York City. The deep basement (bathtub) portion of the site covers a four-city block (330 meter) (1000 feet) by two-city block (165 meter) (500 feet) area some 60 meters (200 feet) from the east shore of the Hudson River (Fig. 1). The deep basement occupies only about 70 percent of the WTC site and is just west of the location on the Hudson River shoreline 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: 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 60-year old, 5 meter (16 feet) diameter PATH tunnels on the west; and the foundation of the twin towers (WTC 1 and WTC 2) on bedrock within the excavation (Fig. 2).

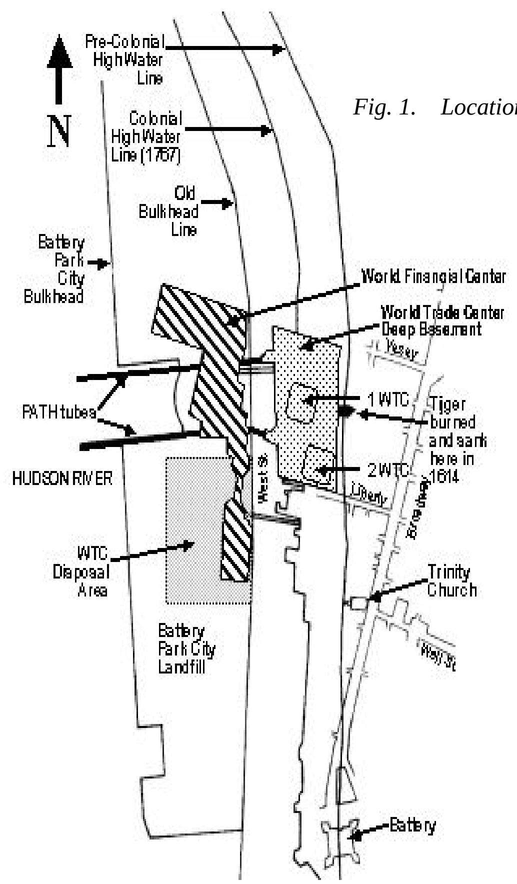


Fig. 1. Location Plan.

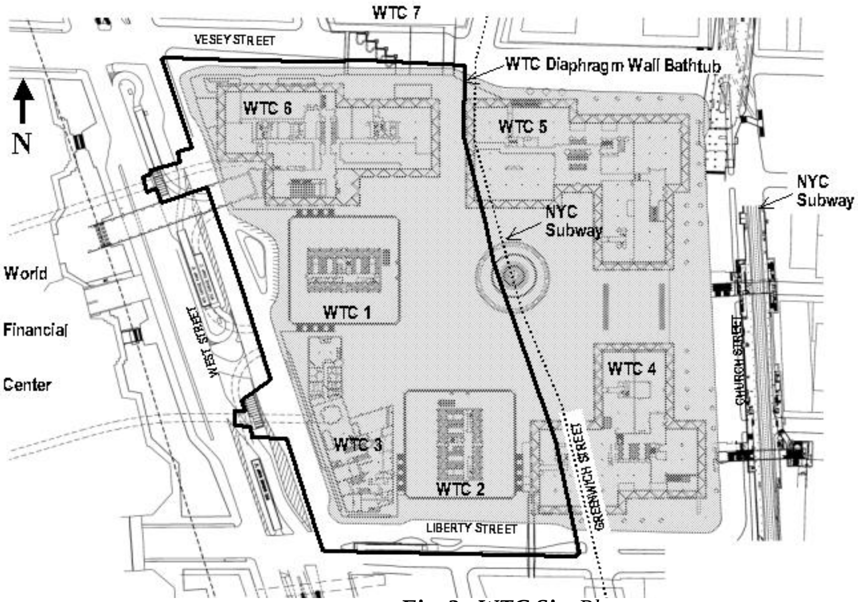


***Fig. 2. WTC Site** Plan.*

The original design required the construction of a temporary anchored perimeter diaphragm wall that would permit the excavation to rock within a watertight enclosure. This wall would also permit the construction of a PATH station and major foundations for the two towers within that enclosure. Multiple levels of below grade structural slabs were then installed to support parking and services as well as to provide permanent lateral support for the slurry walls. The temporary tieback anchors were later released and sealed completing the load transfer to the permanent structure. The construction of shallow basement structures for WTC 4 and WTC 5 followed to the east of Greenwich Street, and later in the 1980s for WTC 7 to the north.

Geology

The geology of the WTC site varies from east to west. On the east (Greenwich Street), 5 to 7m (16 to 23 ft) of fill cover as much as 9 to 13m (30 to 43 ft) of glacial outwash sand and silt, below which are 1 to 5m (3 to 16 ft) of glacial till/ decomposed rock. The Manhattan schist bedrock is found at depths of 17 to 23m (56 to 75 ft). A knoll of quartzite rock intrudes into the site at the southeast corner. On the west (West Street), the fill is 5 to 10m (16 to 33 ft) thick and is underlain by 3 to 9m (10 to 30 ft) of soft organic marine clay (river mud). Below the river mud is a 0 to 5m (0 to 16 ft) thick layer of glacial outwash sand and silt and 2 to 5m (7 to 16 ft) of glacial till/decomposed rock. Bedrock is found at depths of 17 to 32m (56 to 105 ft). Groundwater levels were within two meters (6 ft) 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.

Diaphragm Wall Construction

The basement was bounded by a 1000m (3300 ft) long, by 900mm (36 inch) thick diaphragm (perimeter wall) constructed from grade and socketed into bedrock. Two short segments of the West Street wall projected 20 and 27m (66 and 87 ft) to the west to permit the diaphragm wall to cross over the PATH tunnels where the tunnel invert was buried in rock and the top half of the tunnel was covered with soil. At that location, the diaphragm 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 (Fig. 3).

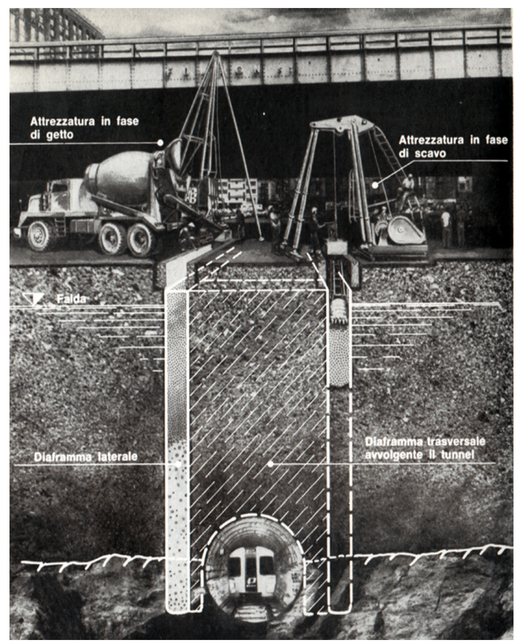


Fig. 3 Cross section through tunnel. Photo courtesy of ICOS.

158 individual panels, each approximately 6.7m (22 ft) long, were used to close the perimeter. During the excavation the trench was supported by bentonite slurry. Next the reinforcing steel cages were assembled on site; each cage weighed as much as 20 tonnes (22 tons). The cages were lowered into the slurry stabilized trench. Panels were then filled with concrete using tremie methods. Simple pipe endstops were used to provide a watertight connection between the individual panels. The diaphragm wall was installed within a 12-month period ending in 1968.

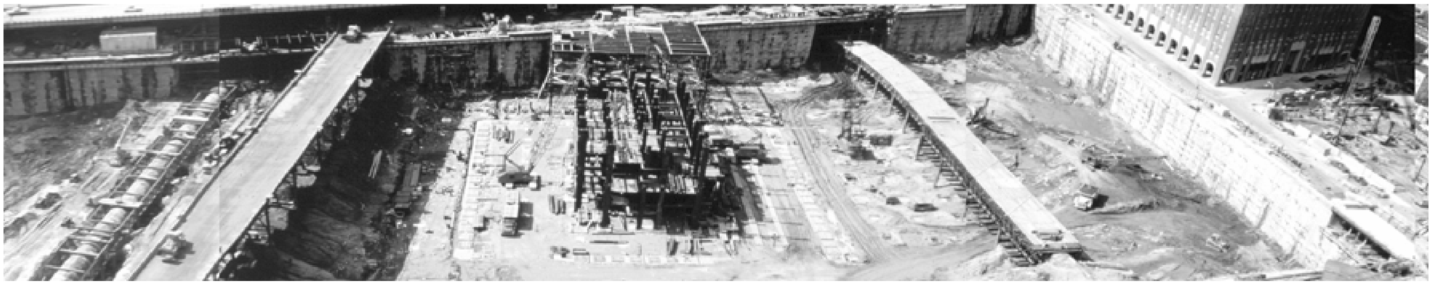


Fig. 4 Composite of the WTC site, c. 1968

The next phase of construction required careful staging and support of the excavation as well as the temporary support of the PATH tubes that traversed the site. 1,400 high-strength tendon tieback anchors were installed to provide lateral support of the wall as the excavation proceeded downward. Four to six tiers of tieback anchors were installed through sleeves ("trumpets") in the diaphragm wall, drilled through the soil using steel pipe casing, and then drilled 9 to 11m (30 to 35 ft) 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 90 to 270 tonnes (100 to 300 tons). Additional anchors were installed to replace anchors that were obstructed during drilling, damaged during installation, or did not reach design capacity during testing.

Over a million cubic meters (1,000,000 cy) of excavation spoil were 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. The excavation phase required a year (Fig. 4). Once the permanent basement floors were capable of laterally 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 diaphragm 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 City up to that time and, for that matter, up to the present. The Port Authority exhibited great courage and foresight when it designed and oversaw the construction of the basement structure.

<u>Bomb Attack of 1993</u>

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 diaphragm 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 remained in good condition.

<u>Attack of September 11, 2001</u>

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 collapse of almost all 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.

<u>Initial Response</u>

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 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., 900-tonne cranes) (1000 ton) mobilized 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, ramps in the streets, and over structural platforms spanning over water. The use of heavy equipment adjacent to the diaphragm walls or over the basement structure itself could cause the collapse of the diaphragm walls or any remaining basement structures. A collapse of the diaphragm wall could 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 diaphragm wall that could not be traversed by heavy equipment. The sketches were provided to the rescue personnel and to the contractors for use in placing rescue, construction, and demolition equipment. The locations of four 2m (7 ft) diameter water lines, ramps to the basement and PATH emergency stairs were also identified. The Port Authority closed valves for two water intake lines shortly after the incident. The other two discharge water lines could back feed river water into the basement during periods of high tide and were sealed a short time later.

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 diaphragm wall, the floor slabs, and the debris fields and judged whether the floor slabs and debris could safely support the diaphragm 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. The engineers and debris removal contractors used the drawings to understand the delicate diaphragm wall support conditions; MRCE used the drawings in the design of their diaphragm wall re-support system. Fig. 5 shows a typical example of a damage assessment drawing for one of the basement levels. The drawings showed that remnants of the existing floors continued to support the diaphragm walls in the northern sector of the site. These floors were found to be in varying states of distress and were partially removed during the recovery effort.

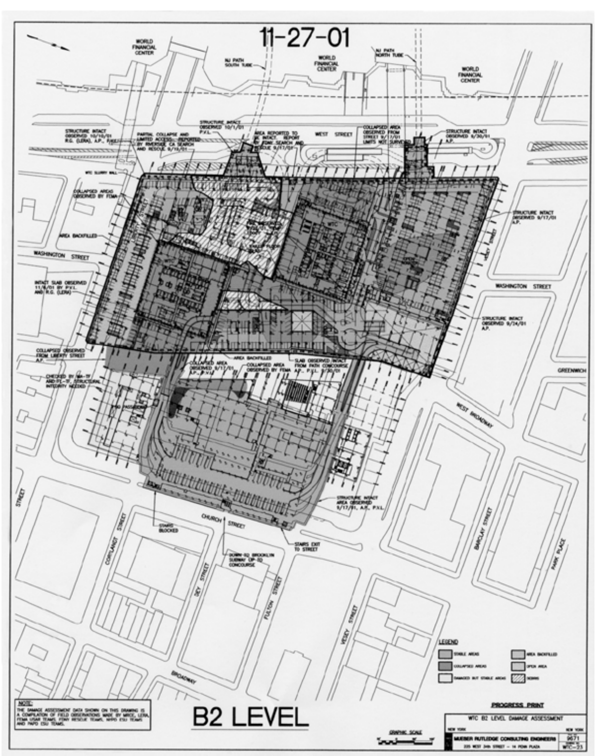


Fig. 5

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 18m (60 ft) height. Ultimately, tension cracks developed in Liberty Street immediately south of the wall, and the top of the wall moved more than 300mm (12 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 (Fig. 6). 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 by as much as eleven meters (35 ft) of head, and instrumentation was installed to measure wall movement. The instrumentation showed that backfilling had reduced the rate of wall movement to the point that an upper tier of tiebacks could be safely installed to stabilize the wall. The wall moved back as much as 75mm (3 inches) after the top tier of tieback anchors were tensioned. The diaphragm wall was eventually found to be mostly intact, except for minor leaks at a few abandoned tiebacks and at the upper half of four panels at the southeast corner that were crushed by falling debris, the damage and repair are described later.

Fig. 6 Backfilling operations at Liberty Street.

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 6m (20 ft) lower than the WTC PATH Station, was serving as a sump for firewater, 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 mid-river low point. Pumps were immediately put into action to keep Exchange Place Station from flooding.

As much as 11,000 liters per minute (3000 gpm) were pumped from the north tunnel for a 12-hour period each day. This flow reduced to about 500 liters per minute (150 gpm) as the site was secured. Tests of the water were inconclusive as to the source; however, most was believed to come initially from the vast amounts of water that were poured onto the debris to extinguish continuing fires and later from seepage into the bathtub from the sidewalls and the bottom.

Within days, a 5m (16 ft) 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 a 24m (80 ft) head of water pressure and were removed once the diaphragm walls were considered secured in mid-January 2002 (Fig. 7).

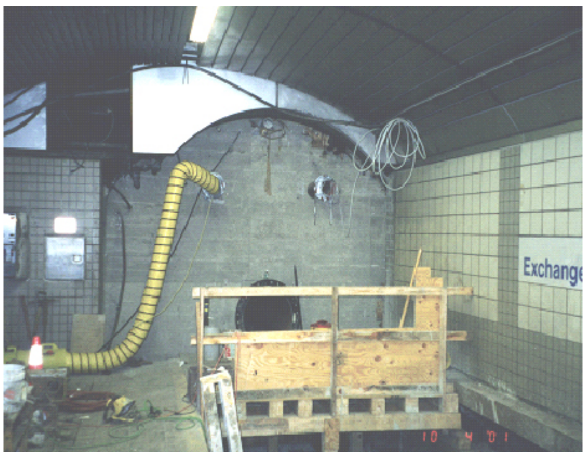


Fig. 7 PATH tube concrete plug.

NYC Transit Tunnels

An inspection of the 1 and 9 subway tunnels immediately east of the diaphragm wall indicated that the south half of the tunnel was either collapsed or had been pierced by falling structure (Fig. 8); 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. The damaged sections of the line were reconstructed and the line was restored to service in the Fall of 2002. The more easterly N and R subway tunnel was found to be almost undamaged and was returned to service late in October 2001.

Fig. 8 Damaged subway tunnel.

Re-support of Diaphragm Walls Using Temporary Anchors

The abandoned "original" tieback tendons were inspected and found to be unsuitable for reuse. Replacement anchors, intended to be "permanently corrosion protected" are now installed. The anchors consist of eighteen 15mm (0.6 inch) diameter strand and are tested to 360 tonnes (400 tons) and locked off at 270 tonnes (300 tons). Because of staging problems, 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 upper tiers of anchors was set sufficiently high so that the anchors would not fail prior to development of the ultimate moment capacity of the wall. Load cells located at Liberty Street indicated a drop in load with time. This is attributed to the effect of higher lock off loads than necessary, the movement of the wall away from the excavation and the installation of lower tier anchors. Tieback work was performed from inside the excavation using crawler-mounted drills set on timber mats or low headroom rigs at interior areas where remaining slabs could be used as a temporary work platform. Tiebacks were also installed from outside the excavation using "floating leads" extending over the wall. The floating leads were used where the interior working surface was unsafe (Fig. 9). A massive crane was used to support the 23 tonne (25 ton) leads during drilling operations. (Excavation equipment fell several floors through the debris on two occasions.)

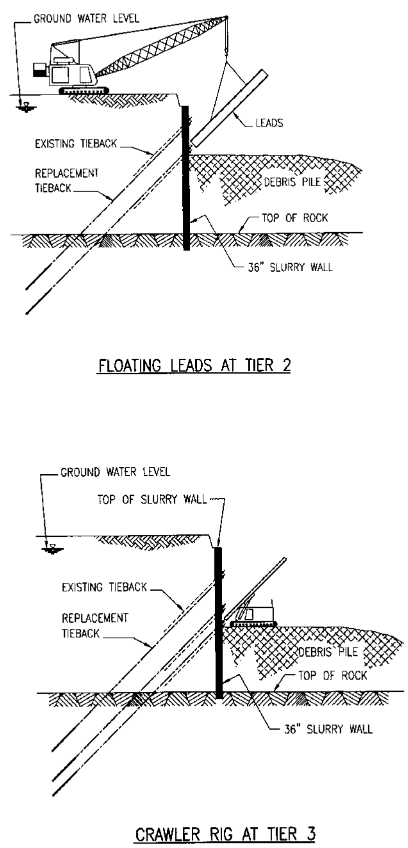


Fig. 9 Tieback Installation

The current design generally 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 a distance from abandoned original anchors.

The anchors at the Liberty Street wall were completed first (Fig. 10). Anchor installation on West and Greenwich Streets proceeded from south to north as workspace became available. Tiebacks were also installed on a segment of the Vesey Street wall where falling debris had punched through WTC 6 and three levels of basement floor slabs. The recovery effort was completed on May 30, 2002, within an eight and one half-month period working 24 hours a day, seven days a week (Fig. 11). At that date approximately 950 temporary anchors were installed to provide lateral support to sections of slurry wall left unsupported as a result of damage to the below grade slab structure. An additional 120 anchors may be needed if and when the remnant basement structures at the north end of the site (Fig. 12) is removed to accommodate development of the site. Eventually all anchors are to be de- tensioned and sealed before they corrode and lose capacity.

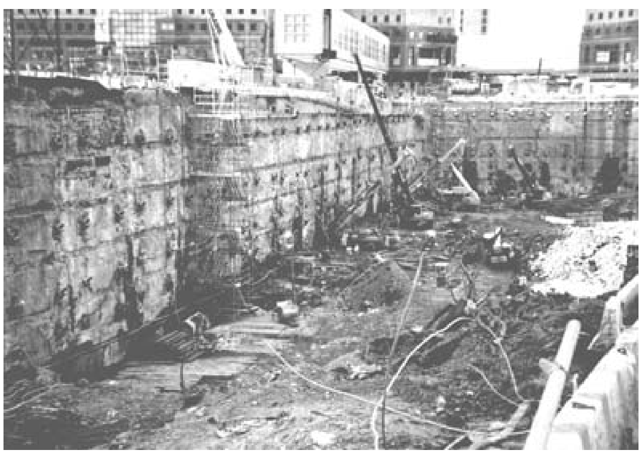


Fig.10 Tiebacks reinstalled at Liberty Street.

Fig. 11 Site Photo from May 2002.

Fig. 12 Remnant basement structure at Vesey Street.

<u>Maintenance of the Diaphragm Wall</u>

Chemical grouting of diaphragm wall joint leaks is an on going operation. (Fig. 13) Climatic changes cause small movement and the re-opening of previously sealed joints. A continuing program of joint grouting to reseal joints will be required until the diaphragm walls are permanently re-supported. Where the diaphragm wall is to be exposed permanently, it will be necessary to provide quick access in the event of leaks and a continuing program of grouting in order to prevent flows of water into the “bathtub”. A climate control enclosure will also be necessary to protect the wall during prolonged periods of below freezing weather and to minimize damage from ice. (Fig. 14)

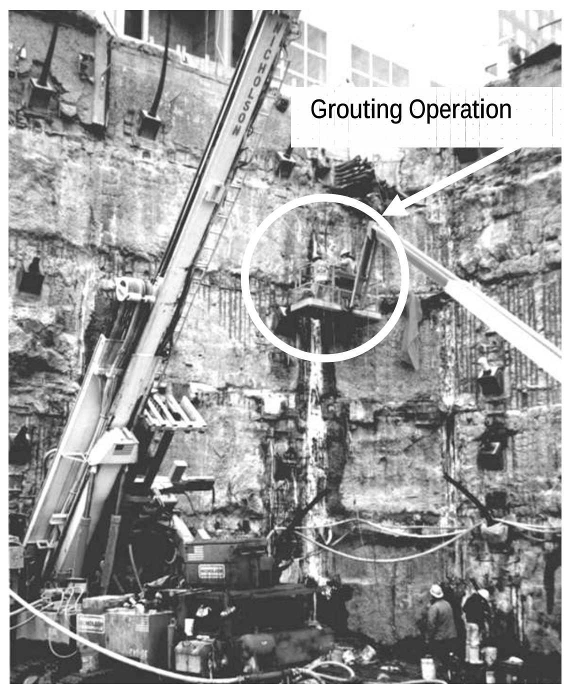


Fig. 13 Sealing of leaks is a continuing operation

Current pumping efforts within the bathtub have been reduced to about 500 liters per minute (150 gpm).

Fig. 14 Icicles form at leaking joints during freezing temperatures

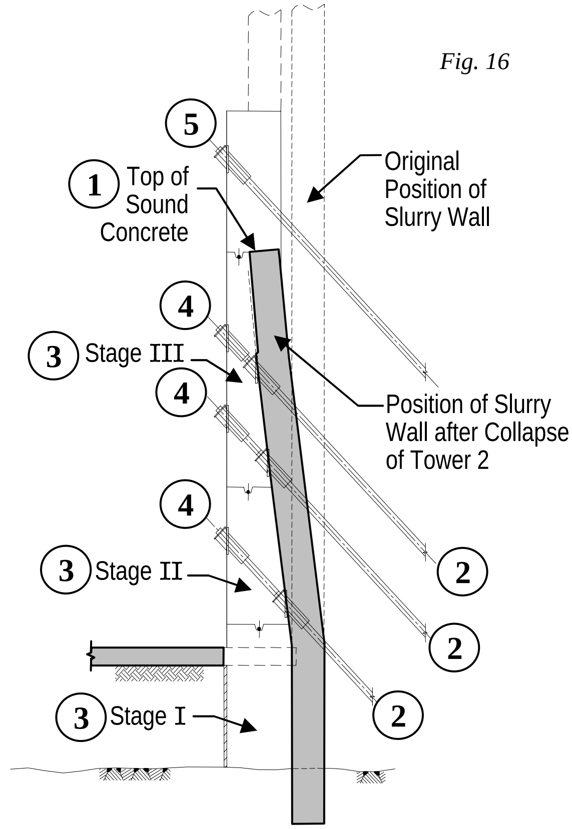
Major Repair at Greenwich Street

The east top section of the WTC 2 tower collapsed to the east, crushing both the IRT subway tunnel and about 30 meters (100 feet) of diaphragm wall along Greenwich Street. The top of the remaining diaphragm wall moved 1.4 meters (4.5 feet) west into the bathtub. (Fig. 15)

Fig. 15 Section of crushed wall at Greenwich Street

Wells were installed behind the wall to keep the water below the top of the damaged wall and the damaged wall was temporarily tied back. A new liner wall was constructed in front of the damaged wall. That wall was then supported by the extension and securing of the anchors through the new wall (Fig. 16).

Fig. 16



Sequence of work for the repair of the Greenwich Street slurry wall:

1. Demolish the top of the slurry wall down to "sound concrete."
2. Install 3 levels of temporary anchors through the existing sections of sound slurry wall in stages.
3. Construct a permanent liner wall against the slurry wall in stages.
4. Extend and re-tension the three levels of temporary anchors installed in Step 2 above.
5. Extend the "liner wall" above the level of "sound concrete": and install the top tier of anchors.

Liner Wall at Liberty Street

A 76 meter (250 feet) long by 6 meter (20 foot) high section of liner wall was installed along the lower level of the Liberty Street wall and forty two 325mm (12.75 inch) diameter drilled shafts for future liner wall construction were installed at the south end of the West Street diaphragm wall. Reconstruction of PATH tracks will preclude construction of the liner wall at a later time (Fig. 17). The liner wall along Liberty Street is supported by concrete piers to rock and is doweled into the original diaphragm wall. The tiebacks installed during the recovery effort will provide temporary support for the two walls. Windows that are 760mm square (2.5 feet) have been provided in the liner wall to permit de-tensioning and sealing of the tieback sleeves in the future.

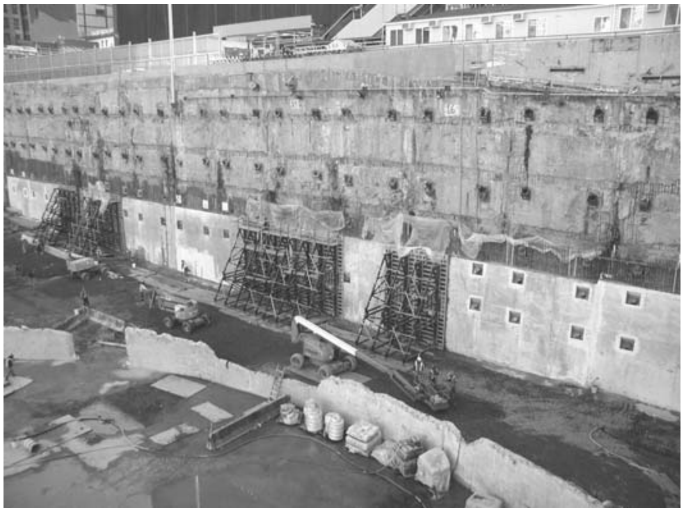


Figure 17 – Construction of liner wall at Liberty Street

Repairs to Other Sections of Diaphragm Wall

The slurry wall was damaged by the impact of the collapse, by subsequent fire and by continuing exposure to the elements. Temporary repairs, maintenance and protection of the diaphragm wall is being provided by sandblasting the exposed concrete surfaces, removal of delaminated concrete, realignment and anchoring of diaphragm wall reinforcement and application of a shotcrete cover. Depending upon future conditions, these sections of slurry wall may or may not require additional support and protection by a liner wall. (Fig. 18).

Fig. 18 Repairs of damaged slurry walls

Permanent Diaphragm Wall Lateral Support

Permanent lateral support of the diaphragm walls will be obtained from future floor slabs. Where floor slabs are not present, a system of permanent struts, buttresses and/or trusses will be installed so that the temporary anchors may be de-tensioned and sealed. These supports will have to be capable of supporting individual 6.7meter (22 feet) panels in a configuration closely conforming to the original wall support design. (Fig. 19)

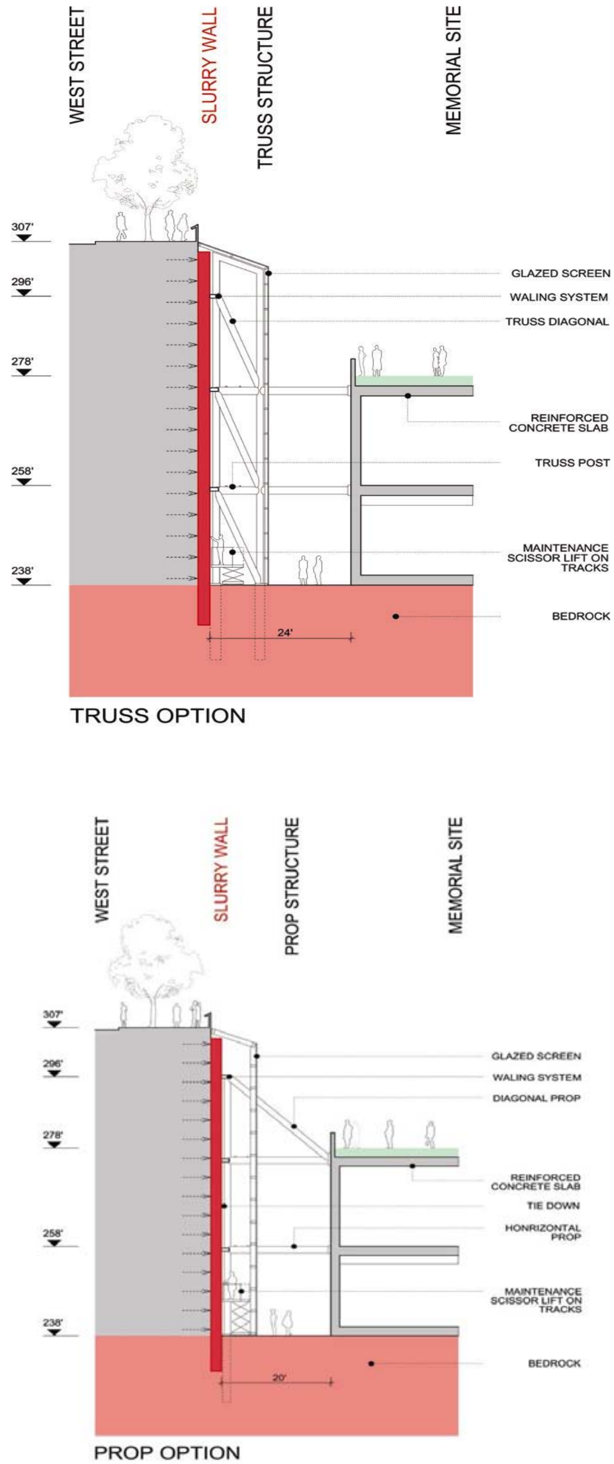


Fig. 19 Proposed re-support of slurry wall where wall is to remain visible

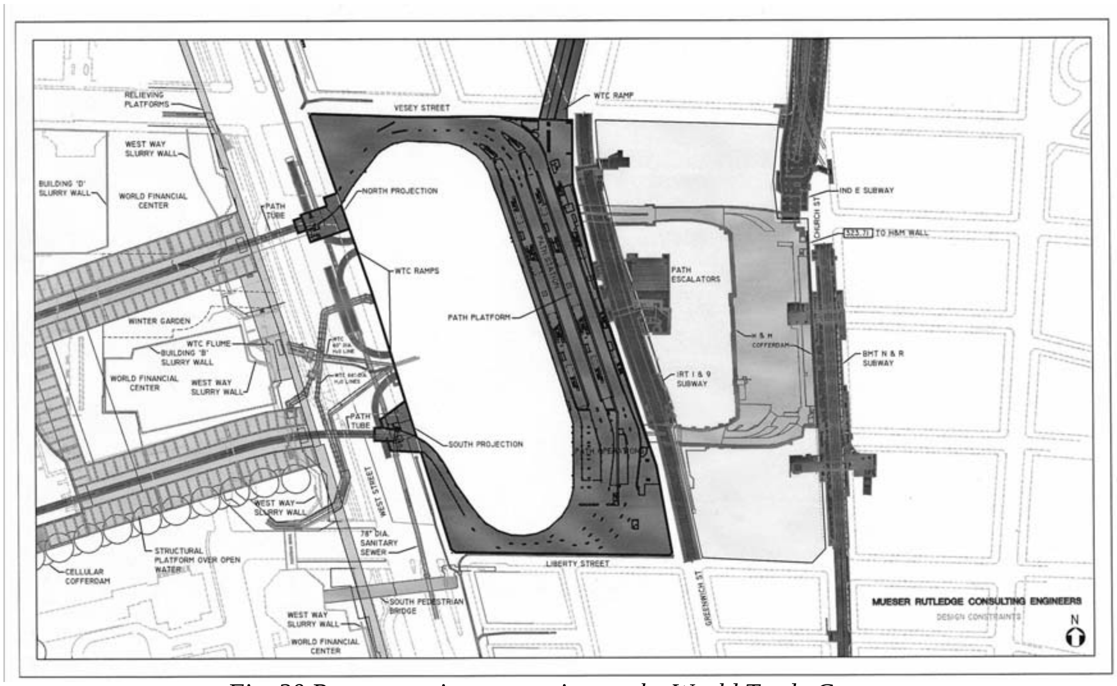


Fig. 20 Reconstruction constraints at the World Trade Center

<u>Remnants of Original Construction in Current Use</u>

Remnants of the original construction remained after completion of the recovery effort. For example, the original diaphragm wall has been temporarily re-supported with tiebacks and reused as the support of the excavation, permitting reconstruction of the temporary PATH station. Other elements such as the escalator “tunnel” under Greenwich Street and selected levels of below grade slab structure are incorporated into the plans for the temporary station and the support of Vesey Street. Basement walls east of Greenwich Street are serving as temporary retaining wall support for Vesey Street, Church Street and Liberty Street. About a third of the former caissons for WTC 7 have been incorporated into the foundations for the new structure.

<u>Impacts of Future Construction</u>

The WTC site is bounded or intersected by numerous structures and utilities. Furthermore, the configuration and support of the diaphragm wall affects future construction. (Fig. 20).

The following is a brief listing of the reconstruction constraints:

1. IRT subway tunnel in Greenwich Street.
2. BMT subway tunnel in Church Street.
3. IND subway station at the corner of Vesey and Church Streets.
4. Utilities in the perimeter streets.
5. Remnant basement structure of the former Hudson and Manhattan Terminal (between Courtland, Fulton, Greenwich and Church Streets).
6. Remnant foundations of WTC 4 and WTC 5.
7. North and south diaphragm wall projections into West Street.
8. Temporary diaphragm wall rock anchors in the bed of Vesey, Liberty, West and Greenwich Streets. The rock sockets for anchors in Vesey and Liberty Streets are within adjacent properties and conflict with future work. (Fig. 21)

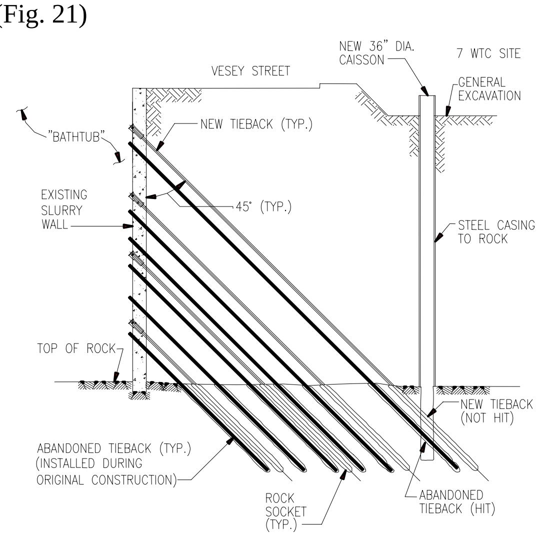


Fig. 21 Anchor/Caisson conflicts in Vesey Street

9. Former large diameter river water lines and auto ramps in West Street and a truck ramp in Vesey Street.
10. Remnant basement slabs at the north end of the "bathtub".
11. The new multi-level temporary PATH Station paralleling Greenwich Street consisting of a 6 meter (20 feet) high track shed and an elevated electric sub-station along Liberty Street occupying part of the footprint of the former WTC 2.
12. The PATH tubes in West Street.
13. Bulkheads, structural platforms and the World Financial Center below grade structures west of West Street.
14. South pedestrian bridge over West Street.

<u>Reconstruction</u>

The Port Authority has constructed a temporary PATH station over the footprint of the former station, has rehabilitated the PATH tunnels and has expanded the Exchange Place Station.

Current plans for reconstruction of the site contemplate the construction of a minimum two level below grade structure within the "bathtub". The lower level of the slurry wall can then be re-supported by structural slabs. Portions of the upper level of the diaphragm wall along West Street are proposed to remain exposed. A multi-level, permanent PATH station, with improved platform layout, is proposed along Greenwich Street while a "Grand Concourse" is proposed to transverse the site, east to west, to connect NYCT services and the Fulton Street Transit Center to the east and the World Financial Center to the west.

The "bathtub" would also contain a memorial, most probably covering the footprints of WTC 1 and WTC 2 as a minimum, and a tower taller than the former Towers 1 and 2, located in the northwest sector of the "bathtub".

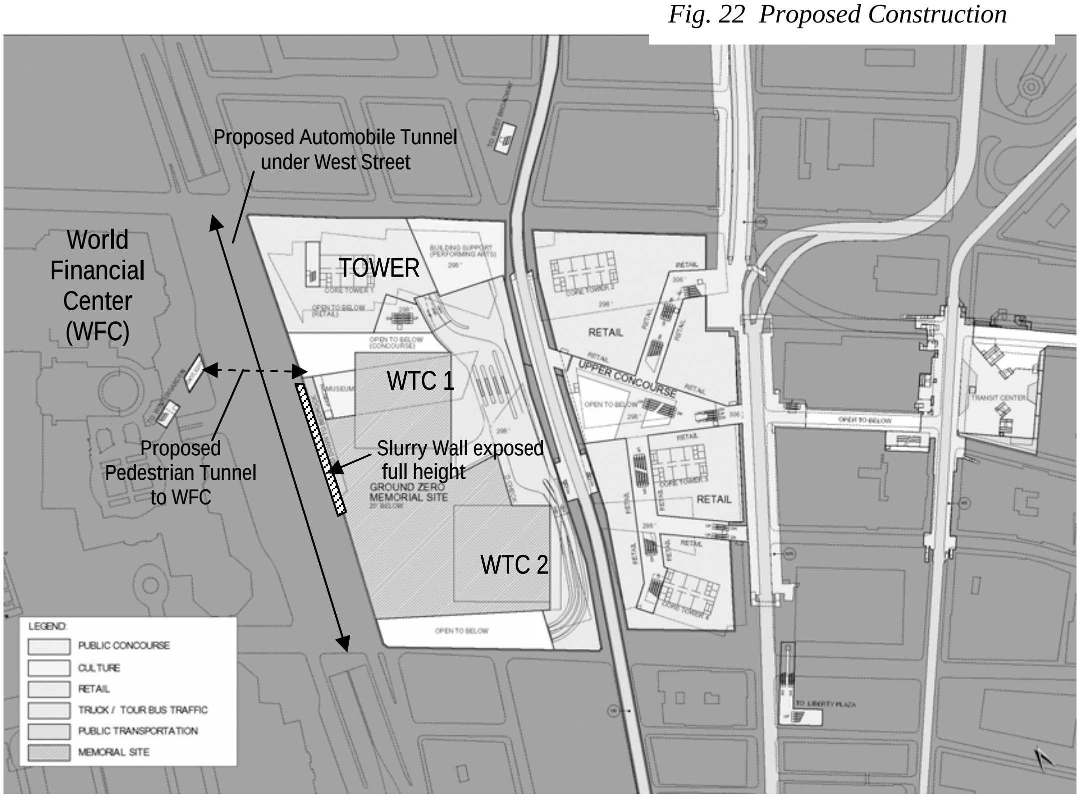
Major office construction is proposed to occur east of Greenwich Street, probably requiring construction of a second, smaller "bathtub" following the property lines of Vesey, Church, Liberty, and Greenwich Streets.

Reconstruction of West Street may require the Construction of a short tunnel or depressed roadway from Liberty Street to Vesey Street. Location and depth of construction will be defined by the existing slurry wall projections into West Street where the PATH tubes enter and exit the "bathtub" and by the existing temporary tiebacks and major utilities in the bed of West Street. The existing PATH tunnels and the proposed "Grand Concourse", which is to pass beneath the roadway, will also have to be accommodated. (Fig. 22)

SUMMARY

Reconstruction of the World Trade Center is currently under way. The development of the full program will take a substantial period of time as well as ingenuity from the government officials, developers, designers and constructors involved in the reconstruction.

Fig. 22 Proposed Construction



Acknowledgements

Labor, contracting firms, engineering firms and governmental agencies working on the recovery effort are to be commended for their tireless effort in bringing the recovery phase of the work to a safe and successful conclusion.

This paper has been prepared using information and exhibits obtained from the many parties collaborating in the reconstruction effort. Permission to use these documents is appreciated as is the help obtained from the many Mueser Rutledge engineers who have assisted in the preparation of this paper.

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