WORLD TRADE CENTER: CONSTRUCTION, DESTRUCTION, AND RECONSTRUCTION

The Tenth Spencer J. Buchanan Lecture

By

Arnold Aronowitz

Tuesday November 19, 2002

College Station Hilton
810 University Drive
College Station, TX 77840 USA

http://ceprofs.tamu.edu/briaud/buchanan.htm

SPENCER J. BUCHANAN, SR.

Spencer J. Buchanan, Sr. was born in 1904 in Yoakum, Texas. He graduated from Texas A&M University with a degree in Civil Engineering in 1926, and earned graduate and professional degrees from the Massachusetts Institute of Technology and Texas A&M University.

He held the rank of Brigadier General in the U.S. Army Reserve, (Ret.), and organized the 420th Engineer Brigade in Bryan-College Station, which was the only such unit in the Southwest when it was created. During World War II, he served the U.S. Army Corps of Engineers as an airfield engineer in both the U.S. and throughout the islands of the Pacific Combat Theater. Later, he served as a pavement consultant to the U.S. Air Force and during the Korean War he served in this capacity at numerous forward airfields in the combat zone. He held numerous military decorations including the Silver Star.

He was founder and Chief of the Soil Mechanics Division of the U.S. Army Waterways Experiment Station in 1932, and also served as Chief of the Soil Mechanics Branch of the Mississippi River Commission, both being Vicksburg, Mississippi.

Professor Buchanan also founded the Soil Mechanics Division of the Department of Civil Engineering at Texas A&M University in 1946. He held the title of Distinguished Professor of Soil Mechanics and Foundation Engineering in that department. He retired from that position in 1969 and was named professor Emeritus. In 1982, he received the College of Engineering Alumni Honor Award from Texas A&M University.

He was the founder and president of Spencer J. Buchanan & Associates, Inc., Consulting Engineers, and Soil Mechanics Incorporated in Bryan, Texas. These firms were involved in numerous major international projects, including twenty-five RAF-USAF airfields in England. They also conducted Air Force funded evaluation of all U.S. Air Training Command airfields in this country. His firm also did foundation investigations for downtown expressway systems in Milwaukee, Wisconsin, St. Paul, Minnesota; Lake Charles, Louisiana; Dayton, Ohio, and on Interstate Highways across Louisiana. Mr. Buchanan did consulting work for the Exxon Corporation, Dow Chemical Company, Conoco, Monsanto, and others.

Professor Buchanan was active in the Bryan Rotary Club, Sigma Alpha Epsilon Fraternity, Tau Beta Pi, Phi Kappa Phi, Chi Epsilon, served as faculty advisor to the Student Chapter of the American Society of Civil Engineers, and was a Fellow of the Society of American Military Engineers. In 1979 he received the award for Outstanding Service from the American Society of Civil Engineers.

Professor Buchanan was a participant in every International Conference on Soil Mechanics and Foundation Engineering since 1936. He served as a general chairman of the International Research and Engineering Conferences on Expansive Clay Soils at Texas A&M University, which were held in 1965 and 1969.

Spencer J. Buchanan, Sr., was considered a world leader in geotechnical engineering, a Distinguished Texas A&M Professor, and one of the founders of the Bryan Boy's Club. He died on February 4, 1982, at the age of 78, in a Houston hospital after an illness, which lasted several months.

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2002	Arnold Aronowitz	“World Trade Center: Construction, Destruction, and Reconstruction”

The text of the lectures and a videotape of the presentations are available by contacting:

Dr. Jean-Louis Briaud
Spencer J. Buchanan ’26 Chair Professor
Department of Civil Engineering
Texas A&M University
College Station, TX 77843-3136, USA
Tel: 979-845-3795
Fax: 979-845-6554
e-mail: Briaud@tamu.edu

You may also visit the website
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AGENDA

The Tenth Spencer J. Buchanan Lecture
Tuesday November 19, 2002
College Station Hilton

5:15 p.m.	Introduction by Jean-Louis Briaud
5:30 p.m.	"World Trade Center: Construction, Destruction, and Reconstruction” by Arnold Aronowitz
6:20 p.m.	Discussion with Darrow Hooper
6:25 p.m.	Closure with Mark Buchanan
7:00 p.m.	Reception at the George Bush Presidential Library and Museum (Buses leave every 10 minutes starting at 6:45 p.m.)

Mr. Arnold ARONOWITZ

The tenth Spencer J. Buchanan Lecture in the Department of Civil Engineering at Texas A&M University was given by Mr. Arnold Aronowitz on November 19, 2002 on the topic of : "The World Trade Center: Construction, Destruction, Reconstruction".

Mr. Aronowitz received his Bachelor's degree in civil engineering from the Polytechnic Institute of Brooklyn, and his Master's degree from Columbia University. He is a Registered Professional Engineer in the States of New York and New Jersey and a Fellow of the American Society of Civil Engineers. He has 43 years of consulting experience most of them with The Port Authority of New York and New Jersey where he was the Chief Geotechnical Engineer. In that capacity, he was responsible for the geotechnical part of major projects including major buildings such as the World Trade Center, major airports such as Kennedy, La Guardia, and Newark, major bridges such as the George Washington bridge, the Bayonne bridge, the Goethals bridge, major tunnels such as the Lincoln tunnel, the Holland tunnel, major port facilities such as Elizabeth, Newark, and Brooklyn. He is very active in the Transportation Research Board and, among other lectures, delivered the 1997 Martin Kapp Lecture.

World Trade Center: Construction, Destruction, and Reconstruction

By Arnold Aronowitz, Fellow ASCE
Retired Chief Geotechnical Engineer, The Port Authority of N.Y & N.J

On September 11, 2001, terrorists destroyed the World Trade Center. They crashed a Boeing 767 into the North Tower at 8:45AM and eighteen minutes later, another Boeing 767 into the South Tower. The towers did not collapse. The North Tower remained standing for 104 minutes and the South Tower remained standing for 62 minutes before they collapsed. The structures fell into the World Trade Center's basement, which had seventy-foot high walls, which remained standing. As part of the recovery effort new anchors were installed to support the walls.

INTRODUCTION

The work to construct the World Trade Center's foundations was an engineering endeavor that even today is not fully appreciated. This paper will deal mostly, with the Geotechnical effort associated with its construction. The foundations were designed and constructed by the Port Authority. John M. Kyle was the Chief Engineer. Martin S. Kapp (Marty) was the head of the Soils Division (Chief Foundation Engineer). He was later promoted to Chief Engineer. I was the head of the Soils Division's Design Section.

The financial, political, and sociological reasons of why and how the World Trade Center was constructed are fascinating but will not be dealt with in this paper. What will be discussed are the Geotechnical contributions that resulted in solving engineering and construction problems and in altering the scope and magnitude of the entire project. The concepts dealing with innovation, creativity and the research required to accomplish these tasks will be explored.

THE SITE

The Port Authority constructed the World Trade Center on twelve city blocks, very close to the Hudson River, in downtown Manhattan. Four blocks were in the north south direction and three bocks were in the east west direction. In colonial times most of the site was below water. Filling the site with twenty to thirty feet of debris, garbage, ships ballast, and other materials, raised the ground surface above the water level. Below the fill, twenty to thirty feet of very soft clays existed on the western side of the site. The bottom of the clay increased in elevation and gradually disappeared approximately one block east of West Street, the western boundary of the site. Other soils, found below the fill or clay soils, generally ranged from silt to sand with different percentage of each in a given sample. Below these other soils, there was from zero to twenty feet of a very dense conglomerate of variable permeability that overlaid the Mica Schist rock. The elevation of the top of rock ranged from fifty to sixty five feet below the Mean High Water elevation in the Hudson River (MHW). The rock had mica and schist stratifications that were close to vertical. The rock was also randomly jointed in all directions.

Two blocks from the western boundary, at Greenwich Street, is an IRT transit tunnel that traverses in a north south direction. Beneath the IRT structure existed two active PATH commuter tunnels. They started in New Jersey and continued in an easterly direction below the Hudson River to New York. The tunnels continued increasing in elevation so that they could reach the elevation of the station on the easterly side of the IRT subway. The PATH trains were on rock at the westerly side of the site, then on soft clay and then on silt and sand soils, as they continued in an easterly direction.

PLANNING AND CONCEPTUAL DESIGNS

Many schemes were studied to accommodate the square footage required for potential tenants of the World trade Center. We made cost estimates to construct the foundations and underground parking garages associated with these schemes. The garages were estimated to be very costly because the high water table, at the site, required that the garages be constructed with thick concrete base slabs or the utilization of vertical tie down anchors. The sheeted excavations and dewatering, close to existing structures, through fill, soft clay and other soils added significantly to the estimated cost. Possible damage to adjacent streets, utilities, and structures could also have added to that cost.

Port Authority Geotechnical engineers proposed a cost effective alternative. We proposed to construct a hollow concrete rectangular structure consisting of horizontal cut-off walls, without a base slab, that would be imbedded into rock. The top of the walls would be above the water level. A drainage system would be constructed above the rock, to collect and discharge minor water seepage that would flow into the structure. This concept eliminated the need for a thick base slab or vertical tie down anchors and facilitated the placement of footings directly upon the rock. These footings could support the garages and the other structures. This concept also provided much more revenue producing space in the proposed seventy-foot deep basement area. Port Authority Planners adopted this concept. However, they enhanced our proposal by relocating the PATH Station to the bottom floor of the new enlarged basement area. This final scheme, a basement with six floors, that extended four blocks in a north-south direction and two blocks in an east-west direction, provided many geotechnical challenges.

THE SLURRY WALL

The first major challenge was to determine the kind of cut-off wall and how it should be constructed. Marty proposed that slurry wall panels should be used. He was instrumental in convincing European contractors along with the only contractor, in New York, who was able to do the work to submit bids on this unusual type of construction. The increased competition lowered the cost of the wall. A slurry wall had never been constructed that was as long and posed as many challenges as the one we proposed to build.

A wall panel was constructed by excavating a three-foot wide trench approximately twenty-two feet long that was continuously backfilled with slurry. The slurry was a mixture of Bentonite clay and water and had the consistency of pea soup. The slurry kept the walls of the trench from caving in. This process also minimized the movement of the adjacent pavements, utilities and structures including the adjacent IRT tunnel. The width of the trench was sufficiently wide to allow the removal of most obstructions and to utilize equipment required to chop out the rock socket. After an excavation was completed, a steel reinforcing cage with inserts for anchors was lowered into the trench. Tremi concrete was then deposited starting at the bottom of the trench. As the concrete filled the trench, it pushed the slurry out, forming a reinforced concrete wall.

The entire site was not available when the construction of the wall was started. Streets had to be kept open. Some utilities had not been relocated and the demolition work had not been completed. However, since each panel could be constructed independently from one another, many rigs worked at the same time in different areas of the site, thereby, expediting the completion of construction.

Pre-stressed "tie-back tendons" imbedded into rock with a maximum design capacity of six hundred thousand pounds were selected to tie back the walls. Four to six rows of anchors were installed as the soil in front of the wall was removed. The required number depended on localized site conditions. Some anchors were de-stressed after anchors at lower elevations were installed. This process was required to minimize the magnitude of the bending moments that developed in the wall. Concrete buttresses were installed near the bottom of the wall if the sound rock elevation was too low for the lowest floor to brace the wall after the rock anchors were removed. Vertical, "tie-back tendons", rock anchors were installed, in front of a buttress to intercept inclined joints in the rock.

A design procedure was developed by Donald York, Marty's assistant, to determine the magnitude of stress in each anchor and the bending moment in the wall at each stage of excavation. Carlson strain meters and slope inclinometer casings were installed inside selected slurry wall panels to facilitate the determination of the bending moments in the wall. Load cells were used to measure anchor loads in test panels. The measured Tie-Back Loads in all the test panels decreased from their "final" pre-stressed values. The data obtained from the strain meters, inclinometers and load cells was used to evaluate the condition of the walls.

The top of a test panel on West Street moved approximately three inches into the soil behind the wall. The measured Tie-Back Loads decreased as the wall moved away from the excavation. They were approximately equal to the "Elastic" Tie-Back Loads that were computed from the wall deflections. The wall movement and the resulting decrease in length of the "tie-back tendons" was most likely due to the yielding of the twenty-five feet of soft clay (called Organic Silt) behind the wall.

The top of a test panel on Greenwich Street moved approximately three inches away from the soil behind the excavation. The measured Tie-Back Loads also decreased but the wall moved toward the excavation. Here the top anchors had to be installed at greater depths than anchors installed in other streets because the bottom of the IRT subway was approximately twenty-six feet below the top of the slurry wall. The panels adjacent to Greenwich Street were temporarily braced at higher elevations, until the top anchors were installed. The most likely reason that the Tie-Back Loads decreased was due to "slippage" since the movement of the wall was toward the excavation. The "apparent" increase in the length of the "tie-back tendons" did not result in an increase in the Tie-Back Load. The soil behind the wall was sand.

The top of a test panel on Vesey Street, the northerly section of the wall, did not move significantly. The maximum movement, thirty feet below the top of the wall, was approximately three eights of an inch away from the excavation. The reason the loads decreased, but with very little movement, could have resulted from a combination of the wall moving into the soil behind the wall and "slippage", to allow the wall to move towards the excavation. The soil behind the wall was sand.

UNDERPINNING THE PATH TUNNELS

The second major challenge was how to structurally support the PATH tunnels during and after the soils around them were being removed because train traffic could not be significantly interrupted throughout the construction period. If too much soil, from above a tunnel, was removed before the water pressure was reduced, the tunnel could have popped out of the ground. If the water pressure was reduced too much the tunnel could have settled. Calibrated Carlson pore pressure (electric) cells were installed thru the bottom of each tunnel, and Casagrande, double tube piezometers were installed outside the tunnels. The instruments were read at critical times, to make sure that the proper exterior dewatering was performed. Long electrical cables were required to read the cells, remotely, because there was no room in the tunnel for a technician to read them, when a train passed through. The PATH tunnels were continuously supported, as the soil was removed, by utilizing the following procedure. Two rows of caissons, adjacent to each tunnel, were first drilled in-to the rock. Steel trusses were next constructed and supported on the caissons. When the adjacent ground reached the mid height of the tunnel, steel flexible straps were installed thru narrow excavated trenches, to underpin the tunnel. The straps were attached to the trusses. Structural saddles were next installed from each side in two pieces and connected beneath the tunnel. The saddles were constructed between adjacent straps and were also supported by the trusses. When a tunnel was supported, the soil below it was removed.

SOIL EXCAVATION

The third major challenge was how to stage the excavation. Critical Path studies indicated that the foundations for the Towers should be completed as quickly as possible. However, in order to construct the foundations soil had to be excavated. However, the soil supported the PATH tunnels, the slurry walls, other structures as well as pavements and utilities. There were two serious soil problems. The clay soils had relatively low shear strengths and also “creeped” under sustained loading. The “creep” behavior could have resulted in a loss of support or an increased loading on the PATH tunnels even if the adjacent slopes had conventionally adequate factors of safety. Local contractors called the sand-silt type soils below the ground water table “bulls liver” because they did not drain well and had the appearance of raw liver. Conventional dewatering was not effective. Excess pore pressures developed when the material was excavated or disturbed by even foot traffic. It was easy to sink into the material immediately after it was excavated. The design slopes for the “bulls liver” and clay soils were based on the assumption that these unexcavated materials remained saturated even after the adjacent soil and water had been removed.

Strain controlled Consolidated Undrained Triaxial tests with pore pressure measurements were performed on “bulls liver” “undisturbed” samples. A Mohr plot of effective stresses vs. shear strength indicated that the “effective” angle of shearing resistance, of the “bulls liver” was greater than thirty-six degrees. However, in the analysis a value of thirty-two degrees was used.

Conventional strain controlled Unconsolidated-Undrained (UU) triaxial tests were performed on “undisturbed” clay samples. However, to asses the issue of “creep” stress controlled Consolidated Undrained (CU) triaxial tests with pore pressure measurements were also performed. The UU, shear strength test results were plotted vs. the field “effective” overburden pressure on each test sample. The calculations to determine the “effective” overburden pressure were based upon site conditions at each boring location that existed before excavation was started. A slope of a straight line through the data indicated that the shear strength was 0.3 times the initial “effective” overburden pressure. The design slopes for the clay soil was based on the assumption that the “conventional” peak shear strength should be reduced by forty percent to compensate for time dependent effects such as “creep”. Piezometers were installed at critical locations throughout the site to monitor pore pressures. Slope Inclinometer casings were also installed on both sides of each PATH tunnel. The Inclinometer readings were obtained and transmitted to a technician who determined the horizontal movement of the casings. If there was movement, the contractor was notified and excavation modifications were made.

ROCK EXCAVATION

The fourth major challenge was the excavation of the rock. The surface of the rock ranged from fifty to sixty-four feet below MHW. A minimum of ten to twenty feet of rock excavation was required to reach the typical bottom elevation of the tower footings and as much as ten feet of excavation was generally required to reach the “general excavation grade”. The least expensive way of excavating the rock was by blasting. However, blasting posed significant problems. We were concerned that structures inside and outside the “bathtub” could be damaged if the blasting was not done properly.

In order to better understand what allowable weights of charges per delay and related distances from a structure should be to prevent it from being damaged, field measurements were made. Seismographs, that measured ground motions, were placed at different distances from test blasts. The weight of charge per delay was also varied. In addition to the measurements obtained during the test blasting, measurements were taken during the production blasting. The data obtained from these measurements, the maximum particle velocity, the distance from the blast and the weight of the charge per delay for each blast was plotted to determine a relationship between these variables, for the World Trade Center site. However, seismograph measurements were still made until the blasting was completed. The relationship was used to facilitate the blasting plans so that the specified particle velocities were not exceeded.

COMPRESSIBILITY AND PERMEABILITY OF THE ROCK-MASS

The fifth major challenge was to determine the “field” compressibility and permeability properties of the rock-mass. Since the rock quality and the joint and stratification patterns varied in all directions within the rock-mass, the examination and laboratory testing of rock core samples were not sufficient in determining the engineering properties of the rock-mass. Samples of the poorest rock could-not be obtained and the effect of joints and stratifications could not be determined by conventional means. The Port Authority retained Don Deere and Skip Hendron from the University of Illinois, pioneers in the discipline of rock engineering, to assist us with these mass-rock behavior problems. They recommended procedures that had previously never been applied to the construction of deep foundation walls and buildings of this magnitude. They recommended that the RQD (Rock Quality Designation) of each rock sample be determined. The RQD designation is a modified core recovery percentage in which only the pieces of core 4-inches or longer of sound rock are counted as “recovery”. Shorter pieces and non-recovered rock are indicative of the quality of the in-situ rock. A high RQD (RQD Number of 93 to 100) indicates that the quality of the rock mass is “Excellent”. A low RQD (RQD Number of 0 to 25) indicates that the quality is “Very Poor”. Compression and seismic tests were performed, in the laboratory and in the field. Modulus of Elasticity (E) values were obtained in the laboratory by mounting strain gages on rock samples that were compressively loaded and seismically on samples, that were loaded axially to 800psi. Tests were also performed on the “mass” rock in the field. The lab tests indicated an E value that was approximately 12 million psi. The field seismic E value was approximately 9 million psi and the full-scale load test indicated an approximate value of 0.2 million psi. The high lab value reflected that the tests were performed on intact samples. The seismic lower field value reflected some joints in the rock mass. The very low value of 0.2 million psi reflected joints beneath the footing that were closed when the test loads were applied. This low value, in many cases, would not have been able to be determined by only examining the surface of the rock or by only drilling a limited amount of depth into the rock. Obtaining samples from adequate depths and RQD designations of the samples can be important because frequently adequate rock can overlay poor rock. The elevation of the bottom of each footing was indicated on the contract drawings. However, the actual elevation was determined in the field, based upon an inspection of the rock.

Field water pressure tests in the rock were performed with packers in order to isolate designated rock zones. Estimates of the permeability of the rock-mass were determined from these tests. The test results were utilized to design the drainage system, which was installed below the lowest basement floor.

HUDSON RIVER LANDFILL AREA

The sixth major challenge was to construct a twenty-four-acre Landfill Area in to the Hudson River, with the one million cubic yards of material that was to be excavated from the World Trade Center site. Initially it was developed into a storage and staging area for the construction of the World Trade Center. Later the area became the first part of Battery Park City to be constructed.

The site was below water and had many abandoned piers. A deposit of soft clay, whose surface elevation ranged from ten to thirty feet below MHW, was above the rock. The surface of rock, Mica Schist, extended from forty to sixty feet below MHW.

The design required that the abandoned piers had to be removed and that a cellular cofferdam wall be constructed to retain the material that was going to be placed on the site. Very large trucks transported the excavated material and was end dumped, on top of the soft clay.

Stability considerations and the construction of the cells required that the soft clay in the vicinity of the cofferdam area had to be removed before the wall could be constructed. However, we felt that it would be difficult to remove the soft clay with a bucket, because the bottom of the clay was on top of the rock. On most jobs, after most of the clay has been removed, the bucket can be made to penetrate into the stronger soil below the clay. The bucket then removes the remaining thin layer of clay by excavating some of the stronger soil below it. Here the bucket could not penetrate into the rock. The excavation problems were resolved by employing appropriate construction procedures and by judiciously selecting the appropriate excavating equipment. Each trench was expeditiously backfilled with a ten-foot blanket of sand, right after closely spaced soundings and probings confirmed that the clay had been removed.

DESTRUCTION AND RECONSTRUCTION

All the studies associated with the collapse of the World Trade Center have not been completed. However many articles and reports have been written and there have been television programs that dealt with the causes of the collapse. Preliminary plans have also been made of how to redevelop the site. I will discuss my ideas, regarding some of the engineering issues.

The towers withstood the impact forces from the aircrafts, without collapsing. The cause of the collapse appears to have been due to fires that were started by burning aircraft fuel. The heat generated by the fires was instrumental in collapsing the floor structures. After a floor collapsed, the adjacent columns were no longer braced and they buckled. The impact of the falling floors then collapsed the floors below them. This mechanism, I think, resulted in a progressive failure that was instrumental in the collapse of both towers.

Structures can be designed to resist very large forces. However, they are not conventionally designed to resist the maximum possible earthquake, wind, flood, or other hazard forces. Waterfront structures are not designed to withstand collisions with the maximum possible size vessel that travels at the maximum possible speed. Even though many people are killed in automobile accidents each year, states do not restrict poor drivers from driving, nor, do they require that people drive in tanks. Society accepts risks.

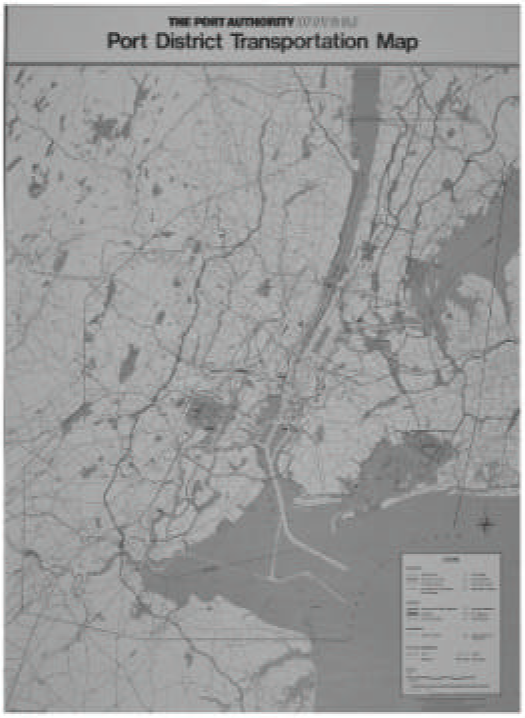
Let us assume that an attempt will be made to design a conventional structure to survive an attack from terrorists. It could be assumed that an aircraft similar to the one that hit the World Trade Center will impact the structure. Is it possible that there may be a bomb on the aircraft that will explode shortly after impact? How big could that bomb be? Could a larger bomb be developed? Is it possible that a larger aircraft may be used? Is it possible that a guided nuclear missile is made to crash into the structure? There is a problem. The design load cannot be readily defined.

How should the structure be designed? Should a strong rigid structure be constructed? That could also be a problem. When a structure is designed to resist a dynamic event, the resulting force is also a function of the rigidity and mass of the structure. If the structure is made more rigid and more massive, the impact forces will be greater. Should the structure be flexible? How far will the aircraft penetrate into the structure? Will the aircraft break up after impact? Can the structure be designed to allow the aircraft to pass through? What are the consequences? There are many more unanswered questions.

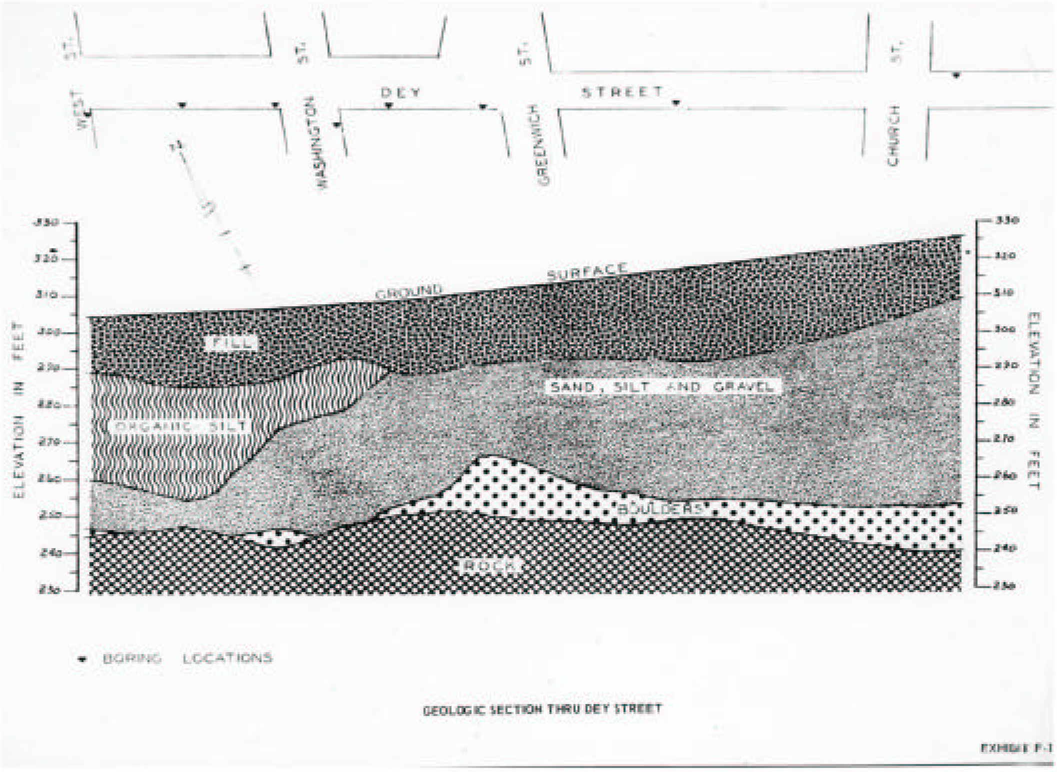
More stairways are better but how many should there be? The issues may be more clearly defined if one considers that the structure is a private residence. Would the owner be willing to sacrifice room space for additional stairways? If the owner were sure that the additional stairways were necessary, he would have them built, if he could afford them. Will most owners think that their homes will be attacked and that they have insufficient stairways? People will form different conclusions.

I think conventional structures will generally not be designed to deal with the worst possible terrorist scenario that can occur nor the scenarios that are presently inconceivable? Eventually codes and standards as well as design and construction procedures will be developed, that are similar to the ones that are now being employed to deal with other hazards such as earthquakes, winds and floods. As a result of "September 11”, there will be changes. Unfortunately, these changes will not make us significantly less vulnerable. The most practical way of dealing with the problem is to become more effective in preventing terrorist acts.

WTC and World Financial Center completed

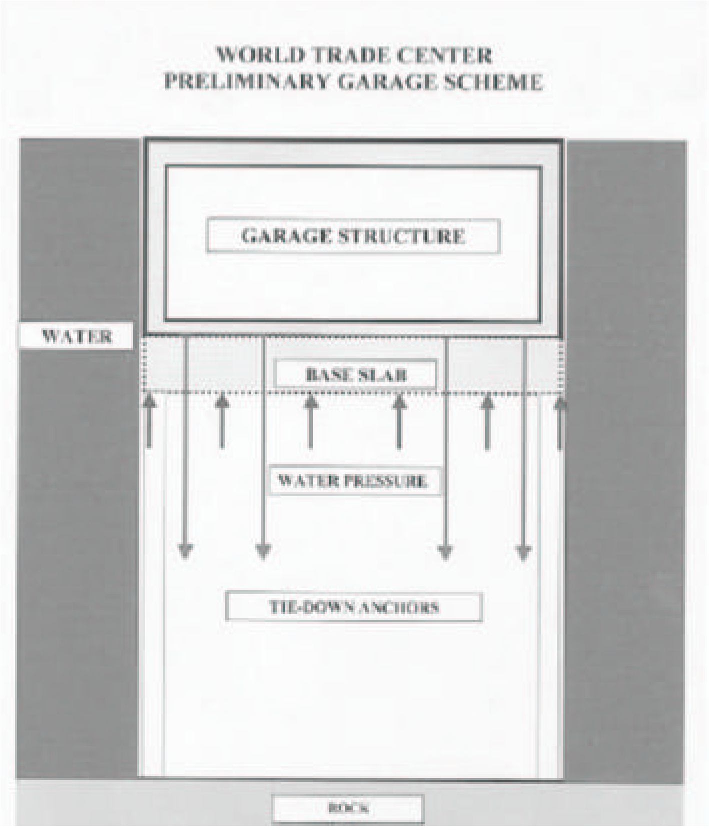


Port District Transportation Map

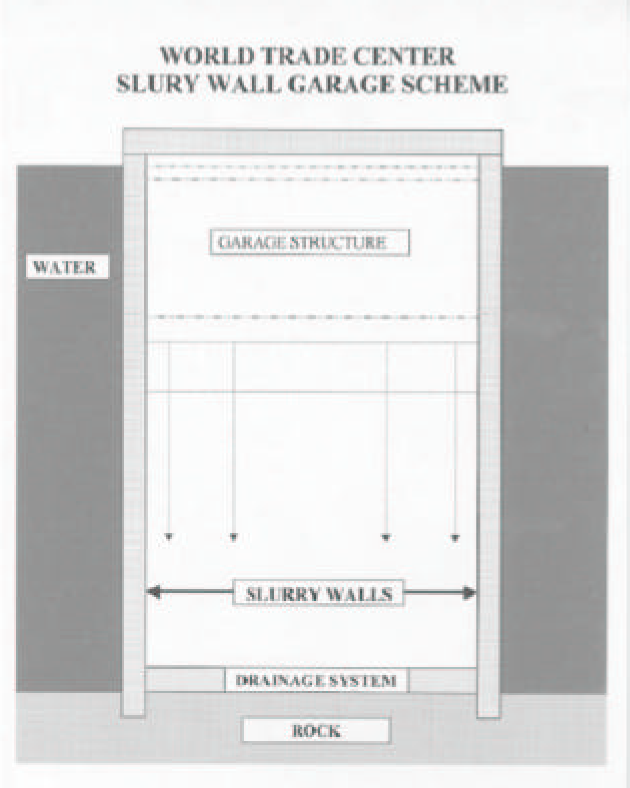


Geologic Section Thru Dey Street

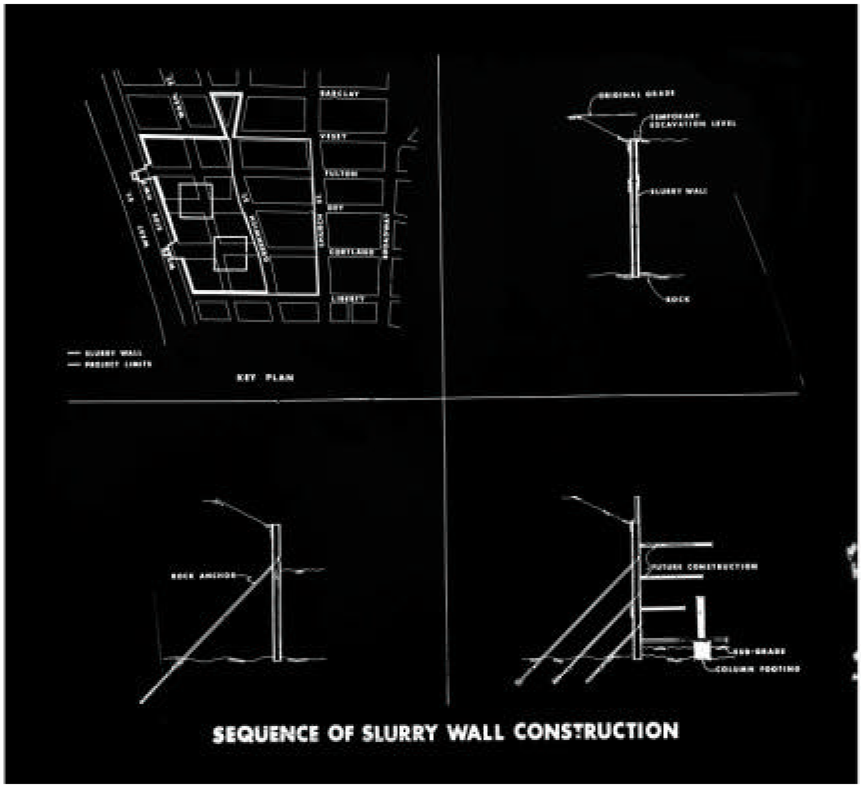
Pre- Construction Utility Excavation



Garage Structure Estimate



Garage Slurry Wall Alternate Estimate



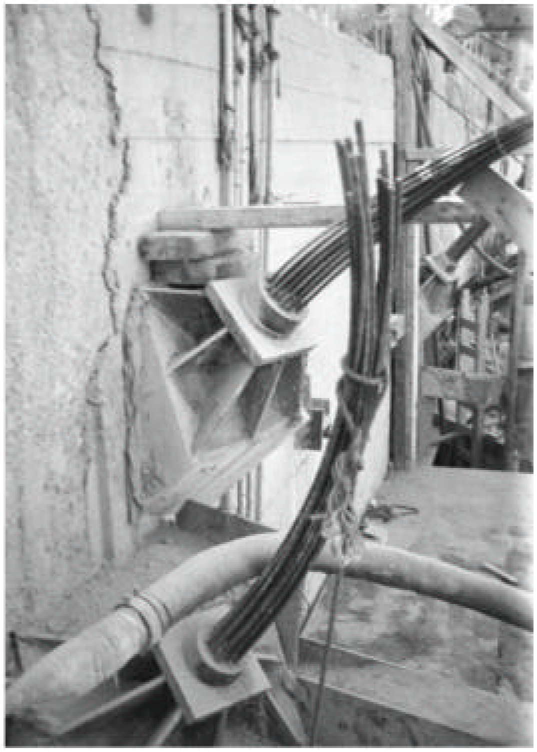
Sequence of Slurry Wall Const.

Rendering of Slurry Wall Const. Stages

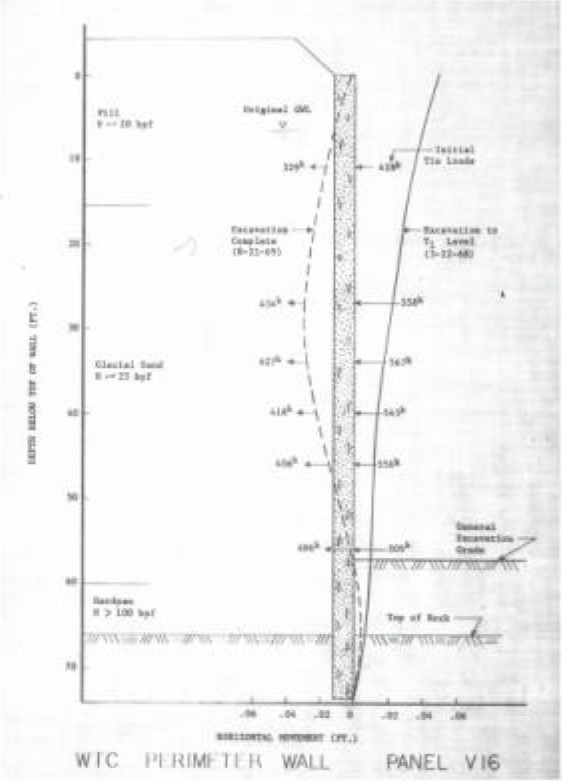
Pre-Excavation Basement Site (Motorola)

Slurry Wall Reinforcing Cage being lowered

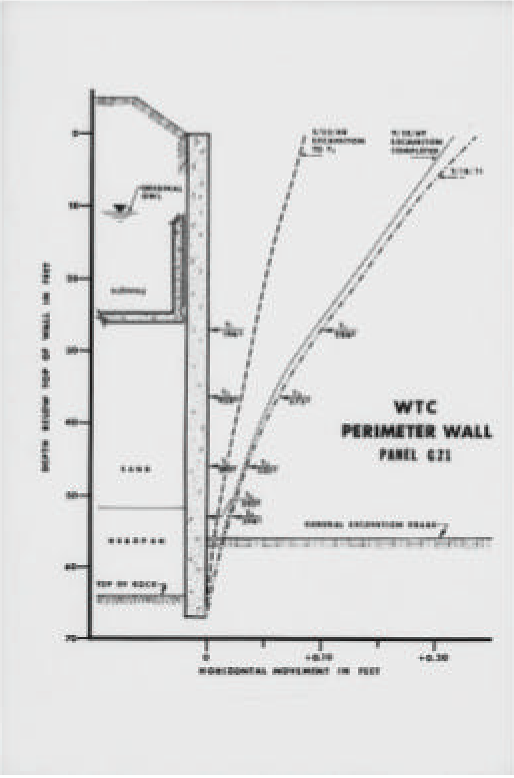
Wall Anchor Installation



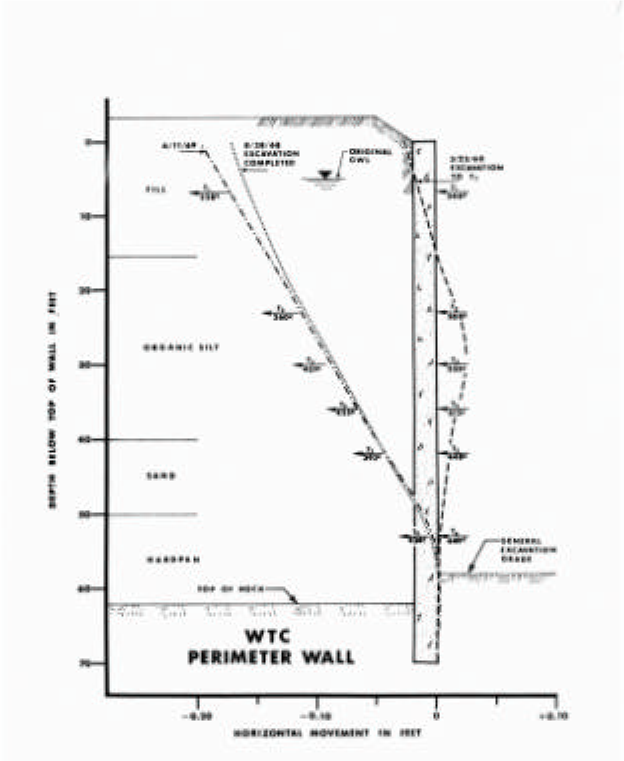
Anchor Weldment



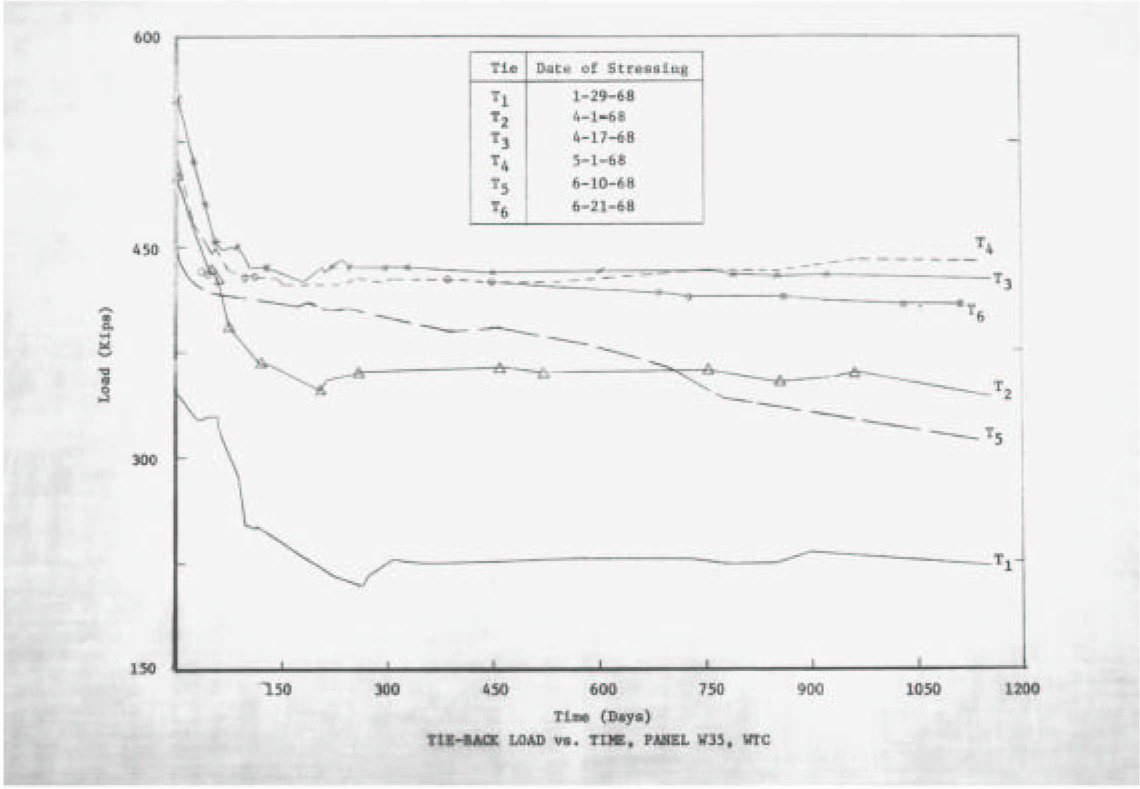
WTC Perimeter Wall Panel V16, Horizontal Movement, Anchor Loads



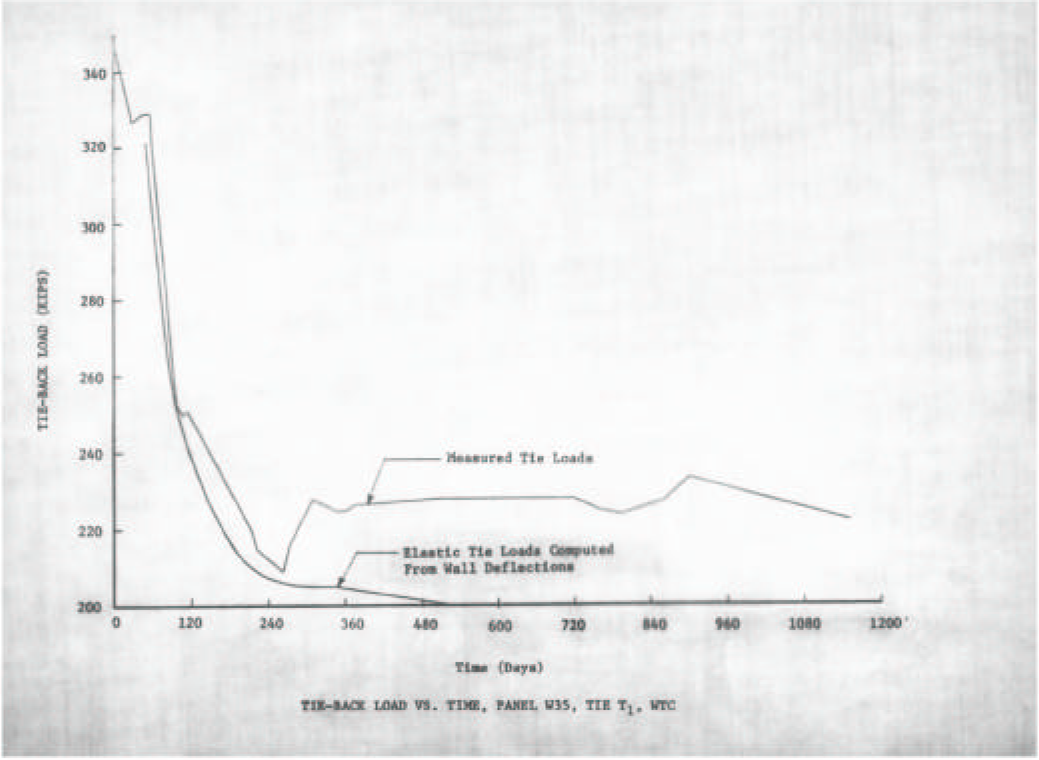
WTC Perimeter Wall Panel G21, Horizontal Movement, Anchor Loads, Subway



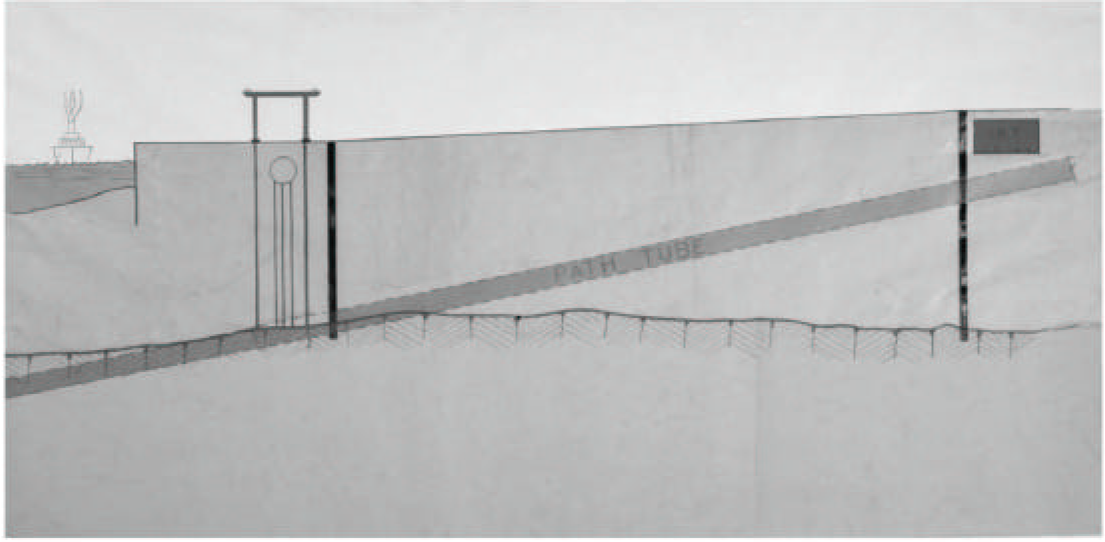
WTC Perimeter Wall, Horizontal Movement, Anchor Loads, (W35, West Street)



Tie Back Load vs Time, Panel W35, WTC, (dates of stressing 1/29/68 to 6/21/68)



Tie Back Load vs Time, Panel W35 Tie T1, WTC, (Measured and Computed Tie Loads)



PATH Tube Section thru un-excavated Basement Rendering

Steel Strap Supporting Path Tube

Truss Supporting North PATH Tube, berm, anchor installation

Construction Bridge, Truss, Caissons, Piez., Slope Incl Casings, Earth slopes

PATH Tube Saddles supported by truss, steel straps between saddles

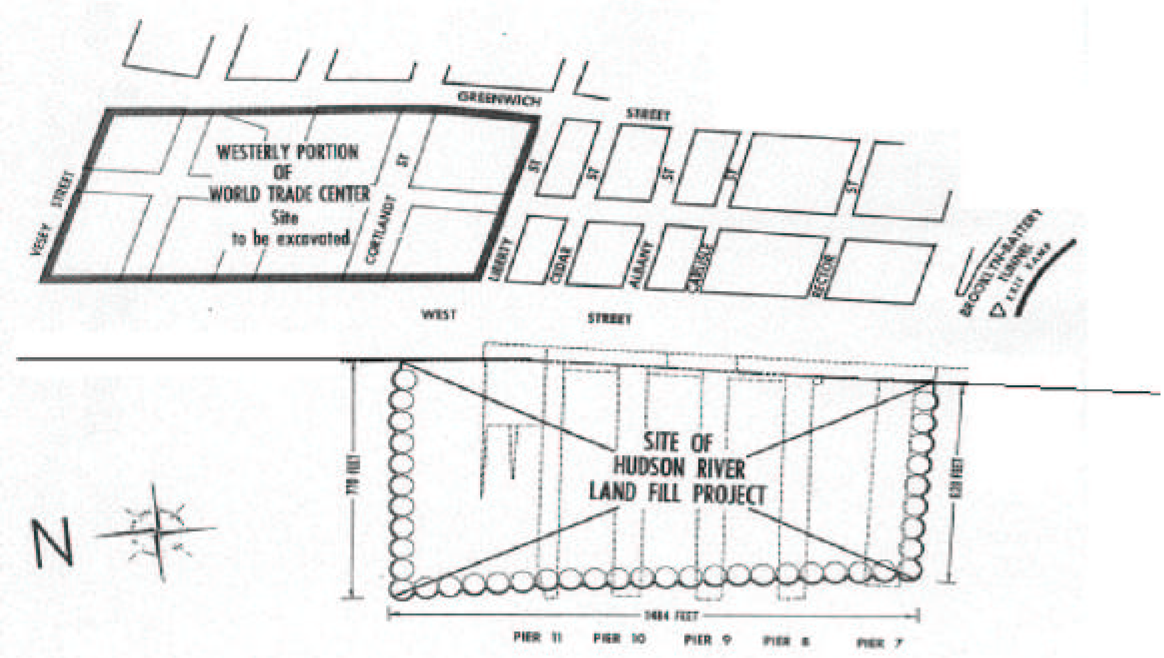
Caisson Supporting PATH truss

Basement excavation, construction bridges under construction, berms & earth slopes, north PATH tube supported

Supported PATH tube at West Street Slurry Wall

Supported PATH Tube at Greenwich Street Slurry Wall, beneath BMT Subway

Completed Greenwich Slurry Wall & supported PATH Tube



Drawing - Site of Hudson River Land Fill Project, 24 Acres, (Future Battery Park City Site)

Basement excavation, construction bridges, north PATH tube, AT&T building

Cofferdam Construction (Cofferdam being filled with Sand)

Cofferdams, piers to be demolished, (South West area at different stages of construction)

Site of future Battery Park City (Cofferdams mostly completed, filling with WTC materials started)

Basement excavation, both tubes exposed, considerable fill placed in Land Fill site, two interior construction bridges

Land Fill site (essentially completed, installing Pump Station sheeting)

Steel grillages being constructed for North Tower adjacent to supported North PATH Tube

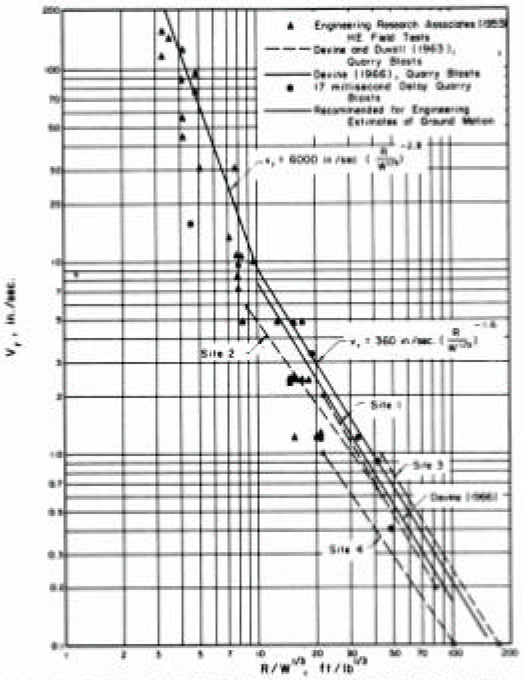


FIG. 3. FIELD MEASUREMENTS OF MAXIMUM RADIAL PARTICLE VELOCITY VERSUS SCALED RANGE.

Drawing - Field Measurements of Maximum Radial Particle Velocity versus Scaled Range

Load Cells utilized for full scale footing load test on Manhattan Schist Rock, (E = 200,000psi, 1/100 of intact rock)

Tower Footing Construction, PATH Tube structurally supported

North and South towers erected with cranes, interior towers in core area supporting four cranes are shown, decking

Lifting prefabricated outside wall section

Steel erection utilizing Kangaroo cranes

Construction of basement floors (they will laterally support Slurry Walls after anchors are cut

DUPLICATE of 48

North and South towers, Land Fill area, partial demolition completed East of Greenwich Street, (BMT tunnel not exposed)

Towers construction observed from basement

Towers completed, Battery Park construction

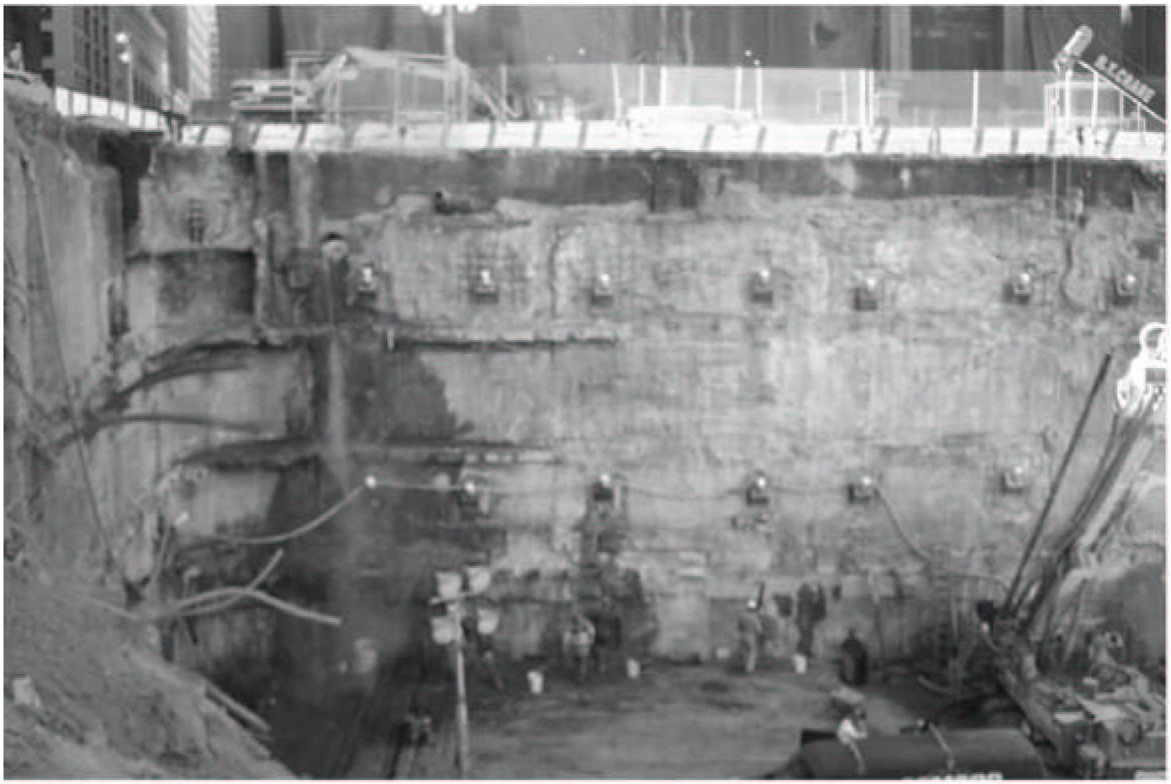
Wp1010052

WTC Destr.

Unbraced columns

Wall & Excav Equip, Demol. Looking at Winter Garden, Earth Ramp

Arnold, John, Liberty Wall, PATH Proj Bracing



Anchor Installation SE corner

Two rows of Anchors, PATH tunnel

PATH Tunnel

Ray, Arnold and Peter

Statue of liberty in front of completed WTC and World Financial Center

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