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Tunneling in Chicago Clay: Pioneering Work in Ground Control

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TUNNELING IN CHICAGO CLAY: PIONEERING WORK IN GROUND CONTROL

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ABSTRACT

Early in his engineering career, Ralph Peck supervised the soil mechanics investigations during subway construction in the soft clays in Chicago, working under the guidance of Karl Terzaghi. A major focus was to determine what should be done to minimize surface settlements of the streets. Squeeze tests, in which clay displacements and construction events in the tunnel were observed, led to changes that significantly reduced surface settlement. Squeeze test reports prepared by Peck and his soil mechanics team are summarized and selected drawings illustrated. The work provides a first view of Peck's observational method: "it demonstrated the enormous practical benefits … that may be derived from simple but intelligently interpreted observations." Over the past 70 years, it has served as a standard for investigation and control of ground movement, examples of which are summarized at the end of the paper.

INTRODUCTION

From 1939 through 1941, Ralph Peck was Assistant Subway Engineer in the Department of Subways and Traction of the City of Chicago, Survey Section, supervising the Soil Mechanics Laboratory during the construction of the Chicago Subway. He was selected by and worked under the guidance of Karl Terzaghi, who was consultant to the City. Ralph Burke was chief engineer for the subway work, and Raymond Knapp was head of the survey section.

One of the questions that arose early in construction was "What should be done to reduce the settlement of the street surface to a minimum" (Terzaghi, 1942a). Answering that question became a major part of the work of Ralph Peck and his soil mechanics team throughout the subway construction. This paper focuses on that work, in particular the series of field test sections, termed squeeze tests, they conducted in the liner plate tunnels.

Ralph Peck, in presenting the first Stanley D. Wilson lecture, in describing the squeeze test data, noted the May 9-12, 1939 date on the drawing projected on the screen and said "I can almost guarantee you that 50 years ago this hour probably I or some of my brothers on the soil mechanics team were in the tunnel making these measurements." He described how they measured the squeeze of the clay into the tunnel during excavation, and related it to the surface settlement. He noted that, although the liner plate method had been used to construct sewer tunnels in Chicago, and it was recognized that surface subsidence and damage occurred due to tunneling; nobody associated construction procedures with specific amounts of settlement. There had been no real understanding of the causes of settlement; it was just known that it was inevitable that settlement would occur (Peck, 1989).

From the perspective of the tunneling practice prior to 1939, the investigations on the Chicago Subway can truly be described as pioneering work in ground control. Looking forward from 1939 to the present, the observations made by Peck take on added significance, because they set a standard for integrated field investigations relating tunneling procedures to ground loss and surface settlement. The work had an even broader significance for geotechnical engineering. As Peck stated "The Chicago Subway project in the annals of geotechnical engineering assumed an importance far beyond its benefits at the time, largely because it demonstrated the enormous practical benefits that occur from even crude observations, crude at least in comparison to today's sophisticated instrumentation. Even today, it exemplifies the benefits that may be derived from simple but intelligently interpreted observations" (Peck, 1999).

Several investigations of ground movements around soft ground tunnels that have built on the standard set in 1939 are described at the end of the paper. The projects used more sophisticated instrumentation, but, most importantly, the ground movements were intelligently interpreted and correlated with detailed observation of construction conditions. Observations have now gone from measuring, timing, and recording construction events in notebooks to assembling and comparing digital records of key machine functions and correlating them with continuous records of ground movements and piezometric levels, which show how a pressurized envelope is maintained around pressurized face shields so that ground movements can be controlled to negligible values.

In addition to Peck's lectures and published papers by Peck, Terzaghi, and Knapp, I have drawn from a volume containing carbon copies and blue prints of the squeeze test reports prepared by Peck and his assistants (Soil Mechanics Laboratory, 1939-1941. The reports provide detailed descriptions of the construction conditions affecting ground movements. Portions of drawings from the volume are presented as figures in this paper.

What stands out in reviewing the squeeze reports is the level of relevant detail in the recorded observations. Over the almost 3-year construction period on the Chicago Subway, Peck applied the observational method in solving subway construction problems. The content and organization of the squeeze reports and drawings, and the way he worked on the braced excavations (Peck, 1942) and other aspects of the Chicago subway project provided a first view of the engineering approach that has been so apparent to those who later studied and worked with him --- integration of theory and practice; use of precedents; field observations. He later formalized the observational method, but, more importantly, he was always observing --- the ground, construction conditions, ground behavior and response of structures. He has stated that "the most valuable instrument is an observant eye coupled to an inquiring mind."

THE CHICAGO SUBWAY INVESTIGATIONS BEGIN

Ralph Peck in his paper "Karl Terzaghi and the Chicago Subway" (1975), not only describes Terzaghi's role but his own participation, early in his engineering career, in these pioneering investigations. Additional, fascinating insights can be obtained by referring to the volume edited by John Dunnicliff and Nancy Peck Young (2006) in which Peck describes how he and Marjorie Peck arrived in Chicago and the work began.

In December 1938, as construction was beginning on the Chicago Subway, Karl Terzaghi gave a lecture in Chicago entitled "The Dangers of Constructing Subways in Soft Clay Beneath Large Cities." His previous experience with the soft clays around the Great Lakes was on the excavation of piers in plastic clay for the foundations of Hudson's Store in Detroit. However, his descriptions of the consequences of tunneling were so graphic (Peck noted that he figuratively scared the audience to death) that he found both the State Street Property Owners Association and the Department of Subways and Traction of the City of Chicago seeking his services. He chose the City, and had three requirements: (1) City to establish a soil mechanics laboratory, (2) Laboratory to be supervised by an individual chosen by him and working under his supervision, (3) Fee of $100 per day. Terzaghi's fee was greater than permitted by City rules so Ralph Burke had to go before the city council to gain approval, which resulted in it being picked up by the Chicago newspapers, bringing him and soil mechanics to the community's attention (Peck, 1975).

At the time, Ralph Peck was at Harvard University, studying under Arthur Casagrande and assisting in the soil mechanics laboratory, after completing his PhD in structural engineering at Rensselaer University and working for part of a year as a structural detailer for American Bridge Company. Terzaghi, on Casagrande's advice, chose Peck to supervise the lab.

Although the Chicago Subway construction was underway when Peck arrived on January 17, 1939, the boring program that included the sampling and soil testing required by Terzaghi, had only recently begun, so this occupied the immediate efforts of the Soil Mechanics Laboratory. Peck supervised a team of young engineers selected from City applicants, preferably those who had master's degrees or had taken a course in soil mechanics. Two-in.-dia. seamless Shelby tubes were obtained from the borings and, later, block samples and water content samples were collected from the tunnels.. Testing was focused on unconfined compression tests and water contents to evaluate stiffness and yield strength of the clay and the details of its vertical and lateral variability.

CHICAGO SUBWAY ALIGNMENT

Most of the Chicago Subway alignment was at a depth to tunnel crown of 25 feet. One of the reasons for such a shallow tunnel depth compared to current subway projects is understood when you realize that access to the subway is by walking down stairs, rather than riding escalators. Another positive effect of the shallow depth was that the heave and settlement troughs due to tunneling were largely contained within the street and sidewalk right of way and had less impact on buildings. Additionally, the work rules for compressed air pressures in the tunnel made it more expensive to tunnel at more than 15 psi, and the air pressures less than 15 psi were not able to fully balance the higher stresses at depth.

There were difficulties and challenges with the shallower tunnel depth. The medium to very soft Chicago Clay (CL to CH), extends from a depth of approximately 20 to 60 feet over much of downtown Chicago. The clay was deposited as Deerfield and Blodgett Tills beneath glacial Lake Chicago in the later stages of the Wisconsinan Glaciation as the ice receded into the Lake Michigan basin. In downtown Chicago (South of the Chicago River, largely within the Loop) the shallow depth put the full tunnel face in the soft clay whereas north of the Chicago River the lower portion of the tunnel was in older, overconsolidated stiff to hard clay tills.

One of Terzaghi's early questions was which tunnels could be constructed by means of the light liner-plate method and where it would be necessary to use the more expensive shield method ($270/ft of tube versus $580/ft of tube, respectively).

Eight-ft-wide freight tunnels had been constructed at the turn of the century in downtown Chicago with vertical sidewalls on the soft clay bottom using compressed air and daily casting of the concrete lining up to the face. Sewer tunnels had been constructed in Chicago with the liner plate method for the previous twenty years. However, it was concluded that the larger subway tunnels could not be constructed by the liner plate method in downtown Chicago. Terzaghi's analysis showed that the bearing capacity of the soft clay beneath the side wall foot blocks was too low to safely support the post loads from the larger subway tunnels (Terzaghi, 1942a).

Thus, in downtown Chicago, on Contract S-3 on State Street and on Contract D-1 on the Dearborn Street Line, tunneling was accomplished with the shield method. North of the Chicago River, on contracts D-3 and D-5 on the Dearborn Street Line, and S4b, S-5, S-6, and S-7 on the State Street Line, the liner plate method was used, because the stiff to hard clays in the invert provided bearing for the vertical posts. In both projects, compressed air was used with air pressures kept to less than 15 psi. In Fig 1, running tunnels are shown in red, tunneled stations in blue, and braced cuts in green. River crossings were dredged for immersed tubes.

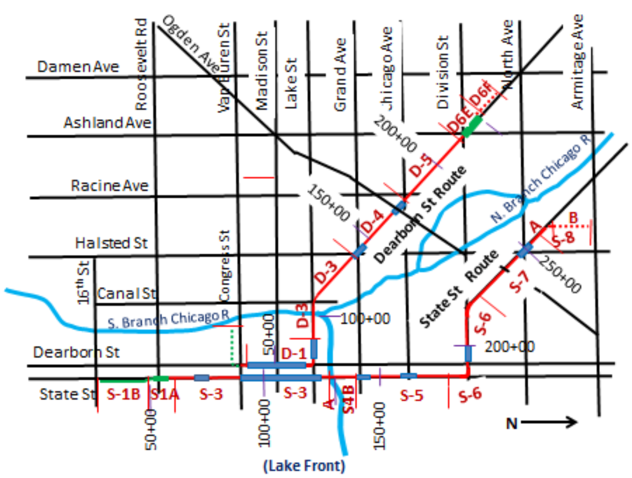


Fig.1: Chicago Subway construction contracts, 1939-1941 (After Terzaghi, 1942a)

SHIELD TUNNELS

In downtown Chicago, the shallow tunnel depth not only placed the shield tunnels within the soft clay but also directly in the path of the 8-ft-wide freight tunnels located down the center of every major street. The tunnels were demolished ahead of the advancing shields, removing the concrete and filling the tunnels with sand, which typically resulted in settlement of 0.5 to 2 inches.

Doors on the face of the shield occupied up to 20% of the area of the face (Fig.2). Through these doors the soft clay squeezed as the shield was shoved forward. As the shield was advanced the effort was to hold the heave of the street surface to less than four inches. Heave of sidewalk vaults was reduced by filling them with 4 feet of sandbags. Harder clays or other obstructions, such as occasional temporary timber support in the abandoned freight tunnel, passing through the shield doors could restrict flow and cause additional heave, which was controlled largely by mining out ahead of the doors to relieve pressures. The 3-in. gap between the tail of the shield and lining was filled with pea gravel. The heave was followed by an even larger settlement due to consolidation of the clay with time following passage of the shield. Figure 3 shows (A) heave of 0.16 feet as the first shield passes followed by (B) rapid settlement of 0.12 feet over a period of 11 days (some likely due to ground loss at the tail) then (C) 0.3 feet of heave as the second shield passes, followed, over a period of 6 months, by (D) a settlement that dropped the street surface 0.5 feet below its original level (Terzaghi, 1942b).

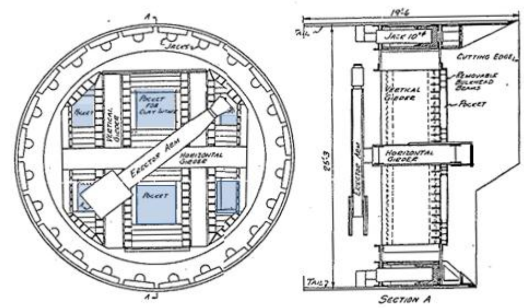
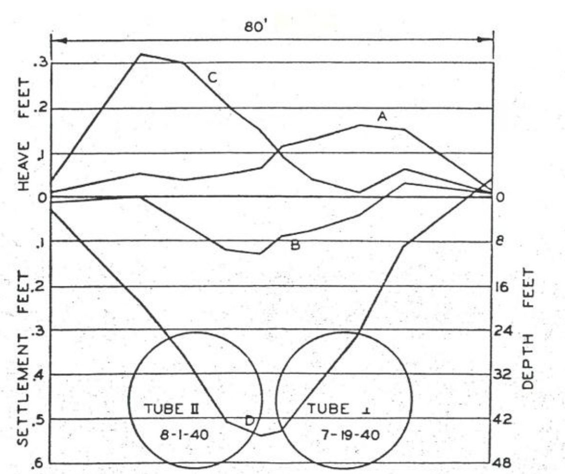


Fig. 2: Shield tunnel on Contracts S 3 and D-1 (after Terzaghi, 1942b)



A. Day 1: (7-19-40): Heave as 1st shield passes
B. ~Day 11: Position of street surface immediately prior to 2nd shield
C. Day 12: (8-1-40): Position of street surface at time of maximum heave due to 2nd shield passage
D. Day 195: (1-30-41) Position of street surface prior to air removal

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Fig. 3: Chicago Subway shield tunnel: heave and settlement (after Terzaghi, 1942b)

Terzaghi (1942b) attributed the consolidation to remolding of the clay in a thin zone around the perimeter of the shield.
More recent experience in Chicago clay, monitoring piezometers and extensometers around advancing shields shows that consolidation will occurs as a result of stress increases due to the shoving, which can be first exhibited as an excess pore pressure, beginning as much as 4 diameters ahead of the shield in a zone of influence of several diameters around the tunnel, with consolidation occurring as the excess pore pressure dissipates. Additionally, if the lining is permeable, additional consolidation occurs due to drainage into the tunnel as pore pressures drop below ambient levels and effective stresses increase (Kawamura and Cording, 1999).

LINER PLATE TUNNELS

Liner plate tunnels were constructed north of downtown Chicago (North of the Chicago River and the Loop), In this region, the depth of the soft clay thinned so that the lower portion of the tunnel face transitioned from the soft clay into older stiff to hard clay tills. This allowed the use of the less expensive basket-shaped liner-plate tunnels in which the tunnel arch was supported on posts along the sidewalls standing on wooden foot blocks in the stiffer clay bottom. The tunnels were sequentially excavated by hand mining, first advancing the top face and installing the steel rib arch on 2-ft 2-in. centers with liner plates set between the flanges.

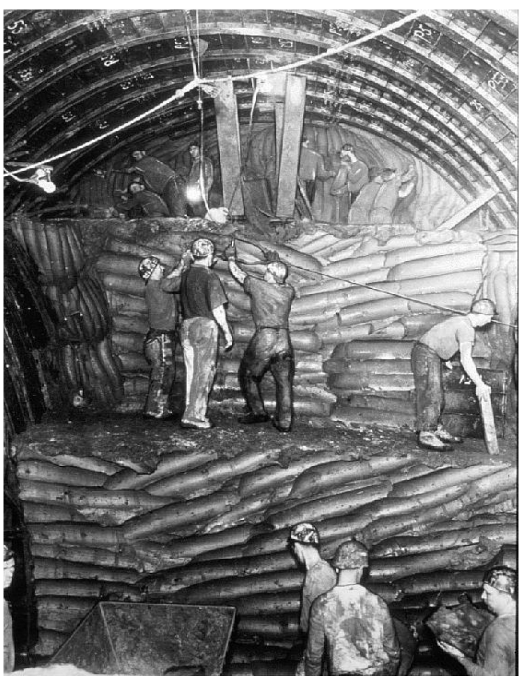


Fig. 4: Photo of sequential excavation (liner plate tunnel)

Figure 4 shows the labor intensive operation (there are 15 miners in the picture). Miners cut the clay into sausage-like pieces, using a clay knife consisting of a loop of steel with a mechanical assist provided by a cable extending to a drum on an air tugger. For each of the miners, there were typically two loaders to carry the clay and dump it in muck cars. In the arch, the liner plate was bolted to the previous ring, which provided immediate cantilever support, and the new arch rib was temporarily supported on the floor of the top face by foot blocks and radial timber braces. The radial braces were setting on the soft clay surface and were close the vertical intermediate face, and therefore had the potential for allowing settlement of the tunnel crown.

The timber braces and foot blocks in the top face were removed as the intermediate face was advanced and load from the arch rib was transferred to the ribs on the side walls. These processes of support, excavation, and re-support resulted in further settlement. The invert section and the bottom lateral braces against the invert section were left in place until just before the concrete invert was placed (Fig. 5).

Throughout, air pressure was typically maintained at 12 to 14 psi, which provided some support of the tunnel face and arch and reduced the loads on the footings beneath the sidewall posts. The air pressure also limited movement of the clay into the tunnel. As noted in the squeeze reports, often the gap between the clay and the installed lining was not filled promptly so that the clay was not in contact with the lining and the air pressure was the sole internal support until the clay surface came in contact with the lining. In some cases, where harder clays were present near the bottom, the liner plate was not extended to the bottom of the side wall.

A typical day's advance would be 20 to 30 feet. Pouring of a concrete invert and concrete arch could follow as closely as the following shift or day; however, on State Street, near Chicago Ave, the liner plate tunnel heading on Contract S-5 was 60 to 150 feet ahead of the arch concreting operation in all four headings, which contributed to the large settlements that developed over a distance of Xxxx when blowouts into utilities in the street caused a loss of air pressure to 9-10 psi.

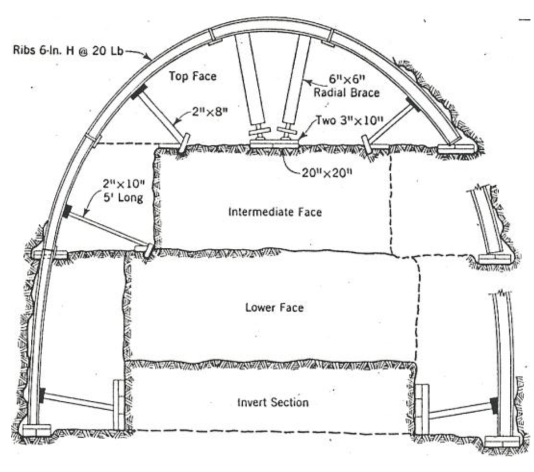


Fig. 5: Sequential heading and bench excavation , liner plate tunnel on Contract S 5 (Terzaghi, 1942a)

SQUEEZE TESTS: RELATING CONSTRUCTION TO GROUND LOSS AND SETTLEMENT

At the time of his December, 1938 lecture, Terzaghi visited an access tunnel being driven from a construction shaft to the line of the subway tunnel. He suggested to the resident engineer that the cause of the surface settlements be investigated by driving spearheads attached to wires ahead of the tunnel face to determine if the clay was displacing into the tunnel excavation during mining. He was provided with the results on his first consulting visit, in late January, 1939, which showed as much as 0.2 feet of displacement toward the tunnel face as the tunnel heading was advanced (Peck, 1975).

In Terzaghi's early visits, he discussed with Raymond Knapp and Ralph Peck guidelines for "squeeze tests" to measure ground movements into the tunnel as the excavation stages were advanced. Peck proceeded to set up and conduct the squeeze tests. The first four squeeze tests, in the period April through August, 1939, were carried out on Contract S-5, the first tunnel section mined on State Street north of the River.

Observations were carried out continuously over a period of 24 to 72 hours during the multiple stages of excavation and support as the tunnel was advanced. In a typical squeeze test, spearheads were driven into the clay approximately 6 to 10 feet ahead of the excavation face to measure axial displacements into the tunnel as the heading was advanced to the location of the spearhead. Rods were embedded 2 feet into the clay in the crown of the tunnel to measure crown settlement and into the clay at several locations in both walls of the tunnel to measure the horizontal displacement across the width of the tunnel using a tape measure.

At the same time, settlements were surveyed across the width of the street every 20 feet along the alignment.. Samples were taken in the tunnel to determine the profile of water content and strength. Throughout, the details of the excavation and support procedures and the location and timing of the multiple excavation stages were recorded. Peck summarized the results on a single blueprint showing a profile and cross-section of the tunnel excavation sequences and displacements of the clay into the tunnel with time, a profile of the clay strength and water content and surface settlement profiles (Soil Mechanics Laboratory, 1939-1941). Figure 6 shows a portion of the information recorded on the drawing for the fourth (August 14-15, 1939) squeeze test. (Crown settlements are highlighted in red, and wall closure in purple, with their locations circled shown on the cross section and longitudinal profile of excavation progress.)

On Terzaghi's next visit, Peck presented him with the blueprint for the April, 1939 squeeze test accompanied by a narrative of the construction events and test procedures. Peck has commented in several lectures and papers that Terzaghi "concealed his pleasure at the results with some difficulty," and he noted the growing respect and confidence that Terzaghi, Peck, and Knapp had in their collaborative effort (Peck, 1975).

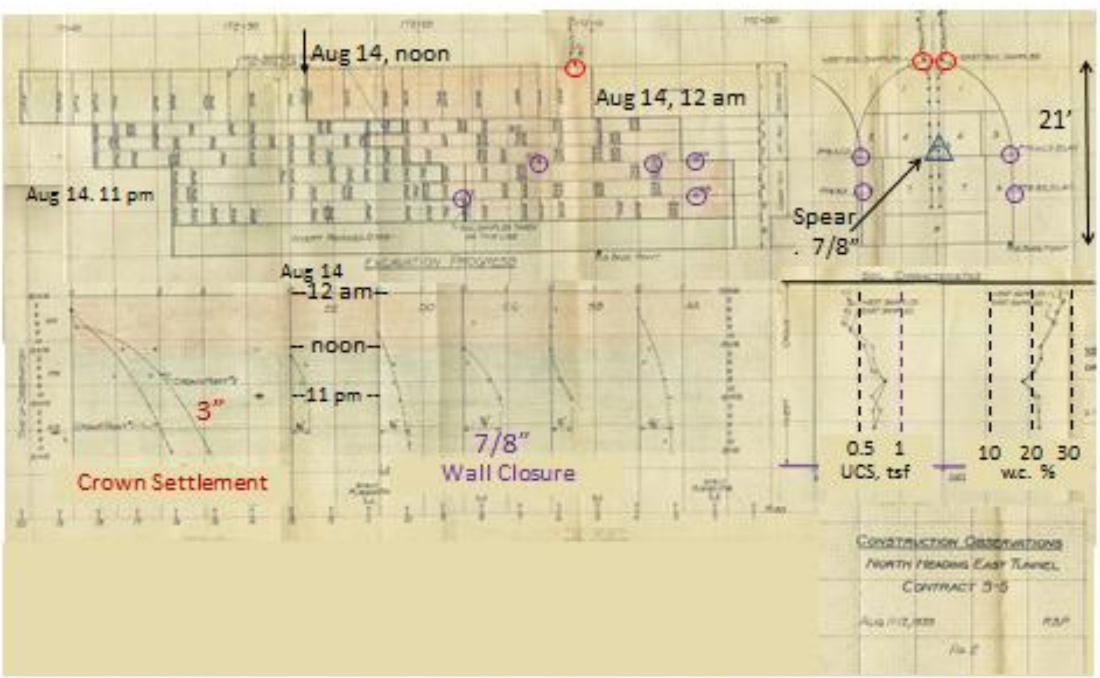


Fig. 6, Contract S-5, August 14-15, 1939 North Heading, NB Tunnel (prepared by RBP)
Excavation Sequence, Squeeze Measurements, and Soil Strength

YOU SHOULD ASSUME THE DATA IS RIGHT UNTILYOU HAVE PROVEN THAT IT IS WRONG

Geotechnical engineers are well aware of how Peck used his lectures not only to communicate lessons learned but to point the way to the future of the profession. His lecture upon receiving the Distinguished Alumnus Award from the University of Illinois College of Engineering was entirely dedicated to describing the lessons he had learned from his mistakes. Few geotechnical engineers would voluntarily give such a lecture.

In his lectures on the Chicago Subway squeeze tests, including the Wilson Lecture in 1989, Peck described the lesson he learned from Terzaghi regarding the interpretation of the squeeze test data. For all four squeeze test sections conducted on Contract S-5 (from April through August, 1939), Peck had drawn smooth curves through the data for crown settlement and sidewall closure. Fig. 6 shows the data for the August 14-15, 1939 squeeze test.

In September, 1939, Terzaghi prepared a long report in which he evaluated the squeeze test data. Instead of smooth curves, he re-plotted the curves to go through the data points (illustrated by the red lines added to the crown settlement in Figure 7). (The distances of the faces ahead of the crown settlement point are also shown in red.) Peck had argued that difficulty in making the measurements caused variations on the order of $\pm$ 1/4 of an inch, which did not represent real behavior. Terzaghi showed that there was a consistent reversal of displacements. As excavation was carried downward and the walls moved in, the tunnel would oval and crown would temporarily displace upward. Similarly, with further advance of the headings, downward movement of the crown would cause a temporary outward wall movement, often occurring at the same time at different locations in the tunnel section, which was considered indicative of a sudden yielding of the clay.

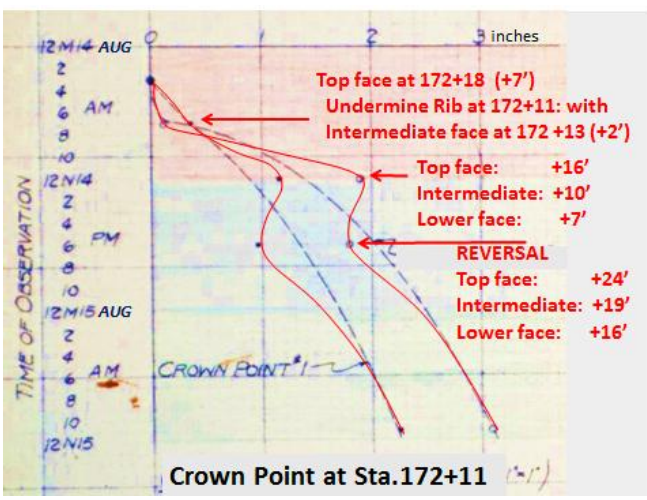


Fig. 7: Contract S-5, August 14-15, 1939 replotting of crown settlement curves to go through all data points.

Peck concluded his lectures with the advice he received from Terzaghi: *"You should assume the data is right until you have proven that it is wrong."*

CONTRACT S-5: THE CAUSES OF LARGE SURFACE SETTLEMENTS ARE IDENTIFIED

Figures 6, 7, and 8 were all obtained from the large drawing Peck prepared for the August 14-15, 1939 squeeze test at Station 172. Figure 8 shows the surface settlements.

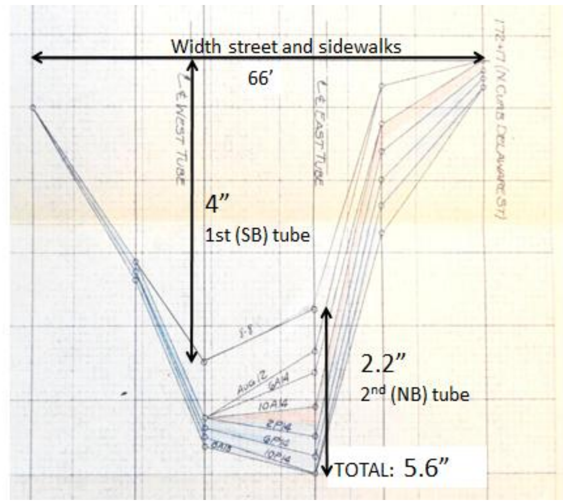


Fig. 8: Surface settlements after excavating 1^{st} & 2^{nd} tubes Contract S-5, August 14-15, 1939 (2^{nd} tube squeeze test).

This squeeze test was conducted in the north heading of the Northbound (NB) tube, which was the second of the twin tubes mined at this location. The two tubes were built immediately adjacent to each other, with a common central wall. The first (SB) tube had produced a settlement of 5 in. The additional surface settlement of the NB tube on August 14-15 was 2.2 in. (Fig. 8).

The second tube of the twin tube sections on Contract S-5 (where tubes were constructed immediately adjacent to each other) produced lesser settlements than the first tube because there were no lateral displacements at the wall of the second tube that was adjacent to the first tube and the loads over the second tube arched onto the concrete lining of the first tube so that there was no soil to be compressed at that side of the tunnel. (On Contract D-3 and D-5, where tubes were separated, by approximately 8 feet, the settlement of the 2^{nd} tube was larger than the 1^{st} due to compression of the pillar).

The squeeze tests in the NB tunnel corresponding to the 2.2-in. surface settlement are shown in Figures 6 and 7. The crown settlement for the second tube was 3 inches which began as the crown rib was excavated, when the timber braces supporting the steel arch in the tunnel crown would have been removed. The maximum side wall closure was 7/8 in.

Throughout, Peck used the squeeze test measurements to compute the volume lost (V_L) into the tunnel and compare it to the volume of the surface settlement trough (V_S) and found that the values were equivalent, an indication that the ground movements into the tunnel were the cause of surface settlement. (For the August 14-15, 1939 squeeze test, is estimated at 13.3 cu ft/ft for the 1st, SB tube. For the 2nd, NB tube, V_S was 6.8 cu ft/ft, which is close to V_L of 5.2 cu ft/ft measured with the squeeze tests in the second tube. Additional squeeze that may occur prior to establishing the points in the tunnel is not included in calculation of V_L.)

Large displacements into the tunnel and large surface settlements were also measured in the other three squeeze tests conducted on Contract S-5 between April and August, 1939. The squeeze test reports showed that much of the settlement was occurring as the arch ribs were undermined and re-supported. Additionally, a large gap and incomplete filling between the erected liner plate and clay was allowing inward displacement of the clay,

CONTRACT S-6: SETTLEMENTS REDUCED BY ADDITION OF A MONKEY DRIFT & WALL BEAM

Based on the observations on Contract S-5, the excavation sequence on Contract S-6 and all other subsequent tunnel contracts was changed to include a wall beam placed in two monkey drifts (Fig, 9 and 10).

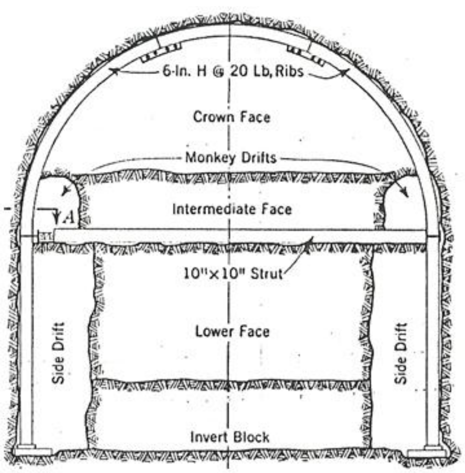


Fig. 9: 21- x 20-ft Liner plate tunnel with monkey drift

The monkey drifts were approximately 3.5 ft wide by 5 ft high and located at the base of the arch. They were mined ahead of the crown face (usually referred to as a top heading) so that a continuous wall beam could be installed before the crown face was excavated (Fig. 9 and 10). Then, as the crown face was excavated, the steel rib arch was set directly on the wall beam. Thus, as the side drifts and intermediate and lower faces were excavated beneath the arch, the wall beam would span the excavation increment and support the arch so that the posts could be placed below the wall beam. Once the intermediate face had been excavated, a 10x10-in. timber strut was extended across the excavation to prevent inward movement of the side walls.

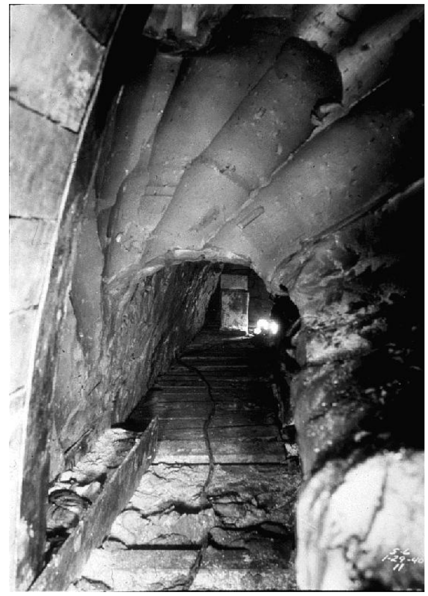


Fig. 10: Monkey drift & wall plate.

Figure 11, is an 8-1/2 by 11 blue print prepared by Chester P. Siess for the squeeze tests on Contract S-6, at Station 201+40 during passage of the 2^{nd} (NB) tube, South heading, March 27-29, 1940. (Siess was a member of Peck's team and a specialist in the use of the Whittemore gauge, a mechanical gauge used to determine stresses from measurement of displacements over a gauge length on steel sections. He went on to earn his PhD and to specialize in reinforced concrete structures, becoming Professor and Head of the University of Illinois Department of Civil and Environmental Engineering.)

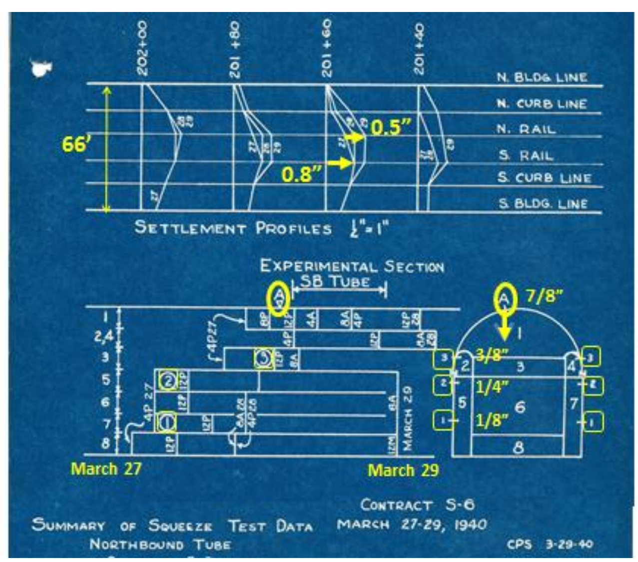
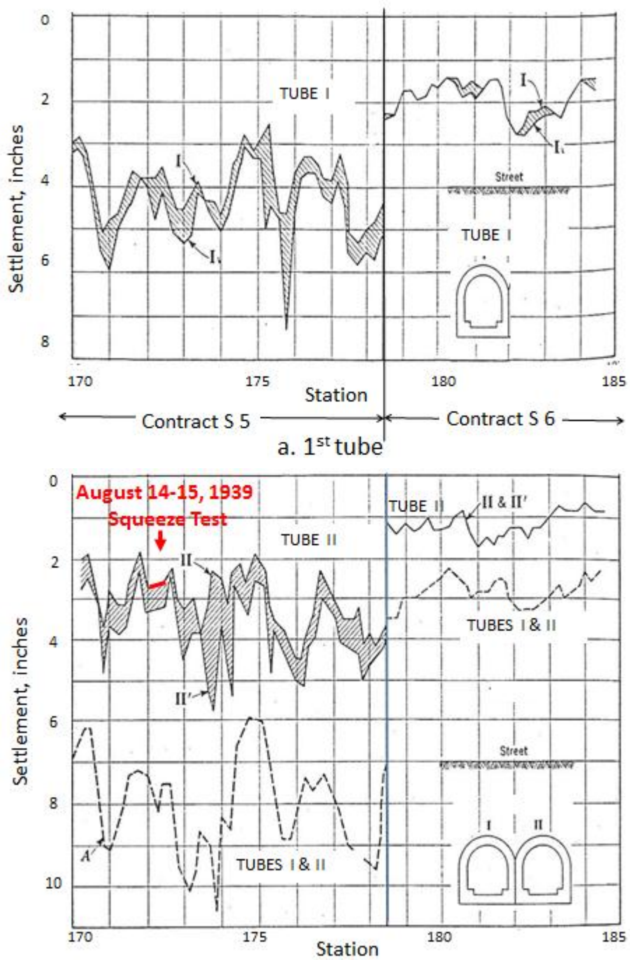


Fig. 11: Squeeze test for liner plate tunnel with monkey drifts Contract S-6 Sta. 202+00 to 202+40, 2^{nd} (NB) Tube, S. Head.

Cross sections at 20-foot intervals in the street showed only small settlements: 0.8-in. settlement for the 1st, SB tube and an additional settlement of 0.5 in. as the 2nd, NB tube passed during the squeeze test. The squeeze measurements in the NB tubel also showed small displacements. Crown settlement was 7/8 in. and lateral closure between the side walls ranged from 3/8 in. to 1/8 in. from top to the bottom of the wall.

(The surface settlement volume (V_S for the 1st, SB tube is estimated as 2.7 cu ft/ft. Vs for the 2nd, NB tube is 1.3 cu ft/ft, approximately equal to V_L estimated from the squeeze tests. The 2nd tube was excavated immediately adjacent to the first tube, resulting in smaller settlement for the 2nd tube.



b. 2nd tube and total for 1st and 2nd tubes
Fig 12: Maximum surface settlements, Contracts S-5 and S- 6 (after Terzaghi, 1942a)

Fig. 12 shows the dramatic reduction in the maximum surface settlement on a 600-ft section of the S-6 contract, excavated with the monkey drift and wall beam (Terzaghi, 1942a).
Settlements for the 1st tubes ranged from 1.5 to 2.5 in., whereas the adjacent 850-ft section of the S-5 contract excavated without the monkey drift had surface settlements in the range of 3 to 6 in. (Fig. 12a).

On both of these contract sections, the tunnels were in a twin tube configuration where the second tunnel was excavated immediately adjacent to the first, so that, on both contracts, the 2nd tube had smaller settlements. For the 2nd tube settlements on Contract S-6, which had the monkey drift and wall beam, were in the range of 1 to 1.5 in., which were less than the 2 to 5 in. settlements on Contract S-5 where there was no monkey drift (Fig. 12b).

CONTRACTS D-5 AND D-3: EFFECT OF TUNNEL DEPTH ON GROUND MOVEMENTS

As the liner plate tunnels were extended to the north on Contract Sections S-6, S-7, D-3, and D-5, the Soil Mechanics Laboratory continued to conduct squeeze tests, confirming the beneficial effects of the monkey drift in reducing settlements, but the Laboratory was also being relied upon to investigate and help resolve problems where large settlements were occurring despite the use of the monkey drift.

Ralph Peck, at the request of Ralph Burke, Chief Subway Engineer, investigated and reported on the factors producing settlements of excessive magnitude over the south heading of the NB (1st) tube of Contract D3. The large displacements started at Sta. 126, where the tunnel crown was 58 feet deep, and increased in magnitude to Sta. 123 as the tunnel dropped in elevation to pass beneath the Chicago River to the south. Squeeze tests and observations were made at Sta. 126 on Nov 29-Dec 1, 1939 and supplemental observations were made at Sta. 123 on Dec 18-19, 1939. At Sta. 126, Peck observed ground movements and construction conditions contributing to the large ground movements: “Energetic motion was observed in all portions of the heading” in spite of the fact that the clay at tunnel depth had unconfined compressive strength (UCS) varying from 1.3 to 3.5 tsf. Squeeze tests showed inward movement of the tunnel face of 0.4 in., tunnel crown settlement of 1.2 in., and lateral wall convergence of 1 in. Maximum surface settlement was 2.3 in. in 24 hours, increasing to 3 in. in two weeks. Peck concluded that 48 to 66 % of the displacements occurred ahead of the face. (Soil Mechanics Laboratory, Dec 19, 1939 report).

Peck’s report describes the causes of the large settlement: As was noted in earlier squeeze test reports, an excessive gap of 2 to 7 in. was being mined outside the lining in the crown and there was a delay in filling it. (On a later contract, a simple wooden template was extended ahead of the last rib to locate the required excavation perimeter and limit over-excavation during mining.) Filling of the gap could be accomplished by placement of pea gravel, cement grout, or wood wedges. At Sta. 126, pea gravel was being blown by air to fill the gap between clay and the liner plates in the crown but was being delayed as much as 18 feet behind the advancing crown face. This meant that the clay squeeze was being initially balanced by compressed air pressure alone and not supported by the tunnel lining until the gap was closed.

Additionally Peck noted that the intermediate face was being held back as much as 9 ribs (approximately 19 feet), which delayed the installation of the strut between the wall plates (Fig. 9), so there was no restraint to prevent inward movement of the wall beams in the monkey drifts, and liner plate was not being placed on the wall behind the wall beams to spread the lateral load and reduce squeezing of the clay.

Ground losses in the D-3 NB tunnel at Sta. 126 to 122 were much larger than those in the D-3 SB tunnel at Sta. 122 (Table 1), even though the same tunneling methods were being used, and both tunnels were being mined by the same crews, who alternated between headings with the concrete crews. Peck concluded that the difference was due to the increased depth and correspondingly higher stresses around the NB tunnel. Procedures acceptable under ordinary conditions (at the 25-foot depth) must be drastically modified when the conditions change. He noted that settlements of 1.5 to 2 in. were inevitable because movements ahead of the face could not be reduced without increased air pressure, but that settlements due to displacements in the crown and sidewalls could be reduced by (a) accurate, close excavation to reduce gap between clay and liner plate, (b) immediate pea gravel grouting and vibratory compaction between clay and liner plate, (c) reducing length of intermediate face to a few feet so that horizontal strut could be placed immediately, (d) placing liner plate behind the wall beams to reduce the pressure of the clay against the wall beam.

Table 1 has been compiled from the squeeze reports and compares ground movements for the deep D-3 and S-4b tunnels driven south toward the river with the S-5 and S-6 tunnels and the shallower D-5 tunnels to the north.

Table 1: Influence of Tunnel Depth, D, on Surface Settlement, Ss

Station	Tube	D	Pa	UCS	OSR	Settlement		
Normal 25' tube depth			**psi**	**tsf**		**Crn**	**Ss**	**Vs%**
S5: 172	**1st**	**25'**	**12**	**0.4**	**4.6**	**3"**	**3-6"**	**4.9%**
S6: 180	**1st**	**25'**	**12**	**0.5**	**2.8**		**2"**	**1.6%**
Shallow tubes, near N end								
D5:209	**1st NB**	**16'**	**9.5**	**0.45**	**1.4**	**0"**	**0.3"**	**0.2%**
D5:207	**2nd SB**	**19'**	**9**	**0.5**	**2.2**	**1"**	**1.1"**	**0.8%**
D5:207	**1st NB**	**19'**	**9**	**0.5**	**2.2**		**0.9"**	**0.6%**
Deep tubes S toward River								
D3: 126	**1st NB**	**58'**	**14**	**1.2**	**4.3**	**1.3"**	**2-3"**	**3.1%**
D3: 122	**1st NB**	**61'**	**12**	**1**	**5.9**		**5"**	**7.2%**
D3: 122	**2nd SB**	**37'**	**12**	**0.5**	**5.7**	**1.7"**	**1.3"**	**1.3%**
D3: 118	**1st NB**	**65'**	**12**	**1**	**6.4**	**1.2"**	**1.2"**	**1.8%**
S4b:134	**1st NB**	**44'**	**12**	**0.5**	**7.5**		**6"**	**6.9%**
S4b:134	**2nd SB**	**44'**	**12**	**0.5**	**7.5**	**1.8"**	**2"**	**2.3%**

Key: Depth to crown: D; Air pressure: Pa; Unconfined compressive strength: UCS, (upper face); Overstress ratio in upper face: OSR = $(\gamma h - p_a)/0.5UCS$*:* γh*: overburden stress. OSR in excess of 6 indicates bearing failure & squeezing (Peck, 1969).Crown settlement: Crn; Max. surface settlement: Ss; Volume settlement trough: Vs% (% of tunnel volume)*

The squeeze tests in Contract S-5 had large ground losses (Vs% = 5%) which were reduced to less than 2% on Contract S-6 when the monkey drift was used to minimize settlement of the tunnel crown. The effects of tunnel depth and high overstress ratio (OSR) can also be seen in Table 1. Vs% was less than 1% for Contract D-5 near the north end of the Dearborn Street tunnels, where tunnel depth was only 16 to 19 feet, and the OSR was low (in the range of 1.4 to 2.2).

For the deeper tunnels approaching the river on Contracts S4b and D3, the air pressures were not increased but maintained at less than the 15 psi limit, thus the increasing overburden forces were not proportionally balanced by an increase in air pressure. As a result, the overstress ratio, OSR, increased above 5 or 6, the clay squeezed, and the surface settlement volume, Vs, increased. The deeper tunnels showed larger surface settlements, Ss, than the shallower tunnels, despite the fact that the increased depth spread the surface settlement over a larger trough width. As Peck recommended, in the absence of increased air pressures, the deeper tunnels required more stringent measures to install the liner plates and ribs early and tight to the clay in order to reduce settlements. Apparently, this recommendation was followed in the NB D-3 tunnel at Sta. 118, where Vs% was 1.8% despite the greater depth.

WASHINGTON METRO: 1970-1973

It was in the classroom that we were introduced to soft ground tunneling, taught by Professor Peck from the perspective of his pioneering investigations on the Chicago Subway. It wasn't until I was a faculty member, directing the University of Illinois contract for geotechnical monitoring on Washington Metro Phase I soft ground tunnels and stations in rock caverns and braced excavations in soil that I had my first opportunity to be in the field with Ralph Peck. He was a member of the Washington Metro Board of Consultants and would make it a point, early in the morning prior to board meetings, to walk with us through the construction sites. I recall a bright winter morning in 1972; Bill Hansmire and I picked up Ralph Peck at his hotel and we went down into the heading of the shield tunnel on Contract A-2. We then came out of the shaft, crossed Pennsylvania Avenue in front of the White House, and walked to our array of extensometers and inclinometers in the middle of Lafayette Square where we discussed our monitoring results and observations, the topic of Bill's thesis. At the start of our soft ground tunneling experience, we were receiving the benefit of 30 years of tunnel observations. What a valuable experience those visits were for us, but I expect that Ralph Peck valued them as well. No matter how many board rooms he sat in over the years, his priority was to go to the site, observe and listen.

The Washington Metro investigation built on the Chicago Subway experience of observing and recording construction events and correlating the volume of ground loss with the volume of surface settlement. In Chicago, the volume of ground loss was measured within the tunnel. On the

Washington Metro, the ground loss and three-dimensional distribution of ground movements was measured with borehole extensometers and inclinometers surrounding the advancing tunnel shield. Just in time for use on our test section, Stan Wilson, inventor of the slope indicator and partner in Shannon and Wilson, Inc. and Slope Indicator Co., , informed us that the Digitilt inclinometer, using a servo-accelerometer to measure tilt, had been developed. It was capable of measuring slopes with a precision of 1/10,000, an order of magnitude better than could be measured with then-existing slope indicators, and precise enough to measure lateral displacements around braced excavations and tunnels. The inclinometer was immediately incorporated into our instrumentation plans for the tunnels and braced excavations.

The digger shield had an open face which, in some cases, could result in inflows and ground loss, but also provided the opportunity to observe the ground and its behavior. The soils were Terrace deposits of stiff clay and dense sand. The tunnel support consisted of 6 in. circular steel ribs spaced 4 ft on center with timber lagging between the ribs, which were installed inside the tail section of the shield and then expanded against the ground as the shield advanced forward.

Digital readouts of machine functions did not exist at the time, so Bill Hansmire, was in the tunnel recording items the shield plumb bob readings and the position of the laser line on the two clear plastic targets on the front and back of the shield to determine the position of the shield and its angle of attack. The data showed that the shield was inclined at an angle in excess of tunnel grade, 12 in. higher at the front than the back end of the shield in order to maintain grade with the extended hood, which gave the shield a tendency to dive. He also kept track of the location and the time that the shield was shoved and called the information up to those reading the inclinometer immediately in front of the tunnel shield to make sure that the inclinometer torpedo was pulled out of the casing before the shield cut through it so that the torpedo did not end up being excavated with the muck.

By measuring the instruments at least once during every 4-foot shove of the shield, the source of the ground loss could be pinpointed (Fig. 13). The large 6-in. surface settlement did not occur due to soil displacing into the open face of the shield as might have been expected, but was occurring over the shield. Almost every shove of the shield was causing large settlement of the extensometer anchor located immediately above the shield. From the front to the back of the shield, the deep settlement totaled 13 in. (Cording and Hansmire, 1975).

The inclinometer in the path of the shield showed a lateral displacement of only 1/4 in. toward the face, confirming that the ground movement into the face was small and was not the source of the large ground losses (Fig. 13).
Based on the observations on the first tunnel drive, the contractor rebuilt the shield hood for the second drive, so that the shield could be driven on grade without plowing. As a result, surface settlements were reduced from 6 to 2 in.

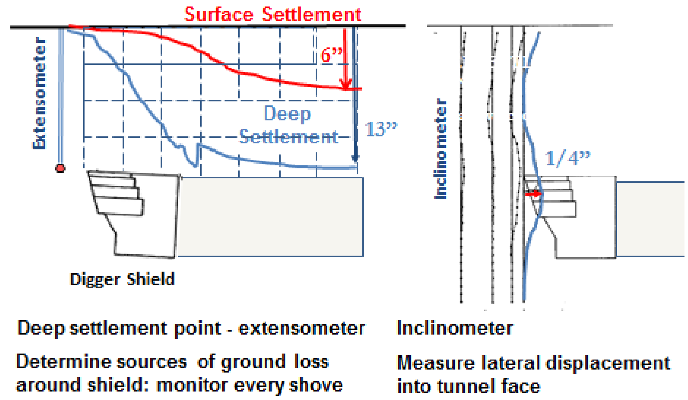


Fig. 13: Washington, D.C. Metro, Contract A2, Lafayette Square Test Section, 1st tunnel

GROUND CONTROL WITH ADVANCES IN SHIELD TUNNELING METHODS

The standard set on the Chicago subway squeeze tests was to continuously monitor and observe both ground behavior and construction conditions in the liner plate tunnels. The Washington Metro test sections set a standard for monitoring ground movements around an advancing shield.

A revolution in ground control has been developing since the advent of pressurized face shields (earth pressure balance or slurry shields) and it continues with improved understanding of the machine functions that must be controlled and monitored to achieve ground control. The understanding is aided by use of observational approaches pioneered on the Chicago subway and used on the Washington Metro.

Observations have gone from timing and recording construction events in notebooks to digitally recording key machine functions in real time and archiving them for future use. Pressurized face shields have a chamber behind the cutterhead in which the conditioned muck is held at pressures that balance groundwater and effective earth pressures, reducing the risk and magnitude of ground loss. The ground in the face cannot be regularly observed and reliance must be placed on the digital record.

The digital information is comprehensive and outstanding and can be overwhelming. However, in the past few years, manufacturers, owner's representatives, and contractors have improved the use and understanding of the key machine functions controlling ground movements. Contractors have engaged their engineers and operators in a team effort to set target levels for the key functions controlling ground behavior, and adjust and respond in real time to the conditions encountered.

The following paragraphs summarize improvements in ground control and reductions in ground loss that have been achieved in the past 70 years. Ground loss, V_L, as it was described by Peck in 1939, is the volume of ground that moves into the tunnel perimeter. The volume of the surface settlement trough, Vs, = V_{L--} ΔV where ΔV is an increase in volume of the soil mass. For dense sands, a significant expansion of the soil above the tunnel can occur. For soft clays, consolidation will cause a reduction in volume. Most of the tunneling industry reports the percentage of ground loss as the volume of the surface settlement trough with respect to the tunnel volume. However, measurement of deep settlements with extensometers allows V_L to be estimated as the shield passes, so that an understanding of the sources of ground loss and the effects of volume change in the soil mass can be assessed. Examples of surface settlement volumes percentages that have been achieved in the past 70 years are summarized below.

1939: Chicago subway: Squeeze tests led to a reduction in surface settlement from approximately 6 in. to 2 in., and Vs% reduced from 5% to 2%.

1972: Washington Metro: Extensometers and inclinometers showed that ground loss of 5% on the first tunnel drive occurred over the shield, and was subsequently reduced to 2% on the 2nd drive.

1994-2000: Evanston sewer tunnels, in deep deposit of soft Chicago Clay, Piezometers as well as extensometers and inclinometers showed the causes of consolidation during tunneling. 12-ft-dia wheeled excavator shield, 4 in. steel ribs, 4 ft on center with timber lagging: Following was observed for the 60' deep tunnel (Srisirirojanakorn, 2005):

1. Immediate ground loss, largely due to 3/ 4" overcut: Surface settlement, Ss = 0.8 to 1.2" (Volume of overcut gap is always lost on non-pressurized shields).
2. Test section 3: Consolidation due to stress change and drainage through the permeable lining:
   Additional time-dependent settlement: ΔSs =1.3"
   V_L +ΔV = 5 cu ft/ft + 8 cu ft/ft; Vs=14 cu ft/ft.
3. Test Section 4: Drainage prevented by placing a membrane around the steel ribs and lagging. Consolidation due to stress change only
   Additional time dependent settlement: ΔSs =1.0"
   V_L +ΔV = 4 cu ft/ft + 4 cu ft/ft = 10 cu ft/ft

2000: In recent years designers on a number of tunnel projects have assumed that ground losses, Vs, of 1% can be achieved with pressurized face tunneling, based on a review of previous experience. For a transit tunnel at depths of approximately two or three diameters, this typically results in surface settlements on the order of one inch. In some of these cases, additional ground control measures, such as compensation grouting, are used to further reduce the settlements beneath structures.

2006: On the 1.8 miles of twin tunnel on the Los Angeles Metro Gold Line Eastside Extension, surface settlements were in the range of 0 to 0.3 in. over the entire alignment, giving a surface volume typically less than 0.25%. Although compensation grouting was installed beneath structures near the start of the tunnel drive, it did not need to be used. As a result of this and other recent EPBM experience, design values for maximum ground loss (Vs%) on several current projects have been reduced to 0.5% or less, and expectations are that smaller ground losses can be regularly achieved.

Extensometers to measure ground loss immediately above the shield are being used on many projects, but often, the frequency of measurements has not been sufficient to locate the sources of the ground loss around the shield and results are not correlated with the key machine functions that limit ground loss. Without understanding what controls ground loss, the designer is reduced to estimating it based on summaries from other projects. The approach does not lead to an understanding of the requirements for controlling ground loss in different ground conditions. Uncertainty regarding the ground control that the contractor can achieve in the tunnel may lead to specification of additional ground control measures such as compensation grouting. Observations on the following two projects provided detailed information on the EPBM functions that limited ground loss to negligible values.

2011-2012: EBP tunnels in Seattle and Toronto: comprehensive test sections were established prior to passing beneath structures; in the first case to verify that settlement over the shield was prevented by filling and pressurizing the large overcut gap with conditioned muck from the tunnel face (Diponio, et al, 2012), and in the second case to determine that the tunnels could be advanced at shallow depth beneath foundations of a structure without damaging settlement and without additional ground protection measures.

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In both cases, machine functions were continuously read that showed not only that face pressures were consistently maintained within target levels both during and after shoving of the shield, but pressures were read and samples taken in the gap around the body of the shield showing that it was immediately filled and pressurized with conditioned muck or bentonite. was injected into the gap. Finally, as is now standard in pressurized face shield tunneling, grout was continuously injected through the tail of the shield to fill and pressurize the gap between the shield and the segmental lining as the shield advanced. Thus a pressurized envelope was being maintained at all times around the entire shield.

Machine monitoring data were correlated with continuous monitoring of ground behavior as the tunnel shield approached and passed the test sections– extensometers and surveys for settlements and piezometers to monitor the advancing pressure wave in the ground water. Ground losses of zero to 0.15%, were consistently achieved, and tunneling beneath the structures was accomplished without significant settlement and with no damage.

CHICAGO SUBWAY INVESTIGATIONS SET THE STANDARD

For the past 70 years, the pioneering work of Karl Terzaghi and Ralph Peck and the Chicago Subway Soil Mechanics Laboratory has set the standard for the investigation and control of ground movements due to tunneling, and for geotechnical investigations, in general. Peck stated it well in his keynote speech at the Geo-Engineering Conference in Urbana, "The Chicago Subway project in the annals of geotechnical engineering assumed an importance far beyond its benefits at the time, largely because it demonstrated the enormous practical benefits that occur from even crude observations, crude at least in comparison to today's sophisticated instrumentation. Even today, it exemplifies the benefits that may be derived from simple but intelligently interpreted observations" (Peck, 1999).

He went on to say: "I have had a 60-year love affair with subway tunnels. The state of the art has changed radically but the rate of change has not perceptibly decreased... most of the changes have not been drive by advances in theory, but by observations based on experience."

Throughout his career, Peck was a practicing engineer and an educator; the two were inseparable. It was apparent that he considered teaching --from theory to practice-- the most important part of his University life. He believed that judgment, or its foundations, could be taught: "*There is actually such a thing as engineering judgment and it is indispensable to the successful practice of engineering*."

Professor Peck communicated those principles in the classroom: when we finished his case history course we had served on his Board of Consultants, participating with him on virtual tours of his projects, observing, and making engineering judgments. They were like detective stories; we observed clues about the ground and its behavior; and I wanted to solve them.

Forty years ago, on the Washington Metro, I and a whole generation of our graduate students had the opportunity to begin our love affair with subways, and subsequent generations of students have followed. Over the years, many of us, former students and engineering colleagues, had the privilege of working with Ralph Peck on subways and many other projects. His presence is missed, his lessons remain. In commemorating Ralph B. Peck's legacy we remind ourselves of -- and introduce others to -- the lessons he learned and taught to the profession.

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