HISTORY OF LOADS AND DISPLACEMENTS FOR A DEEP EXCAVATION IN A MIXED SOIL PROFILE

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A history of the behavior of an 82-ft-deep excavation for the Washington, D.C., subway is presented. Improvements in the methods for limiting and forecasting soil movements should result in reduced construction costs and damage claims. It was found that the largest volume of soil displacement takes place beneath the advancing excavation and accounts for approximately 60 percent of the total lateral displacement. Maximum apparent earth pressure for this excavation can be predicted by a trapezoidal earth pressure envelope of width $0.25\gamma H$.

•DETAILED investigation of an 82-ft-deep excavation for the Washington (D.C.) Metropolitan Area Transit Authority (Metro) subway system was performed by the University of Illinois in coordination with DeLeuw, Cather and Co., the general engineering consultant to Metro. The excavation was opened at the intersection of 7th and G Streets N. W. as part of construction for the Gallery Place Station. The excavation was extended through a soil profile of interbedded sand, gravel, and stiff clay.

This was the first 80-ft-deep excavation for the Metro system; thus, even though no structures were immediately adjacent to the cut, it was considered worthwhile to evaluate the effect of open cutting on soil movement around the excavation. Because soil displacement determines the need for underpinning or restricted excavation techniques to protect adjacent structures, this study would aid in the planning and design of future deep, braced excavations in similar soil profiles for Metro.

An extensive measurement program was implemented to monitor lateral displacements of the excavation wall and the displacements of the soil surrounding the excavation. A special effort was made to evaluate soil displacement in relation to excavation procedure.

Lateral displacements were measured using the more accurate accelerometer-type inclinometers developed in the last 4 years. With these instruments it was possible to observe in detail the lateral displacements at depth resulting from excavation and bracing procedures. The results presented in this paper show that the magnitude and distribution of lateral displacements were controlled primarily by strut spacing, the depth the excavation was carried below a strut level before the next level of struts was installed, and characteristics of berms near the bottom of the excavation.

Observations in similar soil profiles (interbedded granular and stiff cohesive soils) at other sites in Washington, Boston, and San Francisco (2, 3, 8, 13) indicate that the same parameters controlled the magnitude and distribution of movements, even though a variety of bracing schemes was used. The bracing schemes included soldier beams and timber lagging with tiebacks, soldier beams and timber lagging with struts, and slurry walls with struts.

Strut loads were measured at regular intervals throughout construction at the 7th and G Street excavation. Apparent earth pressure diagrams were computed from the strut loads for the full depth of excavation and compared with various design criteria in general use. The design earth pressure envelope computed from the strut loads was generally within the expected range, although significant variations of load in individual struts or strut levels were observed due to details of the construction procedure such as preloading and the depth of excavation below the previously installed braces. Similar variations have been observed in other excavations in sands or mixed soil profiles (1, 3, 5, 6, 7, 9, 10, 11, 13).

SOIL CONDITIONS

The excavation was deepened through the so-called 50-ft terrace deposit of Washington. This deposit is one of four terraces in the capital city that were formed by changes in sea level and stream gradients during the Pleistocene epoch. At the excavation the Pleistocene terrace soils range from elevation +46, at the street surface, to a depth of 78 ft at elevation -32. The soils are composed primarily of sand and gravel; however, a significant stratum of stiff clay exists between elevation +20 and elevation +6. Immediately underlying the terrace deposits are soils of Cretaceous age that extend from elevation -33 to elevation -84, where they adjoin bedrock. Only the upper 4 to 6 ft of the Cretaceous soils were excavated. This soil is a hard, brown clay with slickensided fissures. The Cretaceous soil below the hard brown clay, between elevation -69 and elevation -84, is composed of sand and gravel. This stratum was significant because it contained artesian pressure, which was relieved during construction by means of deep submersible pumps.

A typical soil profile is shown in Figure 1. Basically, five layers of soil are displayed in sequence from the street surface. They are the upper brown sand, middle gray clay, gray sands and interbedded stiff clay, lower orange sand, and hard Cretaceous clay. The standard penetration resistance and description of the strata are provided in the Figure. The unconfined compressive strength of the middle gray clay is approximately 1.5 tsf and of the hard Cretaceous clay is 3.5 tsf.

INSTRUMENTATION

The measuring equipment chosen was such that its accuracy and repeatability allowed for consistent, detailed observation of the excavation behavior. Essentially, four methods of measurement were employed to monitor soil movement and brace loads. They included inclinometers, heave-point extensometers, vibrating wire strain gauges, and precise settlement surveys. The instruments were concentrated in the test section shown in Figure 2. The test section was approximately 78 ft long and 130 ft wide.

CONSTRUCTION SEQUENCE

The pervious nature of the Pleistocene terrace deposits required dewatering as a prelude to deep open cutting. Wells 12 in. in diameter containing submersible pumps were established along the line of intended excavation. In the vicinity of the test section the wells were installed to tip depths at elevation -35.

The excavation walls were constructed of soldier piles and oak lagging. The excavation was deepened to 56 ft, and four levels of cross-lot braces were installed. With the exception of the first-level braces, which were not preloaded, each strut was jacked to one-half its design load and wedged. Because of the large width of excavation (130 ft), the braces were supported in their central portion by two rows of 1-ft-diameter pipe piles, which were located 51 ft from the north and south walls of the cut. The excavation was deepened in its central portion to 82 ft. Berms were left in place against the lower 26 ft of the north and south walls of the cut. The berms were established on a $^{3}/_{4}$ H:1 V slope and were 8 ft wide at the top. Significant sloughing was observed at the south berm. Water flowed into the cut at the base of the berm along a sand and gravel layer just above the Cretaceous clay at a depth of approximately 78 ft. High-capacity sump pumps were operated continuously within the cut for the remainder of excavation to discharge water. The central portion of the 12-ft-thick concrete invert was constructed in three separate sections. The fourth-level braces were then removed as, simultaneously, rakers were installed between the central portion of the invert and the fourth-level wales. The top 16 ft of both the north and south berms was excavated, and the fifth-level braces were installed between the central portion of the invert and the walls of the excavation. Both the rakers and the fifth-level braces were preloaded to one-half the design load. After the fifth-level braces were installed, the base of the berms remaining between the central portion of the invert and the walls of the cut was removed and the extreme north and south sections of the invert were built. The walls and arch sections of the subway were constructed, after which the third-level cross-lot braces were removed.

Figure 1. Observed soil profile.

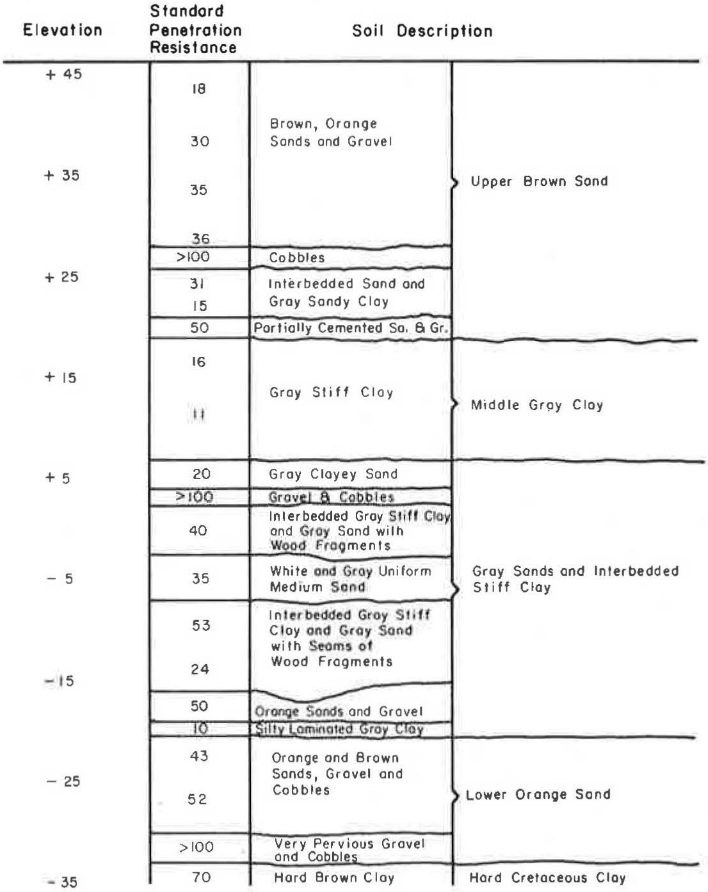
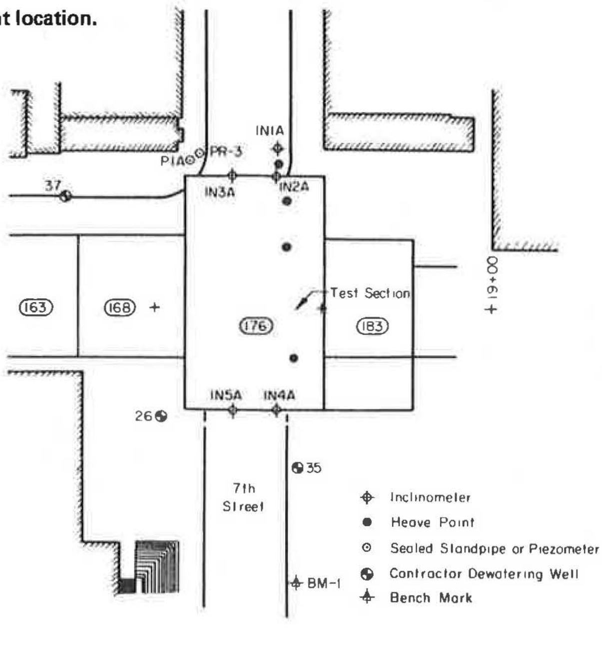


Figure 2. Instrument location.



For all levels of braces the horizontal spacing was 13 ft with the exception of the second and third levels, where the struts were concentrated toward the center of the excavation wall. A graphical representation of construction as a function of time for the test section is shown in Figure 3. Day 0 corresponds to July 31, 1971, at which time soil excavation was initiated. Although not indicated in the figure, the third-level braces were removed from the cut on approximately day 690.

OBSERVED SOIL DISPLACEMENT

A history of the braced excavation is summarized in six diagrams (Figures 4 through 9) that show lateral and vertical displacement corresponding to the successive stages of construction at one cross section. Additional movements are delineated in Figures 10 and 11, which show soil behavior at a different location along the south wall of the excavation.

Displacements at Depth of Cut of 38 ft

Figure 4 shows the observed behavior of the test section just prior to and after preloading the second-level braces. Measurable displacement was recorded as deep as 30 ft below the bottom of the cut, with most of the inward movement concentrated near the top of the soldier piles; 17 ft north of the excavation, lateral movement was recorded throughout a depth of 60 ft. At this location the peculiar distribution of movement near the street surface was caused by trench excavation adjacent to the inclinometer casing. Surface settlement both north and south of the excavation was limited to a maximum of 0.3 in.; ⅛-in. cracks in the street were observed within 10 ft of the cut. Heave-point extensometers indicated an upward movement ranging from 0.08 to 0.18 in. in the gray sands and interbedded stiff clay immediately below the bottom of the cut.

Displacements at Depth of Cut of 60 ft

Figure 5 shows the observed behavior of the test section after the fourth-level braces were installed. Lateral movement of the north wall of the cut was recorded throughout the full depth of the soldier piles. Inward bulging of the excavation walls developed at and below the fourth-level braces; 17 ft north of the excavation, the lateral displacement increased from a maximum of 0.2 in. to 0.3 in. and extended throughout a depth of 75 ft. Adjacent to the cut, surface settlement was a maximum of 0.6 in., whereas deep-seated settlement at 50 ft below the street surface was 0.16 in. Upward movement in the gray sands and interbedded stiff clay increased from a total of 0.15 in. to 0.45 in. Total upward movement in the hard Cretaceous clay was measured by two heave-point extensometers at 0.05 in. and 0.09 in.

Displacement When South Portion of Cut at 82 ft

Figure 6 shows the observed behavior of the test section just prior to construction of the invert. The inclinometers in this cross section showed movement away from the cut in the upper portion of the soldier piles. At the south wall, this outward movement apparently resulted from a small clockwise rotation about the bottom of the soldier pile. Such rotation did not occur at the other instrumented section on the south wall and therefore represents behavior associated only with the soldier pile shown in Figure 6. Possibly, the gradual increase in steel temperature during this time caused the braces to expand. Their interaction with the walls of the cut found expression in the inclinometer measurements as a movement away from the excavation. The outward displacement of the excavation wall resulted in lateral movement 17 ft north of the cut. At this distance, a nearly uniform 0.1-in. movement away from the excavation occurred throughout the upper 40 ft of soil. This resulted in a reduction of the maximum inward displacement from 0.3 in. to 0.2 in. Inward movement of all the instrumented soldier piles occurred below the fourth-level braces. Deep-seated settlement north of the cut increased from 0.16 to 0.20 in., and surface settlement south of the cut increased from a maximum of 0.6 to 0.7 in. Heave-point extensometers indicated that the cumulative upward movement in the hard Cretaceous clay was approximately 0.38 in.

Figure 3. Construction as a function of time.

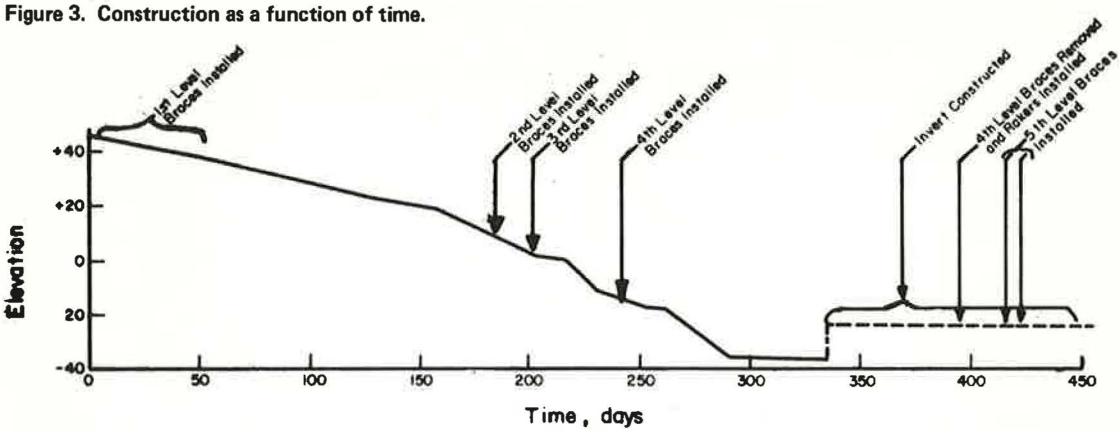


Figure 4. Displacements at depth of cut of 38 ft.

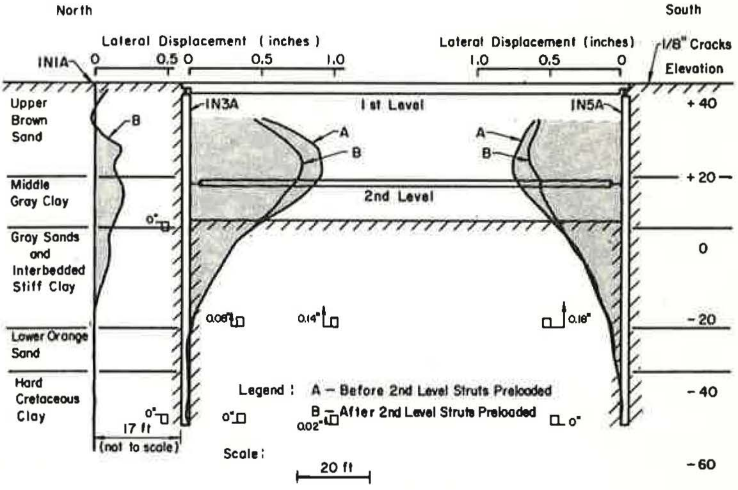
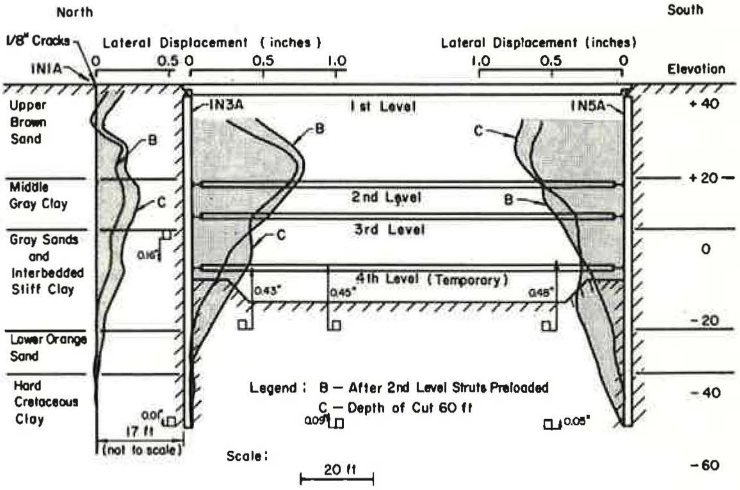


Figure 5. Displacements at depth of cut of 60 ft.



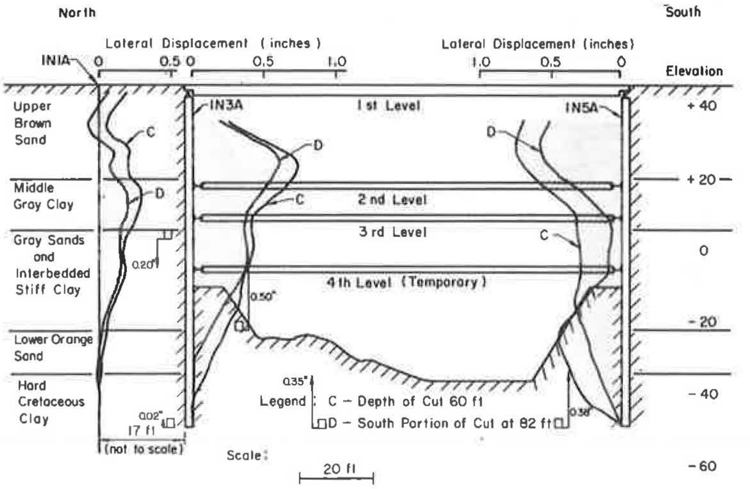


Figure 6. Displacements for south portion of cut at 82 ft.

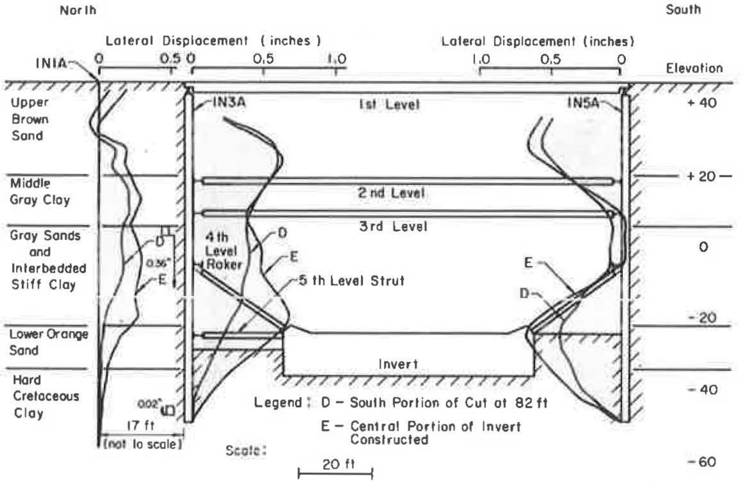


Figure 7. Displacements when central portion of invert constructed.

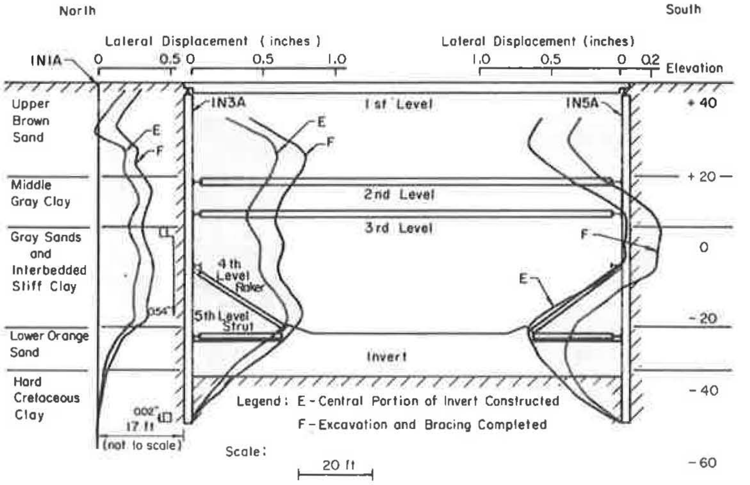


Figure 8. Displacements when excavation and bracing completed.

Displacement When Central Portion of Invert Constructed

Figure 7 shows the observed behavior of the test section just after the fifth-level braces were installed on the north side of the cut. A significant increase in deep-seated lateral displacement was measured at all instrumented soldier piles. The additional displacement occurred primarily in response to excavation of the berms adjoining the north and south walls. The deep movement resulted in lateral displacement 17 ft north of the cut where, at a depth of 65 ft, horizontal movement of the soil toward the cut increased from 0.05 in. to 0.25 in. Deep-seated settlement north of the cut increased from 0.20 to 0.36 in., and surface settlement south of the cut increased from a maximum of 0.70 to 0.85 in.

Displacement When Excavation and Bracing Completed

Figure 8 shows the observed behavior of the test section just after the final portions of the invert were constructed. An outward displacement of approximately 0.2 in. occurred at the south side of the cut for the soldier pile shown. This movement coincides with a corresponding 0.2-in. inward displacement at the north wall of the excavation and apparently relates to a temporary unloading of the fifth-level braces at the north side of the cut; 17 ft north of the excavation a nearly 0.1-in. increase in lateral displacement toward the cut occurred throughout a depth of 65 ft. Deep-seated settlement north of the excavation increased from a maximum of 0.36 to 0.54 in., and surface settlement south of the cut increased from a maximum of 0.85 to 1.2 in.

Displacement After Excavation and Bracing Completed

Figure 9 shows the observed behavior of the test section for a period of 2 to 3 months after the excavation was finished. Almost no additional movement occurred at the soldier piles; 17 ft north of the cut, lateral displacement showed a nearly uniform 0.2-in. increase in southward movement. This additional displacement resulted in a maximum, cumulative movement of 0.5 in. between elevation 20 and elevation -20. Deep-seated settlement increased from 0.54 to 0.62 in. The increased displacement partially may have resulted from voids (as large as 1 cu yd) that existed at a depth of 70 ft behind the lagging on the excavation's north side. The voids later were filled, and additional movement was negligible. The heave-point extensometer north of the cut indicated an upward movement of 0.08 in. in the hard Cretaceous clay. The upward movement corresponds to a temporary 8-ft increase of the water level in the lower orange sand. Maximum street settlement south of the excavation increased to cumulative displacements of approximately 1.5 in.

Additional profiles of lateral displacement at the south wall corresponding to the completion of excavation and at a time 2 months afterward are shown in Figures 10 and 11 respectively. Although the location of these displacement profiles is only 26 ft east of those shown in Figures 4 through 9, the magnitude of movement is appreciably different. The maximum accumulated displacement of the south wall at this section was 1.3 in., compared with the 0.5 in. shown in Figure 9. The deep-seated movement, shown by the conspicuous "bulge" between elevation 0 and elevation -50, developed steadily as the excavation was deepened and never showed the shift in displacement away from the cut that characterizes the movement of the south wall in previous cross sections.

It is believed that the movements shown in Figures 10 and 11 are more representative of displacement at the south wall than movements shown in Figures 4 through 9. The deep lateral displacements that were observed in other nearby excavations correspond more closely with the movements shown in Figures 10 and 11. In addition, the measurements of lateral movement in Figures 10 and 11 were referenced to a point 15 ft below the bottom of the soldier pile. Consequently, lateral displacement of the pile bottom was precisely known.

In summary, Figures 4 through 11 provide a history of excavation movement that shows the close relationship between displacement, the depth of cut, bracing scheme, and excavation sequence. A most important feature of the observations is the development of deep-seated, inward movement at depths in excess of 40 ft. Displacement at

Figure 9. Displacements after excavation and bracing completed.

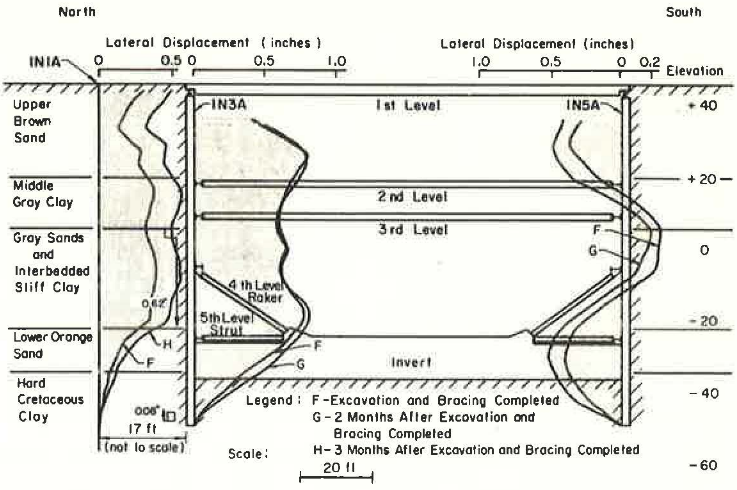


Figure 10. Displacements at south wall when excavation and bracing completed.

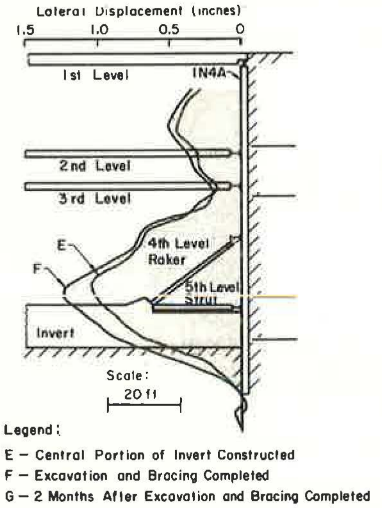


Figure 11. Displacements at south wall after excavation and bracing completed.

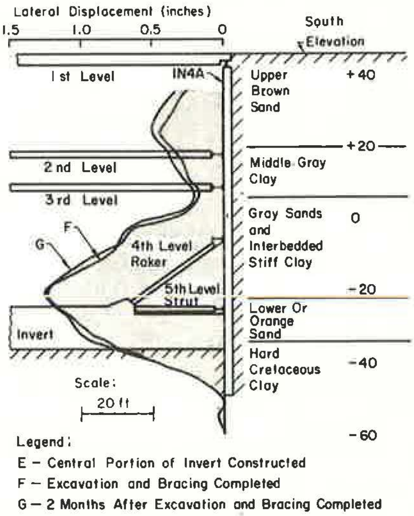


Figure 12. Soldier pile movements below excavation level.

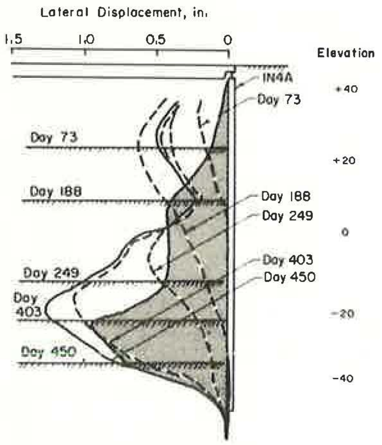
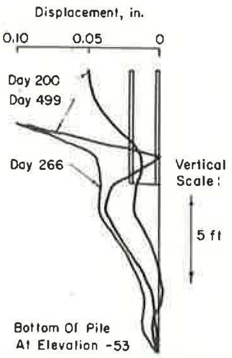


Figure 13. Lateral displacement at base of a soldier pile.



depth leads to loss of ground throughout a greater portion of the surrounding soil, thereby extending the influence area of settlement and deepening the required penetration of underpinning. The magnitude and approximate volumes of the deep-seated displacement are consistent with movement for similar soil profiles published in the literature. Thon and Harlan (13) and Armento (2) show movement profiles for strutted slurry walls that are in close agreement with these diagrams. Liu and Dugan (8) show similar development of displacement for a 55-ft tied-back soldier pile and timber lagging wall in Boston.

Displacement Below the Bottom of Excavation

The greater portion of accumulated displacement occurred below the bottom of the cut. When excavation depths reached 40 ft, lateral movement had developed to the base of the 90-ft-long soldier piles. A comparison of the displacement area that developed below the bottom of excavation at each excavation level and the total displacement area for the full depth of the cut is shown in Figure 12. The cumulative movement that developed below each successive level is shown by the shaded portion of the movement profile. Displacement generated beneath the excavation bottom amounted to over 60 percent of the total lateral displacement. These observations agree with other published data. D'Appolonia (4) has demonstrated a similar accumulation of movement for subway excavation in Boston.

MOVEMENT AT THE BASE OF THE SOLDIER PILES

Special inclinometer casings were extended below the base of selected soldier piles to measure displacement at the pile bottoms. Figure 13 shows the lateral movement that occurred below the base of a soldier pile at the test section. The inclinometer had a repeatability of 0.04 in. over the bottom 15 ft of casing, and thus the measured displacements of 0.05 in. were close to the precision of the instrument. The observations indicate that only a small amount of lateral displacement occurred at and below the base of the soldier pile. Apparently, soil movements caused rotation of the piles about their tips but almost no translation of the tips.

EFFECT OF BERMS ON LATERAL DISPLACEMENT AND STRUT LOADS

The consistent manner in which earth movement developed emphasizes the close relationship between excavation procedure, soil displacements, and strut loads. A good example of this interrelationship is illustrated by the movements and loads associated with excavation below the fourth-level struts where berms were left in place on the north and south walls. The central section of the cut was excavated to subgrade at a depth of 31 ft below the fourth-level struts. Figure 14 shows the development of inward lateral displacement as the cut was deepened and also shows the continuing lateral movement with time after excavation had ceased and berms were in place. These movements are a measure of the berm's behavior and the nature of the soil. As the central portion of the excavation was deepened below the fourth-level struts, the volume of lateral displacement of the south wall increased by 25 percent. Sloughing, seepage at the toe, and construction activity gradually loosened the slightly cemented sands in the berm and allowed additional straining of the wall. After the excavation had ceased with berms in place, the volume of lateral displacement increased an additional 15 percent with time (based on cumulative movement before the central portion of the cut was excavated to subgrade).

The load in all brace levels showed a pattern of development that was consistent with deepening the central portion of the cut and subsequent movement of the berm with time. Figure 15 shows the increase in average strut load at each brace level as a function of time. (The figure shows only the change in load taking place after the fourth-level struts were installed and preloaded.) The loads increased steadily as the central portion of excavation was deepened and continued to increase with time as the berm adjoining the south wall was left in place. The load in the fourth-level braces changed by a maximum of 171 kips, an increase from 91 to 262 kips. The third-level braces

Figure 14. Lateral displacement in response to excavation with berm.

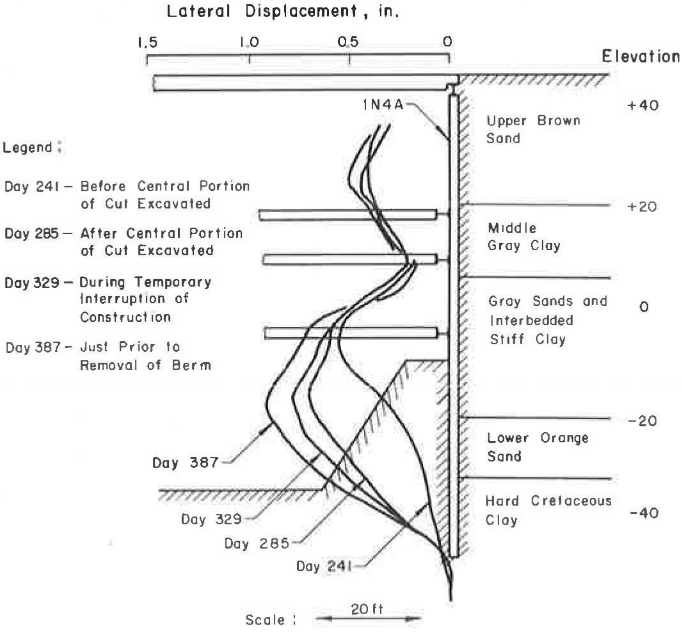
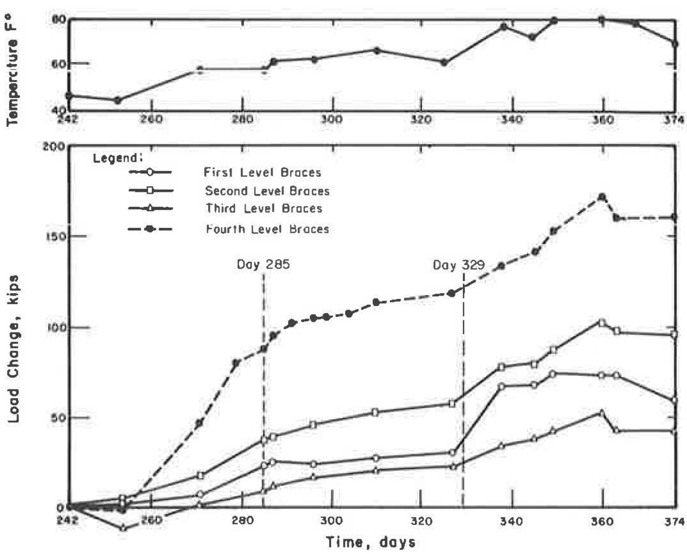


Figure 15. Increase of brace loads in response to excavation with berm.



indicated a load increase that was markedly smaller than all other brace levels. Although this behavior may have been related partially to the smaller wall area against which the struts were positioned, it is believed that the smaller load change resulted primarily from the way in which the soldier piles deformed. The load increase in the third-level braces was limited because the bottom struts acted as a pivot point for the soldier pile. Consequently, movement below the fourth-level braces acted to restrain movement at the third-level braces. The first and second brace levels increased in axial load by a maximum of 74 and 101 kips respectively. It appears that temperature changes affected the development of loads in all levels, but its contribution in terms of load increase is difficult to evaluate.

In summary, the berm appears to have been only partially effective in restraining lateral displacement. The use of the berm at depth resulted in both the relatively large lateral movements beneath the fourth-level braces and the correspondingly high load carried by the fourth-level braces.

SETTLEMENT

As a result of pumping from the deep artesian sand and gravel, local subsidence averaging 0.012 ft was measured south of the excavation. The subsidence was small and its magnitude was close to the precision of the optical survey. The subsidence has been subtracted from the total settlements, and thus the data represent only soil movement that occurred in response to excavation.

Settlement profiles south of the test section are shown in Figure 16. The settlement developed incrementally in response to deepening and broadening the excavation. Time-dependent movement is indicated by a comparison of settlement at 1 and 5 months after the completion of excavation. During this period no further removal of soil was undertaken and the bracing system essentially was unchanged. At all stages of construction the slope of the settlement profile is steeper near the excavation.

Figure 17 shows settlement contours south of the excavation. These diagrams indicate the increase of soil movement that occurred between the time the excavation was 45 ft deep and the time of its completion. The diagrams illustrate the spatial relationship of settlement with regard to the excavation and surrounding structures. For the 45-ft depth of excavation, settlement contours parallel the edge of the cut, whereas, upon completion of open cutting, they indicate a slightly greater displacement behind the central and western portions of the excavation wall.

The final settlement expressed as a percentage of the maximum excavation depth is approximately 0.1 percent. In comparison with the settlements summarized by Peck for sand and soft to hard clay (9), this displacement is small. The relatively low magnitude is a reflection of the number of brace levels used, groundwater control, preloading, and other aspects of the construction procedure.

APPARENT EARTH PRESSURE

The apparent earth pressures for the full depth of excavation are shown in Figure 18. Both the average and maximum pressures are shown. The average apparent earth pressure has been computed from the average of all brace loads in each strut level and the maximum apparent earth pressure from the maximum load in an individual strut at each level. The diagrams have been constructed on the assumption that the struts carry a uniform earth pressure halfway between strut levels and that the bottom of the excavation acts as a brace. Load measurements have been corrected for temperature effects and drift of the strain gauges. The apparent earth pressure shows both the influence of construction technique and the nature of the supported soil. The salient features of load distribution are summarized in the following paragraphs.

1. The maximum apparent earth pressure occurred at the third-level braces. The high load measured in these braces is a function of the relatively large preload and pressure redistribution that occurred during preloading. The proximity of the third- and second-level braces allowed mutual interaction. When the third-level braces were preloaded, the load in the second-level struts decreased by an average of 55 kips. This

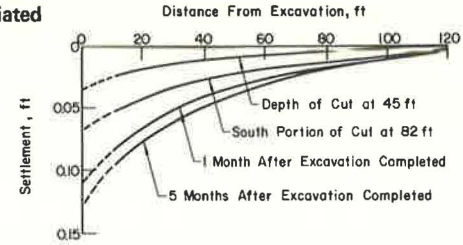


Figure 16. Settlement profiles associated with excavation.

Figure 17. Settlement contours associated with excavation.

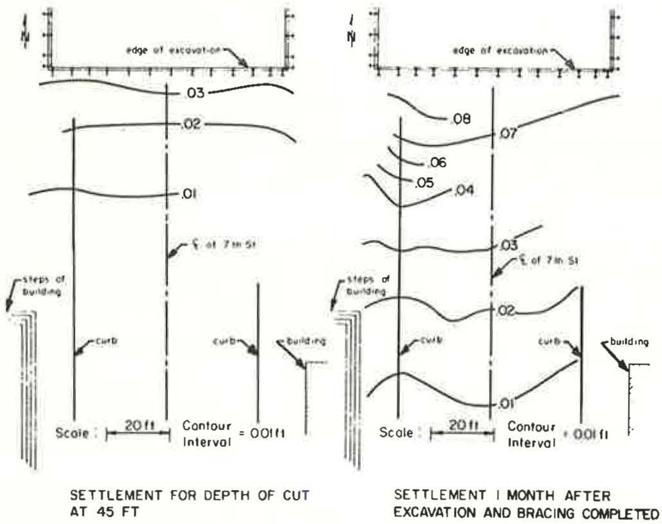


Figure 18. Measured earth pressures.

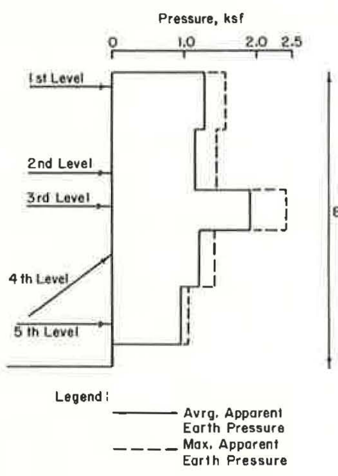
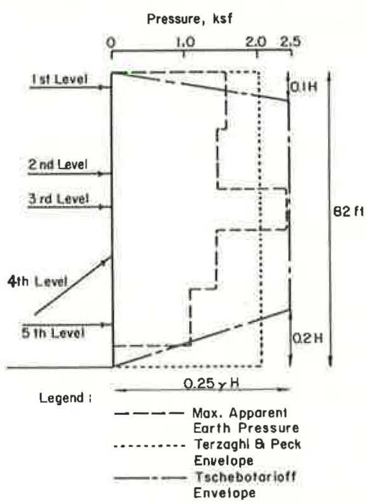


Figure 19. Comparison of earth pressures.



redistribution of load finds expression in the relative magnitude of each pressure. As the excavation was deepened, load in the third-level braces remained proportionately higher than load in other brace levels. Because the design envelope is predicted on the maximum measured load, it often includes a single strut pressure that is anomalously high. Consequently, the design envelope overcompensates for anticipated load. The conservative nature of the earth pressure envelope should be acknowledged and, correspondingly, a limited factor of safety chosen for structural design of the struts.

2. The loads measured in the first-level braces varied through a wide range of values. The variation of load from one strut to another was a function of the construction technique. Initially, the excavation was opened in four separate sections, and a portion of the bracing was installed in each section. As a consequence, the braces were wedged during different times at different depths of cut. The resulting loads show the variable nature of brace installation and early excavation. For the final excavation depth, loads in the first-level braces ranged from a maximum of 243 kips to a minimum of 134 kips.

3. The loads in the bottom-level braces were relatively low with respect to loads in other brace levels. It would be expected that loads would be lower in braces placed very near the bottom of the excavation, particularly when stiffer soils are encountered near and beneath the excavation that allow relatively high lateral stresses to be carried at the base of the excavation. Figure 19 shows the earth pressure envelopes for a braced cut in sand as proposed by Terzaghi and Peck (12) and by Tschebotarioff (14). An angle of shearing resistance, ϕ, equal to 30 deg, and a unit soil weight, γ, equal to 120 pcf, have been chosen as representative of the soil at the instrumented cut. Although both design envelopes approximate the measured load, the trapezoidal distribution provides a better estimate of the reduced load at the base of the cut.

4. All the apparent earth pressures fell within an envelope whose width was equal to $0.25\gamma H$ (Figure 19). Such a value is approximately equal to the maximum apparent earth pressures in a nearby 60-ft-deep cut in the same soil types. Maximum earth pressures in similar soils in Washington have been observed to increase from approximately $0.15\gamma H$ to $0.23\gamma H$ for depths of cut ranging from 28 to 60 ft respectively (3).

CONCLUSIONS

The history of the excavation behavior provides a detailed account of both the magnitude and distribution of movement associated with open cutting in the District of Columbia terrace soils. The records of successive displacement show the relationship between soil movement and various aspects of open cutting, including the bracing scheme, depth of excavation, and construction technique. On the basis of observations and analysis, the following conclusions are offered:

1. It is well known that the protection of structures from ground movements is one of the most important considerations in the design of braced excavations in urban areas. There is a large potential for reduction in construction costs and claims with improvements in the methods for limiting and forecasting soil movements. Thus, primary emphasis in the observation and instrumentation program should be directed toward measuring the significant soil and wall displacements, correlating displacements with construction conditions, and observing their effect on the adjacent structures.

2. Lateral measurements at the line of the excavation wall are most useful in that they can be directly related both to construction conditions and to the surrounding soil displacements. Since the largest volume of lateral displacement takes place beneath the bottom of the advancing excavation, the measurements of lateral displacements must be made with instruments that record the displacements beneath the base of excavation, such as inclinometers.

3. Displacements generated below the bottom of the deepening excavation accounted for over 60 percent of the total lateral displacement.

4. The development of lateral movement was most intense at depths greater than 40 ft. Maximum lateral displacement measured was 1.3 in. at a depth of 60 ft. Since deep-seated displacement leads to loss of ground throughout a greater portion of the surrounding soil and thereby increases the area of damaging movement, the most im-

portant concern should be the method of support and excavation at depth.

5. Construction technique has a significant influence on the amount of lateral soil movement that develops. In particular, the depth of excavation level beneath the lowest previously installed braces is the most influential factor controlling soil displacement.

6. Apparently, steep berms are only partially effective in restraining lateral displacement. Measurements in the instrumented cut show that the volume of lateral movement increased by 25 percent as the central portion of the excavation was deepened and berms were left on the sides of the cut. A further increase of 15 percent in the displacement volume occurred with time after excavation had ceased.

7. As measured by buried heave-point extensometers, total heave of the excavation bottoms was small, being typically 0.4 to 0.5 in.

8. The volume of surface settlement increased 10 percent from the time the excavation was completed to a time 5 months afterward. The final distribution of surface settlement was roughly curvilinear, extending from a maximum 1.5 in. near the edge of the cut to 0.5 in. at a distance of 50 ft and to 0.1 in. at a distance of 120 ft.

9. Inclinometers installed to a depth of 15 ft below the soldier piles indicate that the piles rotated about their tips. Lateral movement of the pile bottoms was limited to 0.05 in.

10. Brace loads are affected by the construction procedure. Large preloads and a large depth of excavation level below the last strut can lead to high strut loads.

11. The maximum apparent earth pressures for the 82-ft-deep excavation can be predicted adequately by a trapezoidal earth pressure envelope of width $0.25\gamma H$ (where γ is the soil unit weight of 120 pcf and H is the full depth of excavation) such as the one shown in Figure 19.

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