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Movements Around Transit Tunnels in Mixed Ground

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Movements Around Transit Tunnels in Mixed Ground

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SYNOPSIS This paper describes the ground movements measured at a Test Section during construction of twin rapid transit tunnels in Cambridge, Massachusetts. The Test Section was located in an area of rock, soft ground and mixed face tunneling, with the alignment of the twin tunnels approximately 100 feet below ground surface. Overburden soils consist primarily of a very dense, saturated glacial till containing cobbles and boulders, with a weakly metamorphosed, fractured shale bedrock below. Instrumentation at the Test Section was installed in three cross-sections: one with the tunnel headings entirely in rock, a second with the tunnel headings in soft ground, and a third in a mixed face area. The field measurements are analyzed to show the effects of ground losses at the tunnel headings vs. distance away from headings, the effects of single vs. twin tunnel construction, and the effects of mixed face vs. rock and soft ground tunneling on ground movements.

INTRODUCTION

Ground movement data obtained on a continuing basis as a tunnel is constructed is important so that knowledge of geotechnical parameters, ground performance, and construction procedures may be continuously evaluated and refined. This paper describes the ground movements measured at a Test Section on the Massachusetts Bay Transportation Authority (MBTA) Red Line Extension - Northwest, Cambridge, Massachsuetts. The Test Section was selected to evaluate advanced methods of subsurface exploration as well as instrumentation used to monitor ground movements associated with tunnel construction. The research performed here on advanced methods of exploration is described by Thompson et al. (1980).

The Test Section was located in an area of rock, soft ground, and mixed face tunneling approximately 100 feet below ground surface. Overburden soils consist primarily of a saturated, very dense glacial till containing cobbles and boulders, with the bedrock a weakly metamorphosed shale that is severely fractured and intruded by igneous dikes. The site represents a typical urban setting with the Test Section located under a major, four-lane divided street, with structures adjacent on both sides.

DESCRIPTION OF TEST SECTION

Site Conditions

The MBTA Red Line Extension - Northwest project will extend from the reconstructed Harvard Square Station to new stations at Porter Square, Cambridge, Davis Square, Somerville, and Alewife Brook Station in North Cambridge, Massachusetts, a distance of approximately 3.1 miles. The Test Section is located between outbound (OB) tunnel stations 203+00 and 206+00, beneath Massachusetts Avenue in Cambridge, approximately 3/4 mile north of Harvard Square, Figure 1. The 300-foot Test Section is occupied by a heavily traveled, major, four-lane artery. Commercial and residential structures varying from one to six stories in height, which are supported on shallow, soil bearing foundations, abut both sides of Massachusetts Avenue. Numerous surface and subsurface utilities line the Avenue, and pedestrian traffic in the area is exceptionally heavy.

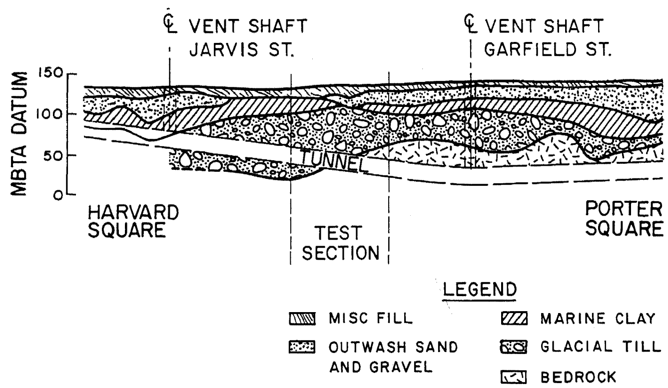

Figure 1. Generalized Subsurface Profile, Harvard Square to Porter Square

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Subsurface Conditions

The deposits encountered at the Test Section, in order of increasing depth from ground surface, Figure 1, are:

1. Miscellaneous Fill
2. Outwash Sand and Gravel
3. Marine Clay
4. Glacial Till
5. Bedrock

Table I summarizes the major geological units and the elevations at which they were encountered by the explorations, relative to the tunnel crown and invert, within the Test Section.

The glacial till was the only overburden unit through which the tunnel was constructed in the Test Section and the major soil unit investigated in detail. The till generally consists of dense to very dense, silty, fine to coarse sand with varying amounts of clay, gravel, cobbles, boulders, and rock fragments of argillite and granite. The stratum was deposited directly over the bedrock surface in thicknesses varying from 51 to 83 feet within the Test Section. The density of the glacial till ranges from dense to very dense with an average standard penetration resistance over 150 blows per foot.

The principal rock type in the Test Section is Cambridge Argillite, a slightly metamorphosed greenish-gray shale which varies from soft, severely fractured and weathered near its surface to very hard and fresh (the quality generally improving with increasing depth). Joints were observed in sufficient number to impart a blocky nature to the rock mass. Igneous intrusions in the form of diabase dikes are common in the argillite within the Test Section. These intrusions are steeply dipping to the southwest and generally strike in a northwest-southeast direction. They have been exposed to surficial weathering and hydrothermal alterations along open joints and shears.

The principal water bearing materials are the outwash sand and gravel, and a zone at the bedrock/glacial till interface. The marine clay and glacial till together comprise an aquiclude between the overlying outwash sand and gravel and underlying bedrock/glacial till interface, resulting in two relatively independent water bearing zones. The normal depth to the water table in the outwash sand and gravel ranges from about 9 to 14 feet below ground surface. Water levels in piezometers constructed in the bedrock before tunnel construction indicated artesian conditions.

Tunnel Cross Sections

The MBTA Extension - Northwest project consists of twin single-track transit tunnels which connect cut-and-cover stations at Harvard and Davis Squares with a deep underground station mined in bedrock at Porter Square.

The design tunnel configurations for soil and rock conditions are shown in Figure 2, with the inside diameter of 19.2 feet selected for the design clearance envelope. Ventilation shafts are located periodically along the alignment, serving initially as construction access shafts and, later during operation, as ventilation and emergency exit shafts.

Table I. Summary of Geological Conditions

TUNNEL STATION	TUNNEL CROWN	TUNNEL INVERT	APPROXIMATE ELEVATION OF			MAJOR ROCK TYPE	OVERALL AVERAGE ROCK QUALITY (RQD)
			TOP OF TILL	TOP OF DECOMPOSED ROCK	TOP OF NON-DECOMPOSED ROCK		
203+00 OB	51.5	29.5	105.5	33.5	31	ARGILLITE	FAIR
203+50 OB	50	28	108	N.D.	38.5	ARGILLITE	N.D.
204+00 OB	49	27	108	42	41	DIABASE	N.D.
204+50 OB	47	25	113	42	40	DIABASE	POOR TO EXCELLENT
205+00 OB	45.5	23.5	111	N.D.	50	DIABASE	VERY POOR TO FAIR
205+50 OB	44	22	116	60	58.5	ARGILLITE/DIABASE	POOR TO EXCELLENT
203+50 IB	52	29.5	112	32.5	30	ARGILLITE	VERY POOR
204+00 IB	50	28	107	N.D.	32	ARGILLITE	N.D.
204+50 IB	48	26.5	114	N.D.	32 - 42	ARGILLITE	N.D.
205+00 IB	47	25	118	42 - 49	41 - 46	ARGILLITE/DIABASE	POOR TO EXCELLENT
205+50 IB	45.5	23.5	114	N.D.	49.5	DIABASE	POOR
206+00 IB	44	22	111	57	55.5	ARGILLITE/DIABASE	POOR TO GOOD

NOTES: 1. N.D. = SAMPLES NOT OBTAINED AND NO DETERMINATION MADE.
2. ELEVATIONS REFER TO MBTA RED LINE DATUM.

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Instrumentation

Three rows of instrumentation spaced approximately 100 to 150 feet apart (one at each end and one approximately in the middle of the Test Section) were designed as high intensity instrumentation sections. These high intensity sections are identified as the north, middle, and south sections on Figure 3.

At the north section, the tunnel headings were entirely in rock. The tunnel crowns at the section were approximately 15 feet below the bedrock surface. The south section has most of the tunnel heading in glacial till, and is designated as the soft ground section. The middle section is in a mixed face area, with the tunnel heading in glacial till overlying rock.

The typical instrumentation at these three high intensity sections is shown on Figure 4. Instrumentation consisted of the following:

a. Surface settlement points installed at approximately 10 foot intervals across each section to clearly define the ground surface settlements.

b. Deep settlement points installed over the tunnel crown, just outside of the tunnel springlines, and in the pillar between the inbound and outbound tunnels to measure vertical displacements of the soil mass at various depths.

c. Inclinometer casings installed just outside of the tunnel springlines, and in the pillar between the inbound and outbound tunnels, to measure horizontal movements of soil and rock at various depths.

Also, surface settlement points above the tunnel centerlines and building settlement points on buildings on both sides of Massachusetts Avenue were placed throughout the Test Section.

Two different types of settlement instruments and inclinometer casings were utilized. One system measured vertical ground movements by means of an electrical inductance probe which monitors the positions of wire rings mounted on a corrugated PVC casing. The second system consisted of telescoping casing sections connected with a coupling which allows each casing section to move up or down independently. Vertical ground movements were determined by means of a mechanical hook probe, which locates the bottom of each casing section. Horizontal ground movements were determined from conventional slope inclinometer surveys integrating the inclinations of the grooved inclinometer casing from the bottom up.

A more detailed description of the instrumentation, including equipment, and installation and monitoring procedures, is presented by Thompson et al. (1983).

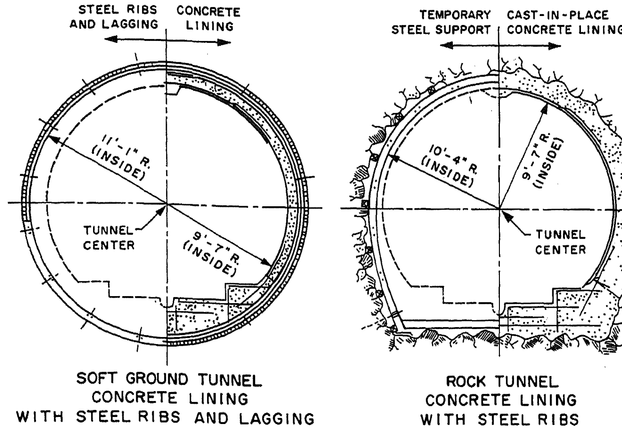

Figure 2. Typical Red Line Tunnel Sections

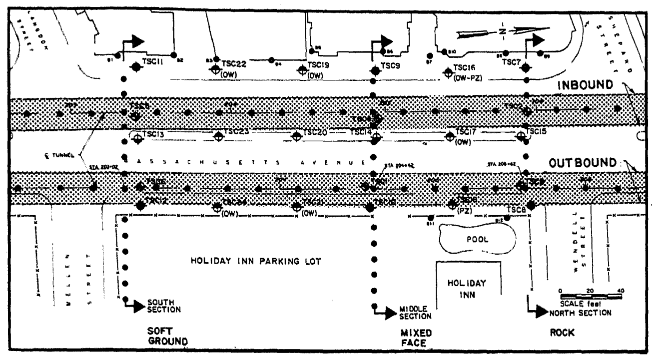

Figure 3. Instrumentation Location Plan, Test Section, Cambridge, Massachusetts

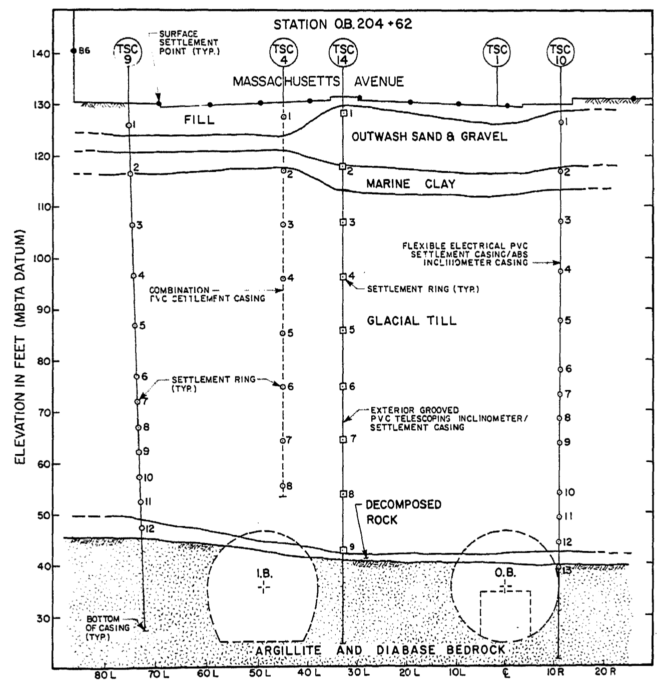

Figure 4. Mixed Face (Middle) Section Profile

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CONSTRUCTION PROCEDURES AND PROGRESS

The tunnel excavation through the Test Section took place over a period of about 18 months. Various tunneling and temporary support methods were employed to drive the tunnel headings through this area. An excavation summary, including heading sequence, tunneling methods, advance rate, and support type is presented on Table II. Figure 5 pictures the sequence of tunneling.

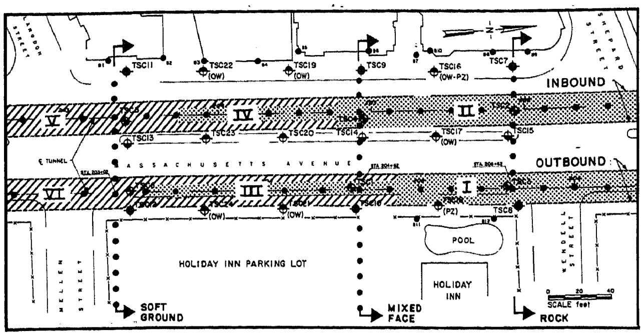

Figure 5. Sequence of Tunneling Procedures (Refer to Table II for Tunneling Phase)

The twin tunnels passed through the rock (north) section from the north during August through October 1980, using drill-and-blast excavation techniques. The outbound heading preceded the inbound heading by about 150 feet. The tunnel headings passed through the soft ground (south) section from the south by means of soft ground shield excavation procedures in August 1981 (inbound) and October 1981 (outbound). The mixed face (middle) section was first passed by a 10-foot by 10-foot pilot drift in the invert of the outbound tunnel in October 1980, followed by the full faced excavation for the inbound tunnel in December 1980. Both of these excavations were advanced from the north using drill-and-blast rock excavation techniques. The outbound tunnel was completed in late November 1981 as the soft ground excavation advanced from the south.

RESULTS OF FIELD MEASUREMENTS

Rock Section - North

Ground movements which developed in the rock section as the outbound and inbound tunnels passed were small. Ground surface settlements

Table II. Excavation Summary

TUNNELING PHASE*	TUNNEL HEADING AND DIRECTION	EXCAVATION METHOD AND CONDITION	LENGTH (LINEAR FEET)	DATES EXCAVATED	ADVANCE RATE**	SUPPORT
I	OUTBOUND - SOUTH STA. 206+00 - STA. 204+84	FULL FACE: ROCK	114	JULY 1980- OCT. 1980	1.9 L.F./DAY ***	STEEL RIBS (W8 X 30) 2-FOOT CENTERS
II	INBOUND - SOUTH STA. 206+31 - STA. 204+80	FULL FACE: ROCK	150	OCT. 1980- DEC. 1980	2.7 L.F./DAY ***	STEEL RIBS (W8 X 30) 2-FOOT CENTERS
III	OUTBOUND - SOUTH STA. 204+84 - STA. 203+20	INVERT PILOT DRIFT 10' X 10': ROCK	166	OCT. 1980- NOV. 1980	5.0 L.F./DAY	8" TIMBER CAP AND POST 4-FOOT CENTERS
IV	INBOUND - SOUTH STA. 204+80 - STA. 203+72	INVERT PILOT DRIFT 10' X 10': ROCK	104	DEC. 1980- JAN. 1981	5.1 L.F./DAY	8" TIMBER CAP AND POST 4-FOOT CENTERS
V	INBOUND - NORTH STA. 203+31 - STA. 204+80	SHIELD DRIVEN	150	AUG. 1981- SEP. 1981	7.1 L.F./DAY	RIB & LAGGING 4-FOOT CENTERS
VI	OUTBOUND - NORTH STA. 203+00 - STA. 204+84	SHIELD DRIVEN	186	OCT. 1981- DEC. 1981	4.2 L.F./DAY	RIB & LAGGING 4-FOOT CENTERS

* REFERS TO FIGURE 5 – SEQUENCE OF TUNNELING PROCEDURES.
** ASSUMES 6-DAY WORK WEEK.
*** NON-CRITICAL PATH WORK.

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were less than about 0.015 feet (0.2 in.) and occurred fairly uniformly across the section. Settlements observed here were negligible during soft ground and mixed face tunneling operations downstation.

Soft Ground Section - South

Figure 6 summarizes the settlement observations for two selected surface settlement points in the soft ground section. These points are located within 10 feet of the centerlines of the inbound and outbound tunnels. The settlement points responded immediately as the inbound tunnel passed on 21 August 1981, and surface settlements continued to develop over the next two weeks. Then, from about 10 September to 15 October 1981, just before passage of the outbound tunnel, additional small time dependent surface settlements slowly developed. Settlement rates increased again as the outbound tunnel passed through this section on 16 october 1981, and for the next two to three weeks. Then, additional small time dependent surface settlements slowly developed through 8 January 1982.

Table 3 summarizes the settlements that were observed at these two points in the soft ground section. An attempt has been made here to distinguish between immediate settlements, occurring within 2 to 3 weeks after the face had passes, and delayed settlements, attributable to long-term adjustments of the ground.

Figure 7 summarizes the surface and deep settlements which developed in the soft ground section. The surface settlement trough caused by the inbound tunnel construction extended beyond the limits of Massachusetts Avenue, a total width of more than 150 feet. A maximum surface settlement of about 0.035 feet (0.4 inch) was observed over the centerline of the inbound tunnel. As the outbound tunnel passed through this section, a maximum incremental surface settlement of 0.052 feet (0.6 inch) was observed, 10 feet to the left of the outbound centerline. The combined surface settlement trough, showing the effects of both tunnels, showed a maximum total surface settlement of 0.078 feet (0.94 inch) over the inbound tunnel. The settlement trough has a very gradual slope over its 150-foot width.

The deep settlement points, Figure 7, show settlements of the same order of magnitude as observed at the ground surface, with one exception. The deep settlement point over the inbound centerline showed a settlement of 0.418 feet (5.0 inches), mostly due to some substantial losses of ground at the tunnel face and crown. Despite this, these large ground movements did not propagate very far away from the tunnel because of the ability of the dense glacial till to carry load, or arch, over any opening caused by ground loss.

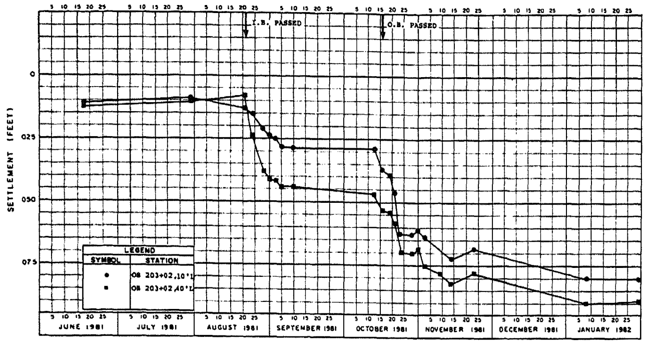

Figure 6. Typical Surface Settlement Point Observations - Soft Ground Section

Table III. Summary of Ground Surface Settlements, Soft Ground Section

DATE	SETTLEMENT IN FEET		COMMENTS
	IB CENTERLINE (10 FT. RIGHT)	OB CENTERLINE (10 FT. LEFT)	
17 JUNE '81	0	0	---
10 SEPT. '81	0.032	0.017	INCREMENTAL, IB TUNNEL
13 OCT. '81	0.003	0.000	DELAYED, IB TUNNEL
	0.035	0.017	TOTAL IB TUNNEL
23 NOV. '81	0.031	0.040	INCREMENTAL, OB TUNNEL
8 JAN. '82	0.012	0.012	DELAYED, OB TUNNEL
	0.043	0.052	TOTAL OB TUNNEL
	0.078	0.069	TOTAL IB AND OB TUNNELS

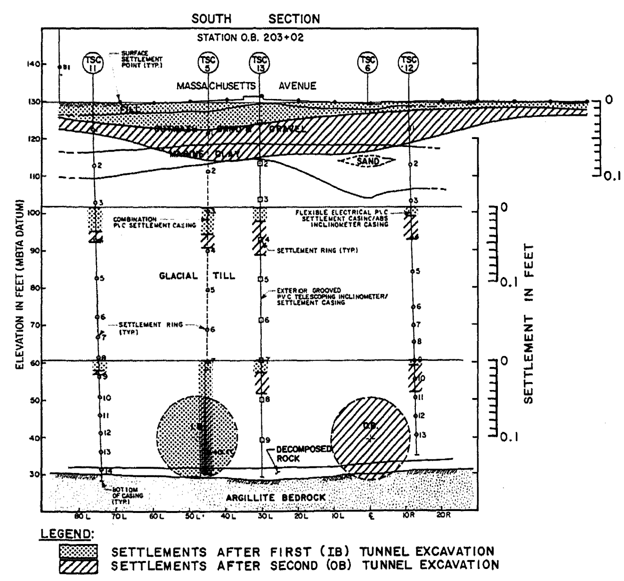

Figure 7. Profile of Settlements - Soft Ground Section

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Mixed Face Section - Middle

In the mixed face section, the ground movements were small as the inbound tunnel and outbound pilot drift, both in rock, passed from north to south in 1980. This is very similar to the behavior observed in the rock section. Ground surface settlements here remained small until the outbound tunnel passed the mixed face section at the end of November 1981. A total settlement of 0.075 feet (0.9 inch) was recorded on 8 January 1982, with three-fourths of it occurring as the outbound tunnel passed.

Summary of Settlements

Figure 8 presents contours of the total measured surface settlements due to the twin tunnel construction on a plan of the Test Section.

Horizontal Displacements

The measured horizontal displacements were very small. The maximum horizontal displacements accumulated at the ground surface were less than 1.5 inches. For example, Figure 9 shows selected inclinometer profiles at casing TSC 12.

The shape of these profiles clearly show that a zone of soil near the springline of the outbound tunnel experienced significant deformations as the tunnel passed on 16 October 1981. This zone extended to about 18 feet above the tunnel crown (El. 68) by 27 October 1981. These data indicate that for normal tunneling operations, with no large, sudden ground loss, the zone of greatest soil deformations extended no more than about one tunnel diameter above the tunnel crown. This is consistent with the data from the deep settlement points, Figure 7.

ANALYSIS OF PREDICTED AND MEASURED SETTLEMENTS

General

Detailed analysis of the settlements measured over the soft ground and mixed face tunnels are instructive, particularly regarding the geometry of the settlement troughs. These settlements will also be compared to the collection of case history data first published by Peck (1969) and later supplemented by Cording et al. (1976). Their procedure for estimating settlements first requires that an estimate be made of the volume of ground lost at the tunnel, V_L. The volume of the settlement trough at the surface, V_S, is usually less than the volume of ground loss at the tunnel. This is due to volume expansion of dense granular soils over the tunnel crown during construction.

Predictions of ground surface settlements due to tunneling through the Test Section were made before any major tunneling work had yet passed through the Test Section. For the

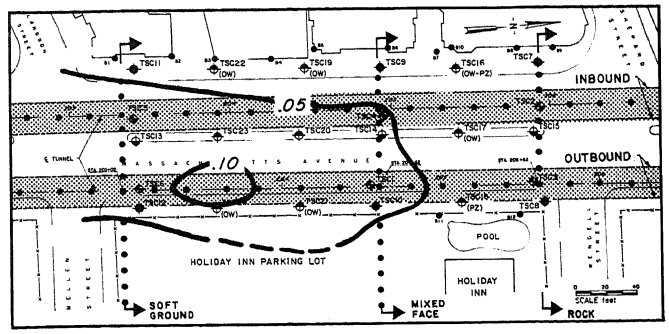

Figure 8. Summary of Surface Settlements Observed During Study

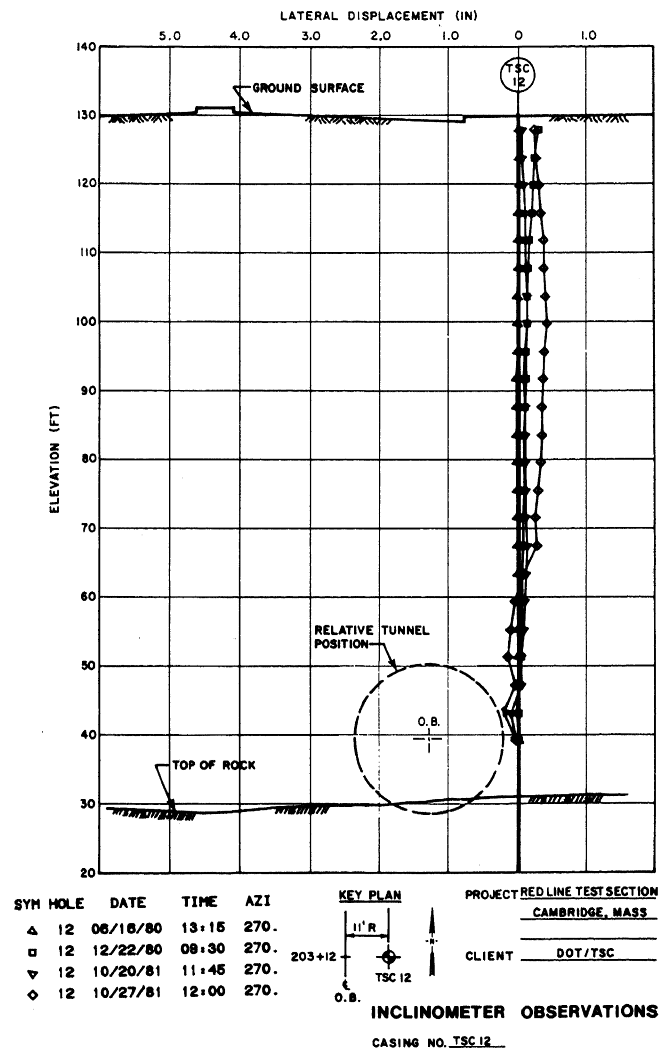

Figure 9. Selected Inclinometer Observations - TSC 12

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passage of a single soft ground tunnel, V_L was estimated to be two percent and the corresponding volume of the surface settlement trough, V_S, 0.8 percent, based upon the case history studies by Cording et al. (1976).

For the twin soft ground tunnels, the additional volume of the settlement trough due to interference between the two tunnels was estimated to be 0.4 percent, giving a total V_S of two percent.

Soft Ground - Single Tunnel

Figure 10 shows the settlement trough at the soft ground section after the first (inbound) tunnel was excavated. Since the settlements were small, the data points indicate some scatter due to survey error.

The measured volume, V_s, of 0.76 percent shows excellent agreement with the predicted value of 0.80 percent. A triangle of trough width, W, equal to 92.2 feet provides a reasonable approximation to the shape of the settlement trough. This corresponds to an i/R (normalized trough width) of 3.1.

Direct application of the Peck/Cording relations, using i/R of 1.5, computes a settlement trough that is much narrower and a maximum settlement that is much greater than measured values.

Soft Ground - Twin Tunnels

Figure 11 shows the total surface settlements at the soft ground section after both the inbound and outbound tunnels were excavated. The settlement volumes corresponding to single tunnel excavations (V_1, Figure 10, and V_2, assumed equal to V_1) and the interference volume (ΔV_S), are also shown. This trough is non-symmetrical and shifted toward the first tunnel, due to the effects of interference between the two tunnels.

The measured total settlement volume, V_S, of 1.92 percent shows excellent agreement with the predicted value of 2.0 percent. However, the measured settlement trough is wider (i/R = 2.8) than would be inferred from the Peck/Cording relationships.

This is shown more clearly on Figure 12. The idealized triangle with i/R of 1.5, corresponding to a direct application of the Cording et al. (1976) relationships, computes a settlement trough that is much narrower, and a maximum settlement that is much greater than measured values.

Mixed Face - Single Tunnel

Figure 13 shows the surface settlements after the first (inbound) tunnel had passed the mixed face section. Here, all but a small part of the inbound tunnel crown was in rock and the tunnel was excavated as a full face, using rock tunneling drill-and-blast procedures. The measured settlements are slightly greater than the settlements measured at the rock section after both tunnels had passed.

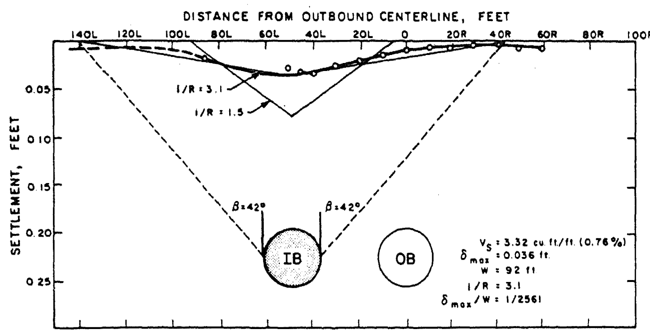

Figure 10. Surface Settlement After Inbound Tunnel Excavation - Soft Ground Section

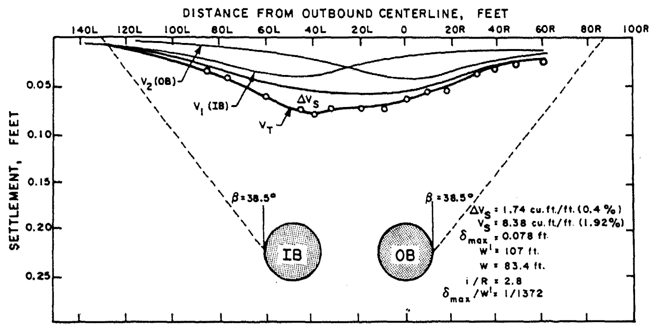

Figure 11. Total Surface Settlement After Inbound and Outbound Tunnel Excavations - Soft Ground Section

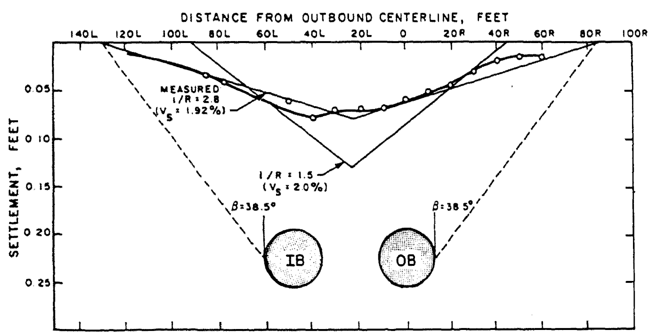

Figure 12. Comparison of Total Surface Settlement Trough with Triangles of Different i/R Values

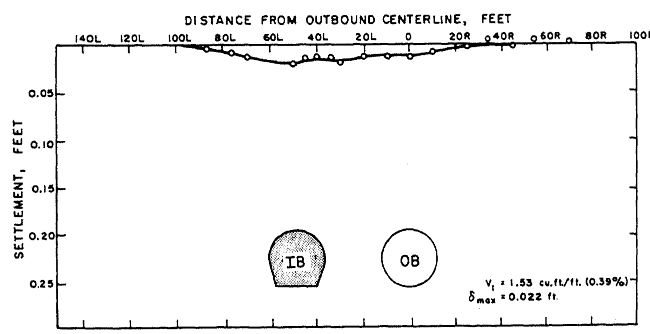

Figure 13. Surface Settlement after Inbound Tunnel Excavation - Mixed Face Section

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These settlements, Figure 13, are about half the corresponding values for the single tunnel in soft ground, Figure 10. This is indicative of reduced compression in the rock outside of the springline of the tunnel, relative to the tunnel in soft ground.

Mixed Face - Twin Tunnels

Figure 14 shows the incremental surface settlement after the second (outbound) tunnel passed the middle section. This tunnel had more of its cross section in soft ground and except for a 10-foot by 10-foot invert pilot drift, was excavated using soft ground shield tunneling procedures.

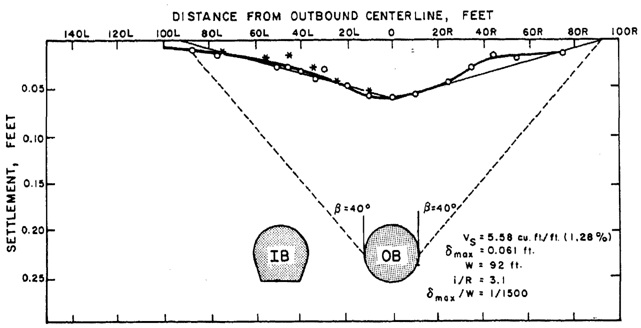

Figure 14. Incremental Surface Settlement After Outbound Tunnel Excavation - Mixed Face Section

The settlement trough is quite symmetrical about the outbound tunnel centerline, as shown by the asterisks, which are the mirror images of settlement data from the right of the tunnel. This symmetry indicates that the interference volume is small. Thus, additional compression of the lining of the first (inbound) tunnel mostly in rock, and compression of the rock pillar between the tunnels must have been small.

On the other hand, the settlement volume, V_S, of 1.28 percent is considerably larger than the settlement volume for the single tunnel in soil, 0.76 percent, Figure 10. This may be reflective of the more difficult construction environment and some major ground losses. Also, the till overlying the second (outbound) tunnel may have been somewhat disturbed by the excavation of the first (inbound) tunnel, even though there was no large interference volume evident here. This would reduce the ability of the till to expand and arch over the outbound tunnel opening, resulting in greater ground losses.

The width of the settlement trough for the mixed face outbound tunnel is almost identical to the geometry for a single tunnel in soft ground. This is shown by the comparison of the normalized trough width, Figure 14, with the corresponding value for the soft ground tunnel, Figure 10.

Summary

Figure 15 plots the i/R values measured at the Test Section on the relationships between tunnel depth and size to settlement trough width for various subsurface conditions published by Peck (1969) and Cording et al. (1976). The three plotted points represent the soft ground section single and twin tunnels, and the mixed face section outbound tunnel treated as a single tunnel. The three points are very consistent with one another, showing i/R values from 2.8 to 3.1.

Although these tunnels were excavated in the glacial till above the groundwater level (dewatered), and the soil profile is predominantly granular, the measured values plot in the region for tunnels excavated in soft to stiff clays. This may be because for small settlements such as these, the soil deformations are elastic rather than plastic, and hence a wider trough develops. The identical observation was made by Cording et al. (1976) in their studies of the Washington, DC Metro, Section F2a, also plotted on Figure 15.

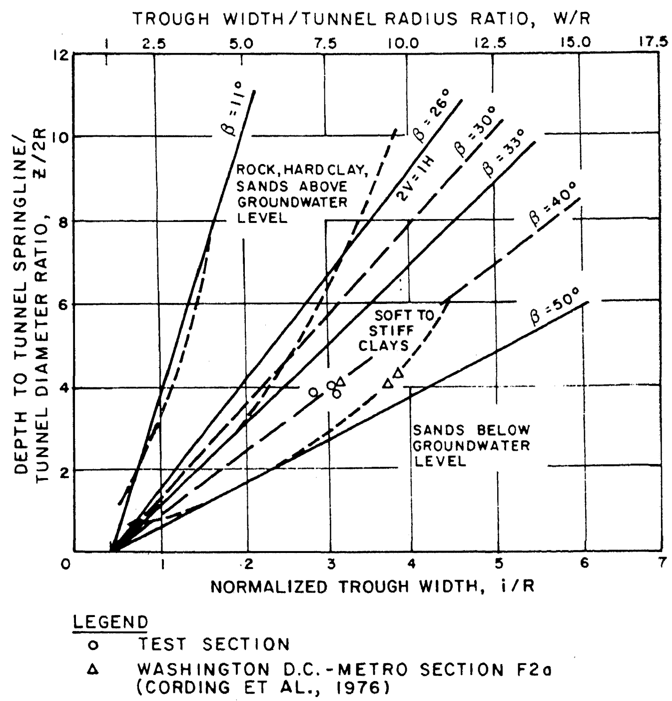

Figure 15. Width of Settlement Troughs, Test Section

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CONCLUSIONS

1. The location of the Test Section in an area of such a high degree of geologic variability provided a unique opportunity to monitor and compare ground movements due to different subsurface conditions (rock, soft ground and mixed face) and construction procedures.

2. In general, ground movements at the Test Section were small, in many cases approaching the limits of accuracy of the instrumentation.

3. At the Test Section, data from the deep settlement points and inclinometers show that large losses of soft ground at the tunnel heading propagated no more than 1 or 2 tunnel diameters from the heading (Figures 7 and 9).

4. Detailed comparison of the measured settlement volumes in soft ground with values predicted from the Peck (1969) and Cording et al. (1976) collections of case history data indicated excellent agreement. However, the settlement troughs were much wider than would be inferred from the relationships published by Cording et al. (1976), Figure 15. This may be because for small settlements such as these, the soil deformations are elastic rather than plastic, and hence a wider trough develops.

5. The surface settlements at the mixed face section show some interesting effects of mixed face conditions. The first tunnel (inbound) excavation mostly in rock, caused slightly greater surface settlements than were observed at the section in rock, indicative of greater ground losses due to soil disturbance. The second (outbound) tunnel had more of its cross section in the soft ground and caused a settlement trough with a greater volume (V_S = 1.28 percent) than was measured for the single tunnel in soft ground (V_S = 0.76 percent), Figure 10. This may be reflective of the more difficult construction environment under mixed face conditions. However, the settlement trough in the mixed face section caused by excavation of the second (outbound) tunnel was quite symmetrical about the tunnel. This indicates that there was little, if any, interference between the first (inbound) and second (outbound) tunnels at this section.

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