Ground settlement in shield tunnelling through soft clay

Tassement de terre dans l'exécution des souterrains à l'aide d'un bouclier au travers d'argile tendre

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SYNOPSIS

The paper presents the observations of ground settlement in shield tunnelling work for Calcutta Metro construction. A pair of tunnels, each 5.1 m diameter and spaced 11 m c/c with their crown depth 10-11 m below ground level, are advanced through the soft to medium silty clay of the Normal Calcutta Deposit. Compressed air has been used to increase the stability of construction. Because of the phase difference in the progress of the two tunnels it has been possible to separate the effect of the two tunnels on ground settlement. The various factors that influence the ground settlement and its distribution have been studied. The beneficial effects of the shield and compressed air in reducing ground loss are highlighted.

INTRODUCTION

The first rapid transit line for Calcutta is under construction along the major north-south corridor of the city from Dum Dum to Tollygung. This has a total length of 16.43 Km and is served from 17 stations. The line will be underground for most parts, except for two stretches near Dum Dum and Tollygung. Most of the underground sections are constructed by the 'Cut-and-Cover' method while a small length of about 1 Km is done by Shield tunnelling.

Ground settlement is a major consequence of any excavation/tunnelling work and its control necessarily becomes one of the most important objectives of the construction methodology to be adopted at site. Tunnelling in soft ground inevitably leads to movement of the soil above the tunnel section and any structure lying within the zone of influence is likely to be affected. Both the magnitude of settlement and the zone of influence are important in determining the likely effect on overlying structures.

Measurement of ground settlement have been made at a number of locations along the tunnelling stretches to ascertain the pattern of settlement above the tunnel section. This paper deals with the observations of ground settlement at five such locations. The measurements were taken for different positions of the tunnel face with respect to the observation point and the data have enabled a preliminary study of the effects of various factors on the pattern of ground settlement in shield tunnelling through Calcutta Soil.

TUNNEL ALIGNMENT AND TEST SECTIONS

Fig. 1 shows the complete Metro alignment from Dum Dum to Tollygung and Fig. 2 shows part alignment of shield tunnelling work in the northern section of the Metro. The work extends from Belgachia to Shyambazar and covers a total length of about 1100 metres. The alignment has to pass underneath a heavily built-up area and a busy canal where 'Cut-and-Cover' method - adopted for rest of the Metro alignment has not been found suitable. A pair of tunnels, each 5.1 m diameter and spaced 11 m c/c with their crown depth 10-11 metres below G.L. are being constructed by the 'Shield' tunnelling technique. The first phase of the shield tunnelling work - from the west of

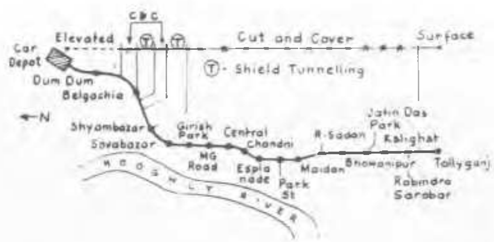

Fig. 1 Calcutta Metro Alignment

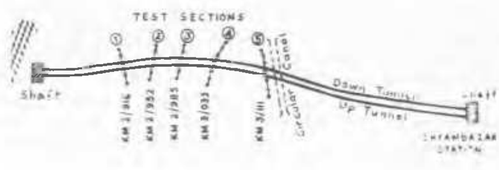

Fig. 2 Shield Tunnelling Work and Test Sections

Chitpur Yard to Shyambazar station - has been in progress since 1980. The Down tunnel was taken up for construction first and the Up tunnel has followed with a lag of 100 metres. By May 1984 the Down Tunnel has covered a length of 498 metres and the Up tunnel a length of 387 metres. Ground settlements have so far been observed at five sections across the tunnel alignment. They are indicated as sections 1,2,3,4 and 5 in Fig.2. There was a heavy concentration of buildings above the tunnel alignment and the test sections had to be so chosen as to coincide with a cross road which was not necessarily perpendicular to the alignment.

SUBSOIL CONDITION AT TEST SECTIONS

Fig. 3 shows the subsoil stratification at test section 1. The relevant engineering properties of the different strata are also indicated in Fig. 3. The subsoil consists generally of silty clay/clayey silt formations of the Normal Calcutta Deposit overlying Dense sand approximately 16-20 metres below Ground Level. The location of the tunnels with reference to the ground surface shows that the tunnels pass mainly through Stratum III and partly through Stratum II of the Normal Calcutta Deposit. These strata consist generally of soft to firm grey/bluish grey silty clay with undrained shear strength of about 2.0 t/m^2 in stratum II and 4 t/m^2 in stratum III.

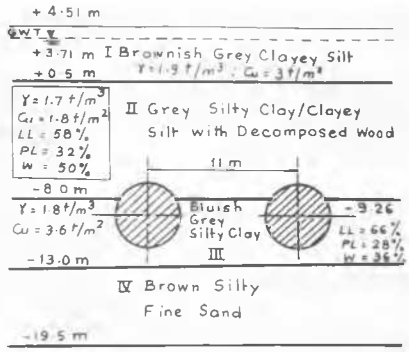

Fig. 3 Subsoil Stratification

CONSTRUCTION PROCEDURE

The shield tunnelling is done by a hollow steel cylindrical shield propelled by 19 nos 100 tonne capacity hydraulic jacks fixed along the periphery of the shield. The jacks react against the already erected cast iron/RCC linings at the rear. To keep the cutting face stable and to keep the ground water out of the working area compressed air of 1 atm gauge pressure was used. A complete cycle of tunnelling operation involves excavation of the earth for one lining ring in segments, advancing the shield by the same amount, erecting the lining ring in position, grouting the erected lining and caulking the joints of the lining. The interspace between the lining and the bore made by the shield is grouted with cement-sand (1:3) grout at 5 atm pressure immediately after erection. The final neat cement grouting at 8-10 atm pressure is done after a fortnight of the erection of linings.

MEASUREMENT OF GROUND SETTLEMENT

Settlement of the ground has been measured at each test section generally on a line extending in the north-south direction on either side of the tunnel alignment. A reference datum was established at least 60 m away from the alignment and a number of settlement points were established on the measuring section. Each settlement point consisted of a steel rod embedded about 1 m below the ground in a pit which was kept covered by a concrete slab. At the time of taking readings the concrete slab was removed and one end of the levelling staff was held on the steel rod. The levels of the settlement point with respect to the reference datum was taken on different dates and the difference in level between any two dates gave the relative movement of the point between these dates.

RESULTS OF OBSERVATION

The ground settlement profiles on different dates were plotted for each test section to follow the settlement data with progress of tunnelling. The typical data for Test section 4 are shown in Fig. 4. The positions of the two tunnels with reference to the test section are shown in tabular form alongside Fig. 4. Because of the phase difference of more than 100 metres between the first (Down) and second (Up) tunnels it has been possible to separate the effect of two tunnels on the settlement profile. The solid curves in Fig. 5 give the maximum settlement profile for the first tunnel and for the combined effect of the two tunnels for Test Section 4. Similar settlement troughs for individual and combined effect have been obtained for the other test sections.

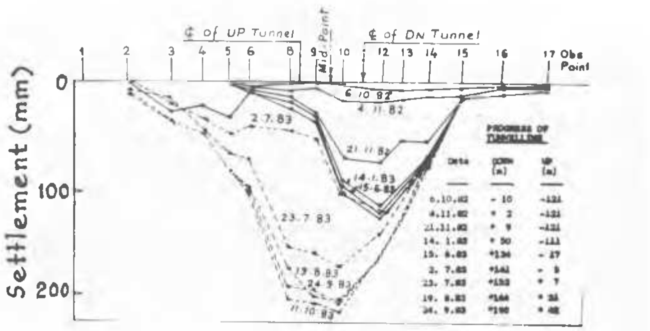

Fig. 4 Settlement Profile on Different Dates

MAXIMUM GROUND SETTLEMENT

The maximum settlement for each test section is summarised in Table I. The maximum settlement (max) for the Down Tunnel varies between 40 mm and 125 mm (average 80 mm) and for the combined effect between 140 mm and 250 mm (average 195 mm). The position of the maximum settlement does not, however, remain the same in two cases. In general, the maximum settlement occurs more or less above the tunnel centre for the single tunnel and above the mid-point between the two tunnels for the combined effect. Also, the maximum settlement due to the 2nd tunnel has been 60-70% more than the maximum settlement due to the first tunnel. This is only to be expected because the soil has already undergone some strain due to the first tunnel and the settlement due to the second tunnel is the result of addition strain on the soil.

ZONE OF INFLUENCE

The zone of influence on either side of a tunnel can be ascertained from the settlement profiles for each test section. The data are summarised in Table II which gives the length of influence zone on either side of the Tunnel axis (for single tunnel) and the mid-point between the tunnel centres (for the combined effect). The average length of influence zone works out to

Table I : Maximum Settlement Data

Section	Maximum Settlement			Ratio
	Dn Tunnel (S_1) mm	Combined effect (S_2) mm	(S_2-S_1) (mm)	$\frac{S_2-S_1}{S_1}$
1	65	150	85	1.30
2	60	195	135	2.25
3	110	250	140	1.30
4	125	240	115	0.90
5	40	140	100	2.50
Average	80	195	115	1.65

16.2 m and 22.2 m respectively. These values compare well with the approximate values of 18.7 m and 21.7 m which are obtained by drawing 45° lines from the edges of the tunnel/tunnels upto the ground surface.

Table II : Zone of Influence

Test Section	Down tunnel		Combined Dn & Up tunnel	
	North (m)	South (m)	North (m)	South (m)
1	16	16	20.5	21.0
2	15	15	21.5	21.0
3	15	19	19.5	24.5
4	18	17	29.0	22.0
5	15	16	14.0	23.0
Average	16.2		22.2	

GROUND SETTLEMENT PROFILE

The ground settlement profile for the single tunnel as well as for the combined effect of two tunnels indicate similar pattern of settlement distribution along a given cross-section. Peck (1969) has proposed that the settlement trough for a single tunnel can be represented with reasonable accuracy by an error function distribution. Calculations have been made to determine the settlement trough at each test section by fitting an error function at the maximum settlement, max. The data for test section 4 are plotted in Fig. 5. For the purpose of calculation the origin of co-ordinates has been taken at the point of maximum settlement on the observed settlement profile. It can be seen that correlation between the observed curve and the theoretically predicted curve is extremely good.

The same procedure has been adopted to predict the settlement trough for the combined effect of Down and Up tunnels. Two methods of calculation have been adopted. The two tunnels have been represented by a single tunnel of effective diameter 11 m (i.e. the distance between the two tunnel centres) in method 1. In method 2, the effective tunnel diameter has been taken as the diameter that gives the combined area of the two tunnels. The results are plotted in Fig. 5 (lower curves). No major difference is noticed for the two methods of calculation. Although the correlation between the theoretical and observed data are, not as good as the single tunnel the basic pattern of settlement can still be established by an error function for an effective tunnel diameter.

DEVELOPMENT OF SETTLEMENT WITH PROGRESS OF TUNNELLING

In order to study how the ground settlement with progress of tunnelling the settlement data for each test section has been examined against the position of tunnel shield. The settlement data for a typical point on Test Section 4, Fig. 6, shows that the settlement begins to occur when the Down Tunnel is still a few metres away from the test section. The settlement continues to increase almost linearly until the shield has moved 20-30 metres ahead of the section. Thereafter the settlement ceases to increase until the Up tunnel comes to within 10-15 metres of the test section. The effect of Up tunnel is then felt and the settlement continues to occur until the Up tunnel has moved ahead of the test section by about 20 metres. Similar pattern of settlement behaviour is observed for all the test sections. On average, the settlement appears to occur for the movement of the tunnel shield from -10 m to +30 m, +0 being considered on the test section itself.

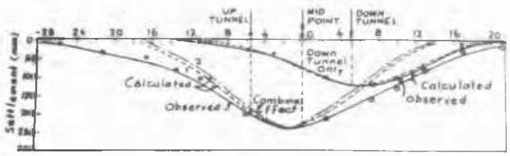

Fig. 5 Maximum Ground Settlement Profile

RATE OF TUNNELLING

The rate of tunnelling in the vicinity of each test section has been worked out for both Down and Up tunnel. On average the Down tunnel has required 1.89 days per metre of tunnelling while the Up tunnel has progressed somewhat slower at a rate of 2.22 days per metre. No significant effect of the rate could, however, be noticed on the magnitude of ground settlement.

VOLUME OF LOST GROUND

The observed settlement profile at each test section enables one to calculate the volume of lost ground at the respective test section.

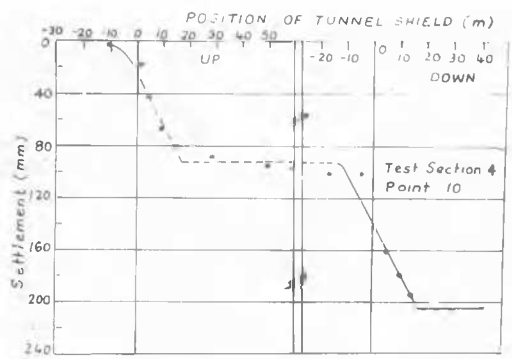

Fig. 6 Ground Settlement and Progress of Tunnelling

Table III gives the volume of lost ground as a percentage of the tunnel volume. For combined effect the tunnel volume has been taken as the sum of the individual tunnel volumes. It can be seen that the average volume of the observed settlement trough works out to 5% of the tunnel volume (for single tunnel) and 7.73% of the two tunnel volumes (for double tunnel). The measured values compare well with the volume of the theoretically calculated settlement trough obtained by error function fitting described earlier.

GROUND LOSS AND STABILITY-FACTOR

The stability factor, defined as $N_c = \frac{p_o}{C_u}$ where p_o is the vertical overburden pressure at the level of tunnel centre and C_u is the undrained shear strength of the clay has been used by Cough and Schmidt (1981) to ascertain the potential ground loss of an unlined tunnel in soft clay. A simplified theoretical analysis has been made to estimate the volume of lost ground by summing up the displacements around the periphery of the tunnel resulting from removal of in-situ stresses. For Nc values greater than 1 the volume of lost ground is given by

$$\frac{\Delta V}{Vo} = 0.003\ e^{\left(\frac{p_o}{C_u} - 1\right)} \quad \ldots \quad (1)$$

The N_c values for the five test sections, with and without air pressure, are shown in Table III. For the purpose of calculation Cu has been taken as the average shear strength of the clay between the top and bottom of the tunnel. It will be seen that the average N_c value without compressed air is as high as 9.10. This value is likely to be higher if the building surcharge on the ground is taken into account. This would lead to excessive ground settlement and an unstable face and would require full face support for stability (Schmidt and Clough 1981). This face support is provided by the tunnel shield and compressed air. For the present problem compressed air of 1 atmosphere has been used. This reduces the stability factor to 5.35. The theoretical ground loss then works out, by Eqn.1, to 23%. A comparison of this theoretical ground loss to the observed values (5% for single tunnel and 7.73% for two tunnels) shows that the actual volume of loss ground has been considerably less than that predicted by Eqn. 2. This may be considered to be the effect of the tunnel lining and the tunnel shields which reduces ground settlement substantially.

Table III : Stability Factors at Different Test Section

Section	Average $Cu(t/m^2)$	Depth to centre of tunnel Z(m)	Stability Factor: With no Air pressure	Stability Factor: With Air pressure 1 Kg/Cm^2
1	2.70	13.77	8.7	5.01
2	2.46	13.16	9.8	5.72
3	3.20	13.49	4.55	4.41
4	2.40	13 55	10.00	5.87
5	2.50	14.13	9.70	5.72
Average	2.65	13.62	9.10	5.35

CONCLUSIONS

Shield tunnelling through soft to medium clay leads to appreciable settlement of the ground surface. When two tunnels are made side by side with aphase difference between them the settlement due to the second tunnel may be higher than that due to the first tunnel. Ground settlement at a section begins to occur when the tunnel shield is still 10-12 metres away and it continues till the shield has moved about 25-30 metres ahead of the section. The settlement profile is predicted well by error function fitting. The shield and compressed air appear to be quite effective in reducing the ground settlement due to tunnelling.

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