SURFACE SETTLEMENTS DUE TO SHIELD TUNNELLING IN ROME

AFFAISSEMENTS DE SURFACE DUS AU CREUSEMENT DE TUNNELS A ROME PAR UN TUNNELIER

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Summary

Extensive field observations have been made of ground settlements associated with driving twin tunnels through a variety of soil types. Analysis of data shows that values of ground settlements are directly related to the size and depth of tunnels, to the soil characteristics, and to timing of grouting operations behind the lining.

Résumé

Beaucoup d'observations in situ ont été faites d'affaissements du sol liés au creusement de deux tunnels jumelés dans des sols de types variés. L'analyse de ces observations montre que les valeurs des affaissements sont directement liées à la taille et à la profondeur des tunnels, aux caractéristiques des sols et aux délais des injections derrière le revêtement.

The present paper describes the results of extensive field observations carried out in connection with the shield tunneling excavation of a pair of parallel tunnels which are part of the subway system under construction in Rome. A section of the tunnels which passes under the downtown area of Rome has been kept under observation during the construction period. A series of measurements were carried out on an established network of markers located at the ground surface above the tunnels. The data obtained were analyzed in detail and a reasonable interpretation of the results is offered together with the results of non-linear finite element analysis of the behaviour of the tunnels.

Two major formations are present in the area affected by the tunnel excavations. The older Pliocene formation consists of layered overconsolidated clay with some thin sandy lenses. The more recent formation, deposited during the Pleistocene, consists mainly of alluvial soils and lacustrine deposits. Over these, there are in some places volcanic deposits and fill material.

A vertical profile of the soils surrounding part of the tunnel section under study is shown in Figure 1. The tunnels were excavated in the more recent formation and more precisely, in varved clays of lacustrine origin, for the first 500 m, then for a short length the excavation was carried out in alluvial soil. The rest of the tunnel runs through the overconsolidated clay of the older formation.

The depth of the tunnels varies between 25 and 50 m (see Table 1). The whole length of the tunnels under observation was excavated using a specially designed mechanized shield. For the various stations traditional methods were used. The tunnel diameter is 6.00 m and the station diameter is 8.00 m. The second tunnel was excavated after the first one had been completed. The distance between the centres of the tunnels is about 20 m. The lining consists of rings made of five prestressed, precast, reinforced concrete elements connected by two semicircular iron bars. The concrete elements were placed around the opening immediately at the back of the advancing shield and grout was injected at low pressure between the lining and the soil in order to fill the clearance between them. Later, a second round of grouting was injected at higher pressure. The inner diameter of the lined tunnels is 5.50 m.

In order to analyze the ground settlements distribution, a model is needed for the mechanism of deformation of the excavation opening.

The scheme suggested by Lombardi (1973, 1975) which takes into consideration the 3-dimensional nature of the problem and the interaction between soil and lining has been adopted.

Figure 2 shows a vertical section through the axis of the tunnel,
### Cross Section

<table>
<thead>
<tr>
<th>SITE</th>
<th>Advance ment (m)</th>
<th>Height asl (m)</th>
<th>Overburden (m)</th>
<th>Distance from closest station (m)</th>
<th>Soil excavated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Via Torino</td>
<td>465</td>
<td>52.8</td>
<td>28.4</td>
<td>80</td>
<td>Silty varved clay</td>
</tr>
<tr>
<td>2 Via Torino-Via Firenze</td>
<td>520</td>
<td>52.5</td>
<td>29.0</td>
<td>134</td>
<td>&quot;</td>
</tr>
<tr>
<td>3 Ministry of Defense (corner of V.XX Settembre)</td>
<td>695</td>
<td>55.0</td>
<td>38.0</td>
<td>288</td>
<td>&quot;</td>
</tr>
<tr>
<td>4 Barberini Cinema</td>
<td>966</td>
<td>34.3</td>
<td>24.0</td>
<td>27</td>
<td>Silt with Pliocene gravel-clay pocket</td>
</tr>
<tr>
<td>5 Via Liguria Hotel Majestic</td>
<td>1234</td>
<td>52.0</td>
<td>41.5</td>
<td>124</td>
<td>Pliocene clay</td>
</tr>
<tr>
<td>6 S. Isidoro</td>
<td>1279</td>
<td>54.0</td>
<td>43.0</td>
<td>124</td>
<td>&quot;</td>
</tr>
<tr>
<td>7 Ist. Sacro Cuore</td>
<td>1560</td>
<td>59.0</td>
<td>47.5</td>
<td>53 1st T 30 2nd T</td>
<td>&quot;</td>
</tr>
<tr>
<td>8 Villa Medici</td>
<td>1710</td>
<td>57.5</td>
<td>45.0</td>
<td>184</td>
<td>&quot;</td>
</tr>
<tr>
<td>9 Muro Torto Wall (upper part)</td>
<td>2268</td>
<td>50.5</td>
<td>35.0</td>
<td>47 1st T 37 2nd T</td>
<td>Sand - Pliocene clay - alluvium</td>
</tr>
</tbody>
</table>

Tab. 1

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Fig. 2: Radial stresses and deformations near the tunnel face including its face located at B. At certain distances from the face, points A and C, the state of stress and strain can be considered 2-dimensional, but from A to C stresses and deformations can correctly be determined only by using a 3-dimensional analysis. The distance between A and C determines the zone of influence of the tunnel face. In this zone, both radial displacements $\delta_r$ and radial stresses $\sigma_r$ vary.

Fig. 3: Radial displacements vs. radial stresses around the opening considering the effect of lining

Figure 3 shows a qualitative diagram $\delta_r$ vs. $\sigma_r$ at section A, as the face of an unlined tunnel advances toward A. At the beginning an elastic behaviour can be assumed for the soil and $\delta_r$ increases linearly as $\sigma_r$ decreases. As the tunnel face gets very close to A and eventually passes over A, the behaviour of the soil is no longer linear and $\delta_r$ increases at a higher rate reaching its final value if the opening undergoes no failure (curve 1). It increases indefinitely if failure conditions are reached (curve 1'). In the case of the presence of lining, the radial deformations of the soil (curve 1) are affected by the radial deformation of the lining (curves 2 and 2'). If the lining starts to work at $\delta_0$, the intersection of curves 1 and 2 at $P$, shows the conditions of equilibrium $\delta_1$ and $\sigma_1$, which will be reached around the tunnel. If the lining starts to work at $\delta_0$, the final conditions $\delta_2$ and $\sigma_2$ will be reached at $P_2$. It is evident, therefore, that in order to reduce radial displacements, the lining has to be constructed as close as possible to the advancing face and there should be no play between soil and lining.

In several vertical sections, perpendicular to the tunnel's axis, the ground settlements were kept under observation for the duration of the excavation work.

For each section, the settlements measured on the ground surface above the tunnel axis were plotted against time.

The most significant parameters are the settlements $\delta$ and $\delta'$ measured on the ground directly above the two tunnel axes, due to the excavation of the first tunnel; the corresponding settlements $\delta''$ and $\delta'''$ due to the excavation of the second tunnel and then, the total settlements. The lengths, AB and BC, which represent the distance within which the influence of the excavation face was felt in the tunnels were also obtained.

The total ground settlements measured range from 4.4 to 18.3 mm with an average value of about 10 mm above the first tunnel and a slightly larger value of about 12 mm above the second tunnel, but in few cases, above the stations, settlements of more than 110 mm were recorded.

Figure 4 shows the time-settlements curve for section 2. The solid line shows the settlements above the first tunnel; the dashed line above the second tunnel. The settlements start to increase a few days before the tunnel face reaches the section and last for a few days after the face has passed through.

Figure 5 shows the same curve for section 1. There the settlements due to the second tunnel, because of a 1-day delay in grouting, were larger than those due to the first tunnel.