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A.A.BALKEMA / ROTTERDAM / BOSTON

Settlement and face stability boring a large tunnel

Tassement et stabilité du front d'un grand tunnel

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SYNOPSIS Various computation methods were adopted to analyse the subsidence induced by the excavation of a large-diameter urban tunnel using a hydroshield machine. A comparison of these data with the deformations measured at the surface confirmed the validity of their distribution according to a normal probability curve. It was also possible to discriminate between the amount of deformation caused by the annular gap between soil and lining and the amount due to face yielding. A correlation was established between the latter and the stability factor of the tunnel face.

INTRODUCTION

The programme for the expansion of railway facilities in Rome also called for a double track tunnel excavated underneath a high-density area for an overall length of 1500 m crossing soils of different types such as Pliocene clays, sands and gravel below ground water (fig. 1).

The severe geotechnical problems caused by this latter fact and enhanced by the size of the excavation section (90 m^2)), were overcome by using a hydroshield machine capable of supporting the face by means of compressed bentonite slurry.

Taking into account the characteristics of the machine and the critical stages of construction, analyses were conducted of the equilibrium and deformation conditions at the contour or the excavation and at the surface by means of both simplified assumptions - that have led to approximated analytical solution - and of a finite element model which allowed for the dishomogeneity of the soils and for the geometric relationship between overburden and size of the excavation.

The excavation has a circular cross-section, its inner radius being 4.7 m, and was lined with precast elements having a thickness of 50 cm.

The excavation shield was 10.6 m in diameter, 9.0 m wide and the thrust device was capable of providing 6400 t overall and maximum advance of 1.25 m. The cover at the crown was 25-30 m with a minimum of 12 m at two morphologic incisions.

Throughout the implementation period a wide range of surface deformation measurements were taken during tunnelling, over a period of some months, and at the end of operations; this made it possible to compare design predictions with real behaviour of soils.

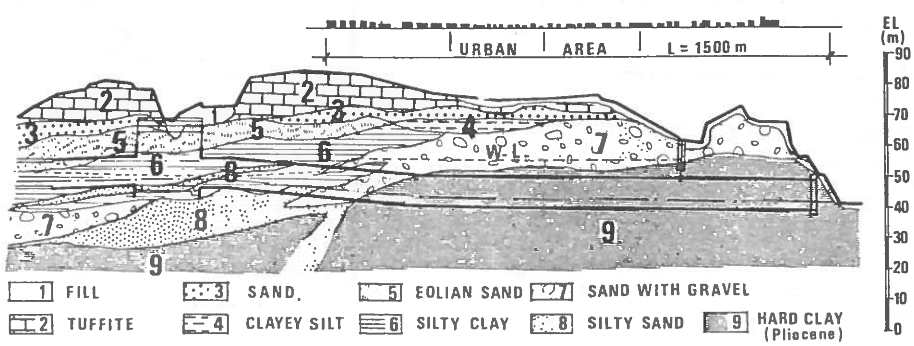


Fig. 1 - Soil profile

COMPARISON OF PREDICTED AND OBSERVED SETTLEMENTS

In tunnelling by means of shield machine highly critical conditions may be encountered when seeking to provide support for the surrounding soil. One is represented by the excavation face; another critical moment is when the support of the soil is transferred from the shield to the precast lining that has been set up from within.

In the latter situations the required space for setting up the lining and the thickness of the shield demand that the anular gap be immediately grouted. In any case surface settlements cannot be totally avoided as extensively shown in the technical literature.

The two effects were evaluated by means of simplifying hypotheses (an elasto-plastic homogeneous medium) considering respectively a semi-spherical and a cylindrical cavity. After determining and adding up the two deformation values, the deformed profiles of the soil surface were reconstructed by means of the empirical correlation proposed by Peck (1969). In Figs. 2_{a-c}, for comparison, the surface settlements measured at points having the same height of overburden, and of course similar stratigraphic layers, were plotted as against the calculated values. The figures also show the results obtained for the finite-element calculations carried out only for the case of the cylindrical cavity. In this case the design settlements, relating to the second critical situation, obviously proved to be slightly lower than the measured values.

The comparison with the values calculated by means of the simplified solutions show that there is considerable difference where the volume variations at the contour of the excavation are equalled to the volume corresponding to the normal probability curve ($Sc/S_{max} = 1$):

$$V = V_s = \pi D u_{ro} = \sqrt{2\pi}\, i\, S_{max}$$

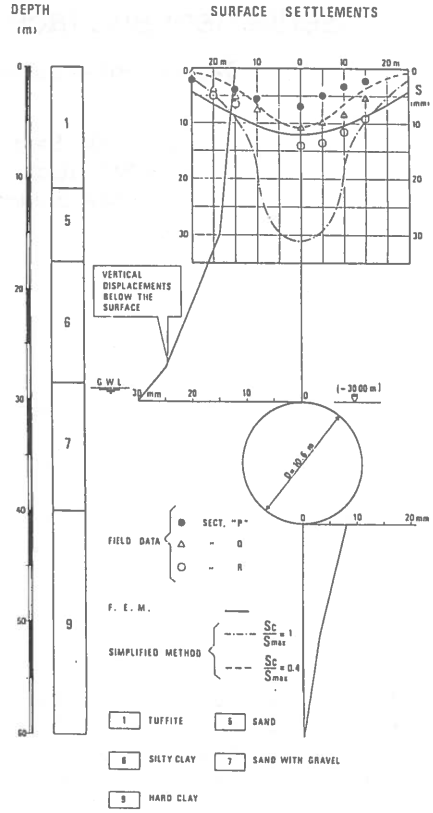
D = tunnel diameter

u_{ro} = theoretical radial soil displacements towards the tunnel

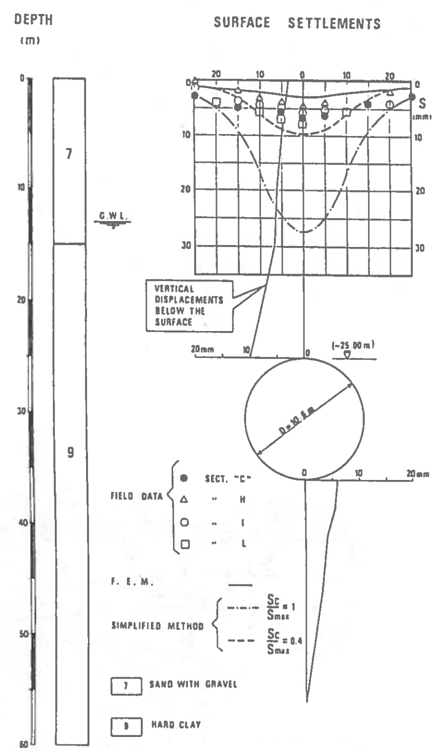
Sc = deformation at the crown

A better correspondence can be obtained if the Sc/S_{max} ratio is assumed to be appreciably lower than 1 as also confirmed by other Authors.

In this case a Sc/S_{max} ratio of about 0.3-0.4 appears to come very close to the measured deformations. This ratio can be also inferred from the numerical calculation.

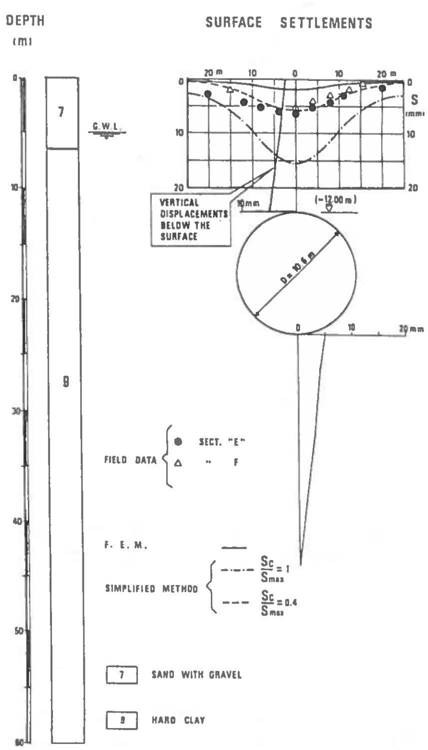


a)



b)

S_{max} = maximum surface deformation



c)

Fig. 2 - Predicted and observed settlements
a) - Cohesionless soil: Overburden 30 m
b) - Hard clay : " 25 m
c) - Hard clay : " 12 m

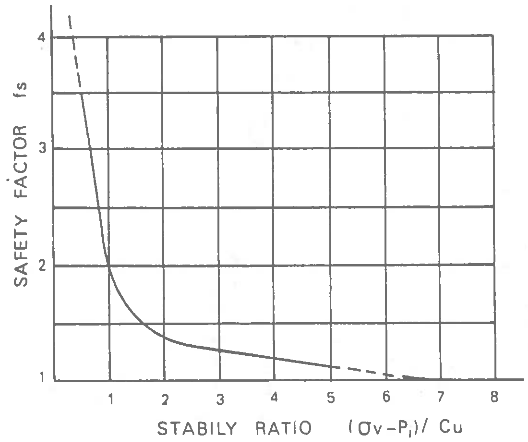


Fig. 3 - Relation between safety factor and stability ratio

FACE STABILITY AND GROUND SETTLEMENTS INDUCED BY FACE YIELDING

The analysis of the face stability conditions was carried out by calculating the boundary horizontal stress and by comparing them with the slurry pressure values (P_i) at 0.25 MPa tunnel axis. In the tunnel stretch where these were not applied (when crossing the Pliocene clays), the degree of stability was evaluated by means of an empirical factor N = $\sigma v/cu$ (Peck 1969) where P_i = 0. For sandy soils (sand and gravel below ground water) the boundary horizontal stress was calculated by taking into account the arching effects induced by soil settlements (Terzaghi 1943).

The set of measurements collected during construction allowed the stability coefficients (f) and relationships (N) to be correlated to the ground settlements due to face yielding.

The first step was to standardize the safety factor and the stability ratio that are very different conceptually. The relationship between the two coefficients (Romo and Diaz, 1981) is shown in Fig. 3.

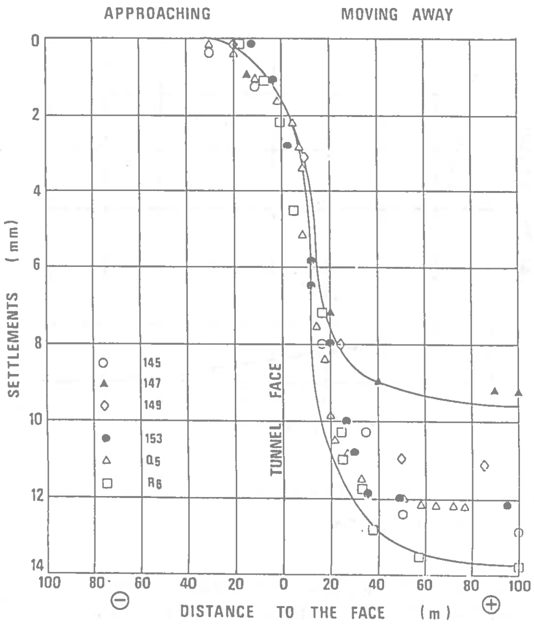
Next, the influence of face yielding on the overall settlements was evaluated and then a relationship between settlements during tunnelling and stability conditions was found.

Given the specific features of the machine and the critical construction stages, two distinct settlement steps can be identified. The sketches in Fig. 4_{a-c} show - for homogeneous groups of control sections - the settlements measured as the hydroshield advances.

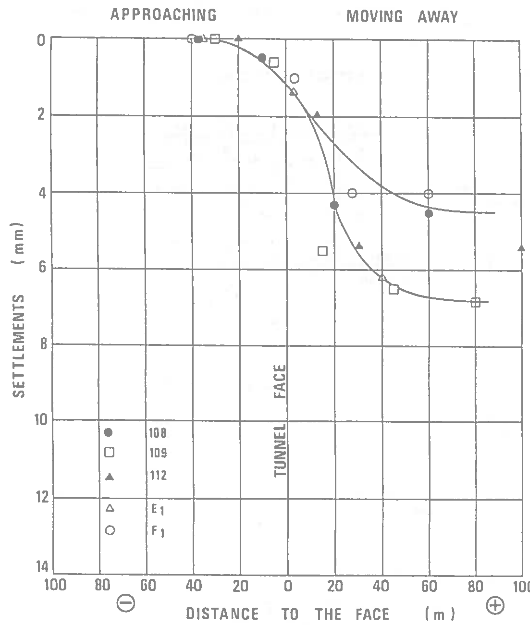
It can be noticed that until the shield does not exceed the plane of the measurement station, surface settlements fall within a small field of variables. On the contrary scattering increases decidedly in the presence of the anular space behind the shield. This may be taken mostly as being due to inevitable delays or difficulties in grouting. In this way it is possible to identify the disturbance induced by the excavation face. Indeed, after an initial horizontal movement along the tunnelling plane, the soil tends to shrink in order to fill the space between the excavated portion and the lining. This movement probably occurs also behind the shield owing to inevitable disturbances in the soil around the contour of the excavation.

Following the above-mentioned criterion, namely by assuming the face settlements equal to the measured value up to the withdrawal of the shield, a correlation was worked out between the latter and the safety factors either computed or inferred indirectly (Fig. 3) by means of the stability ratio.

Fig. 5 shows the trend of this correlation. As can be noticed, in the presence of cohesionless



a)



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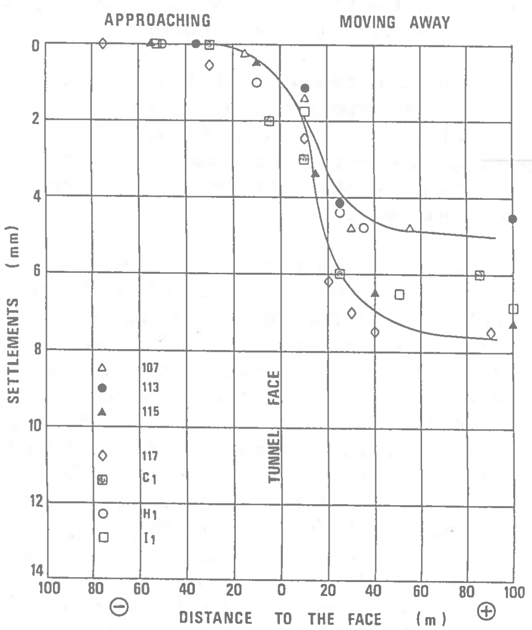


b)

Fig. 4 - Observed surface settlements during tunnelling
a) - Cohesionless soil: Overburden 30 m
b) - Hard clay : " 25 m
c) - Hard clay : " 12 m

soils, where the internal slurry pressure is equal to 0.25 MPa, or of the Pliocene formation where internal pressure is nought, an exponential function is the one that comes closest to the field data. Given f = 1, ground settlements are slightly lower than 1 cm, which according to the present stratigraphic pattern and overburden corresponds to 25-30% of the overall deformation.

RE-ESTABLISHING THE STATE OF STRESS

Another series of information that can be inferred from surface settlement measurements involve the restoring of the stress released upon opening the tunnel.

Figs. 6_{a-c} show space-time ratios of deformations at lining contour induced by the anular gap. The figures refer to the three typical stratigraphic situations mentioned earlier.

As can be seen the state of stress is restored at about 20-25 m from the tail of the shield, that is at a distance corresponding to 2-2.5 times the tunnel diameter. Considering the average tunnelling rate, this condition was reached after 8-12 days independently from the absolute value of the measured deformation. It can be inferred that the disturbance of the state of stress can be noticed at the same distance from the excavation plane on either side.

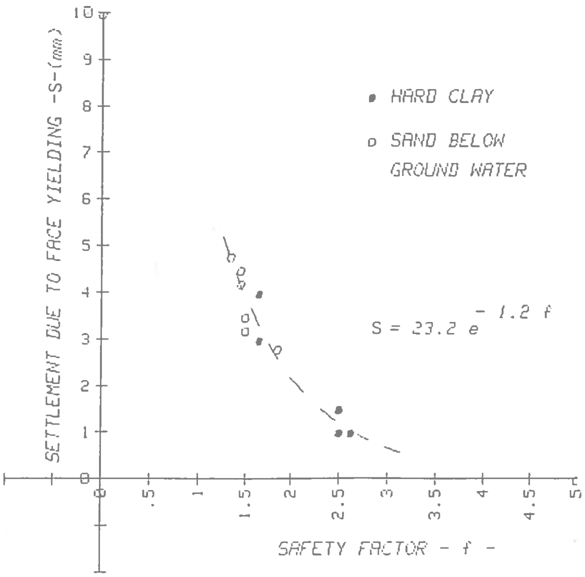


Fig. 5 - Safety factor of the tunnel face vs ground settlements

CONCLUSIONS

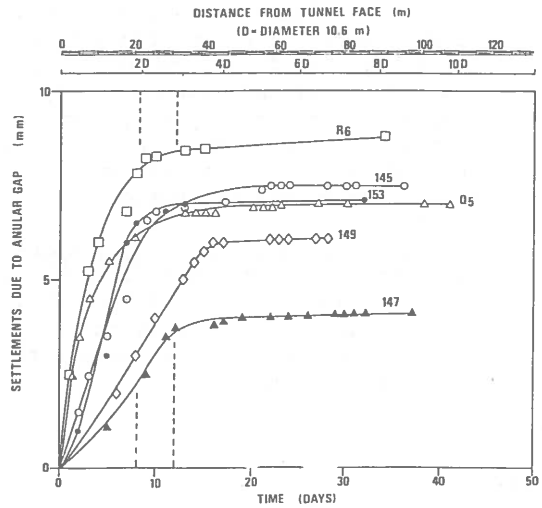
The critical analysis of the data collected and the comparison made with the design predictions for a large-diameter tunnel (D = 10.6 m) excavated with a bentonite shield in fine cohesionless soils of various types, has led to the definition of some general criteria about the behaviour of soils:

- The trend of the normal probability curve of surface settlements was confirmed. The characteristic of the curve "i" maintains the same relationship with the depth of the tunnel z [i/d = f (z/D)] .

- Maximum surface settlement was equal to 30-40% of the settlement calculated for the contour of the excavation.

- Ratio between volume (per linear metre) of surface deformation (V_S) and area of excavation section is equal to 0.2-0.4%.

- Face yielding accounted generally for 25-30%, and exceptionally 50%, of overall surface deformations.



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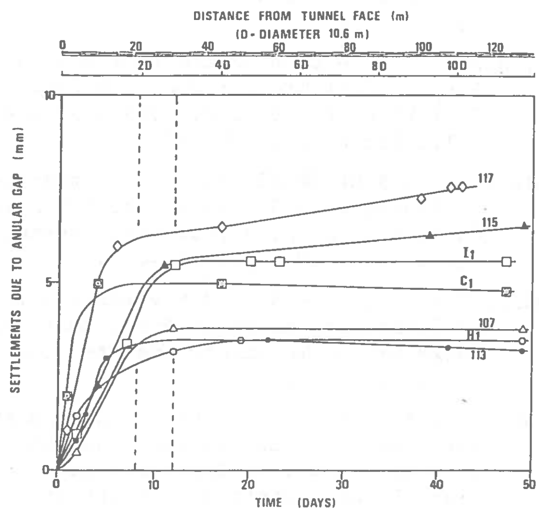

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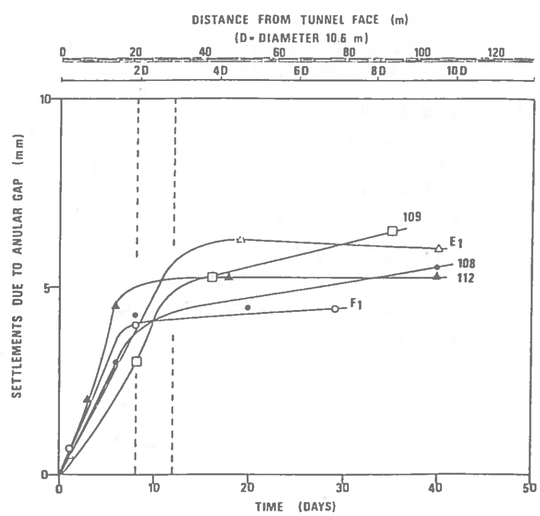

c)

Fig. 6 - Obseweed surface settlements due to anular gap
a) - Cohesionless soil: Overburden 30 m
b) - Hard clay : " 25 m
c) - Hard clay : " 12 m

— Surface settlements induced by face excavations can be correlated with a stability factor. This correlation was found to be of the exponential type. During the approaching phase, surface settlements of the order of a centimetre, seem to point to critical equilibrium conditions on the excavation face.

— Ground settlements induced by tunnelling occur up to distance from the excavation plane of the order of 2-2.5 times the diameter of the tunnel section, thus confirming the experience with smaller diameter tunnels.

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