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"Tunnel dorsal instability: a simple theoretical and practical approach"

"L´instabilité dorsal dans des tunnels: un modele theorique-practique"

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ABSTRACT
The excavation of urban tunnels in ground with low cohesion can produce over-excavations leading to frontal instability phenomena (the most typical, produced in front of and above the shield). But, in the event of there existing layers of sands without any fines above the crown and then resistant ground on top of that, over-excavations, cavities in the sand and surface cave-ins take place up to a distance of a diameter and a half towards the rear (dorsal instability). This paper describes the phenomenon and presents theoretical studies of it, along with solutions for avoiding the problem.

RESUME
L´excavation des tunnels urbaines autour des terraines sans cohesion peut introduir sur-excavation plus important. Dans cettes conditions on peut produir des phenomenes d´inestabilité frontal (sur et avant le bouclier). Mais, si au niveau de la clé, il existe une couche de sâbles contenant peu d´eleménts fins, et sa cohesión est minimale il se produit une sur-excavation et un vide dans le sâble. Limiteé por la présence d´un l´avanceé continue, le vide persiste et quand la longueur du vide dépasse un valeur de le dimètre et demie, il se produit un effondrement du terrain et un affaissement superficiel. Dans cette comunication on décribe ce phenomen et on present des études theoriques sur le même et des solutions pour resoudre ce problem.

1 INTRODUCTION

When tunnels are excavated using a TBM, at full section and of the EPB type, the movement of the ground around it depends on the time that lapses between the excavations and the moment the ring is placed in position and the mortar is pressure-injected behind the voussoirs. As it is contained, the face cannot move towards the excavation, but (in ground with low cohesion) over-excavation can occur and cavities can be included in front of and above the shield. After several advances, this can give rise to an instability which can reach the surface (Fig. 1).

2 DORSAL INSTABILITY

The construction of the Extension of the Madrid Metro (1999-2003) in the south of the city (Metrosur) has been carried out on ground where a lot of sandy layers appear, with not much fines, with or without water. In two particular works – Section 2 of Line 10, in other words Cuatro Vientos-Alcorcón and in the Alcorcón Section of Metrosur – the presence of these sandy layers without fines (with or without water) above the crown has created a lot of problems. In the Alcorcón Section, a cave-in took place at the start of the work in an area of open countryside, which enabled the problem to be studied. It turned out to be a case of dorsal instability shown in schematic form in Fig. 2: the drilling with the tunnelling machine tends to produce a slight over-excavation in the upper part of the front of the machine. If the ground is clayey and cohesive then the over-excavation is very little and it is filled in with mortar injection carried out by the tunneller systematically each time a ring is fitted. But if there exists a layer of sands in the crown with little fines, even though it is Tertiary (Pliocene) its cohesion is minimal and in that case the over-excavation becomes more important, with the formation of a cavity that is limited by the presence of somewhat more cohesive ground above the crown (Fig. 2.a).

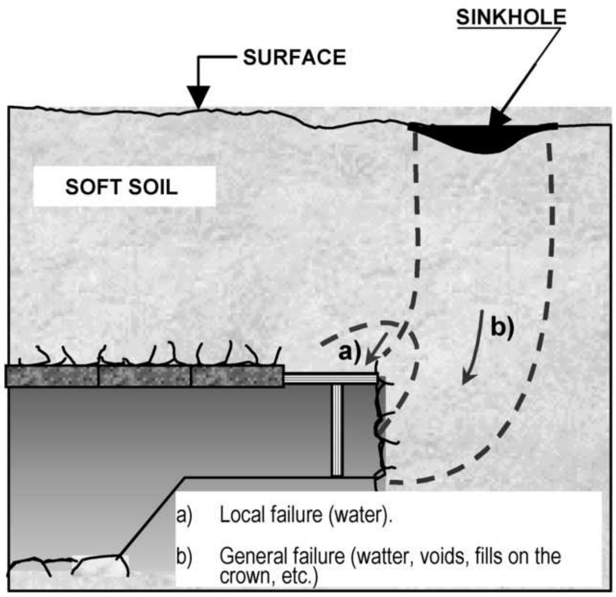

Figure 1. Lay-out of frontal tunnel instability.

In general, the sandy layers without fines had a maximum thickness of 2 m, which means that the cavity that is created initially has a height equal to that magnitude, and a width somewhat less than that of the tunnel (Fig. 3). As the advance continues, so the cavity remains since the ground above it resists on account of its cohesion and the friction it has. When the length of the cavity (L in Fig. 1.b) is such that the shear strength of the ground above is exceeded, then the ground subsides and a large depression appears on the surface (Fig. 2 and 3).

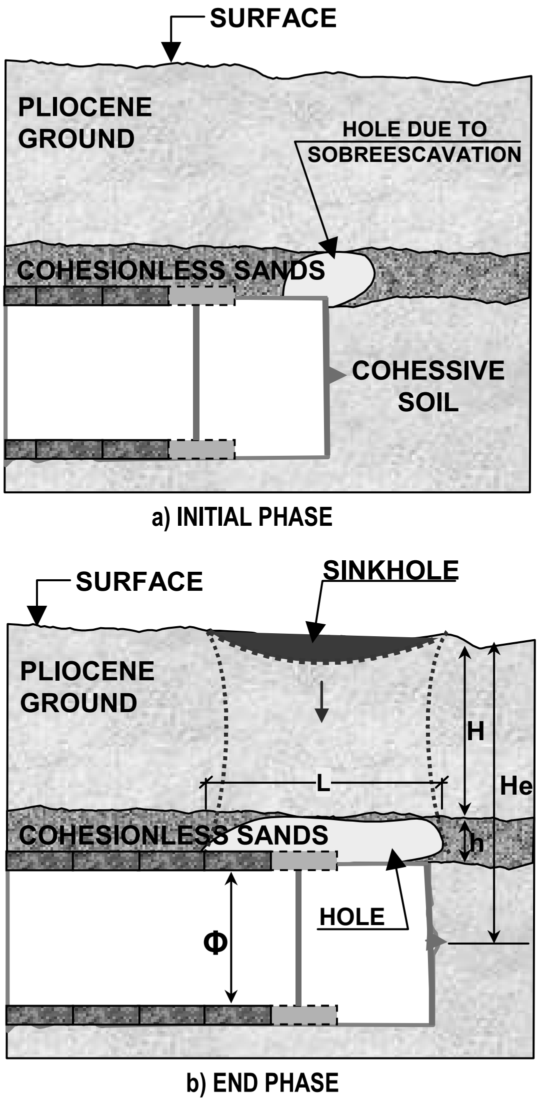

Figure 2. Dorsal instability in E.P.B. tunnels.

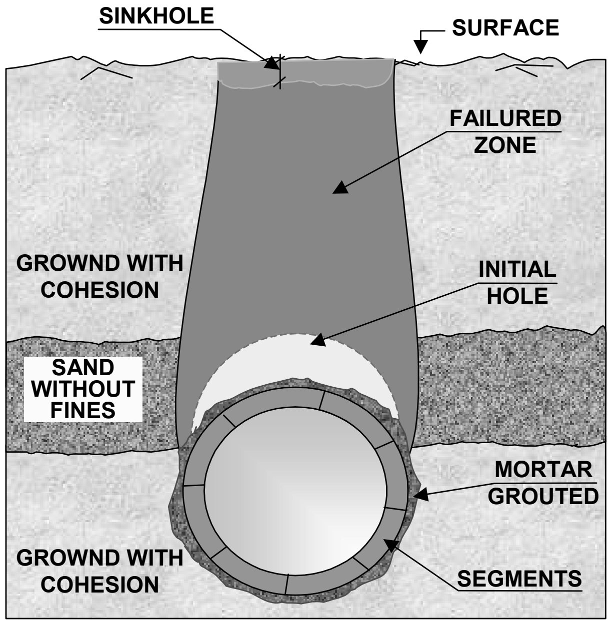

Figure 3. final dorsal instability (cross section).

This phenomenon does not, in principle, prevent the advance from taking place, provided the front chamber is sufficiently full. The speed of advance can be very large. In the area of Alcorcón (line 10 and Metrosur), this situation which we have just described occurred on many occasions. Nevertheless, the tunnel machines were different in both cases: Line 10 consisted of a double tunnel drilled with a Lovat tunneller of Ø 7.60 m with a system of "quasi-pressure of earth" and in the Alcorcón section a Herrenknecht tunneller was used, of Ø 9.40 m and with a genuine EPB system.

In the interior of the TBM, an attempt has been made to monitor the weight of material being extracted by them, though without any practical result on account of the dynamic nature of the extraction. So, the apparent volume of rubble extracted in each ring is monitored by counting the number of wagons filled up with that rubble. This has a certain error (of the order of 10 % of the total volume). In the case of the Ø 9.40 m shield, 11 wagons are normally extracted. If the difference between the number of real wagons and the theoretical (or normal) number in order to excavate the ring is negative, then this means that short advances have been made. If this number is of the order of –1 to +1 then there is no problem of over-excavation (normal error); if it is between +1 and +3 then there is risk of over-excavation and a close eye has to be kept on what happens in the following rings. And if this number is between 3 and 6 in the excavation of a ring, then there exists a serious problem of excavation and a problem of instability, generally dorsal (cavity above the keystone of 20-30 m^3 per ring which, given the width of the tunneller, implies a cavity height of 2-3 m).

3 THEORETICAL APPROACH

The phenomenon has been studied by two methods (Arnaiz, 2003; Oteo, 2003):

– By means of a simple analytical model, assuming a parallelepiped type breakage of the ground, with a scheme (in transverse section) like that of Fig. 5. In the longitudinal direction it is assumed that the unstable mass has a length L (Fig. 2).
– An elasto-plastic analysis using the finite elements method.

In the case of the analytical model, it is assumed that the cavity has a height h above the keystone of the tunnel, of diameter D, and that, above that cavity there exists ground of

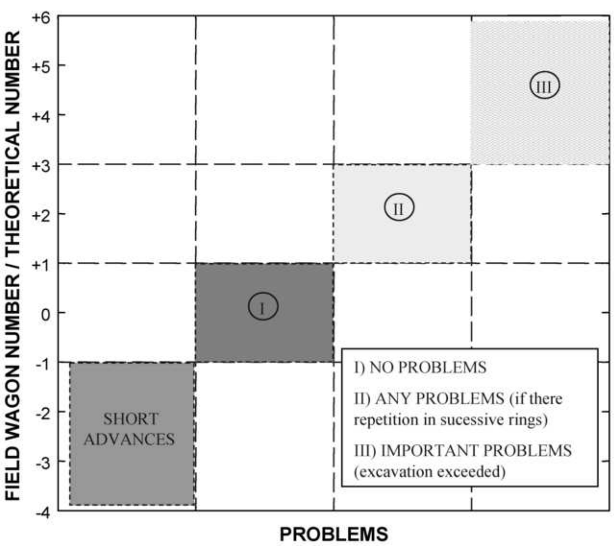

Figure 4. Practical criterium to prevent the instabilities.

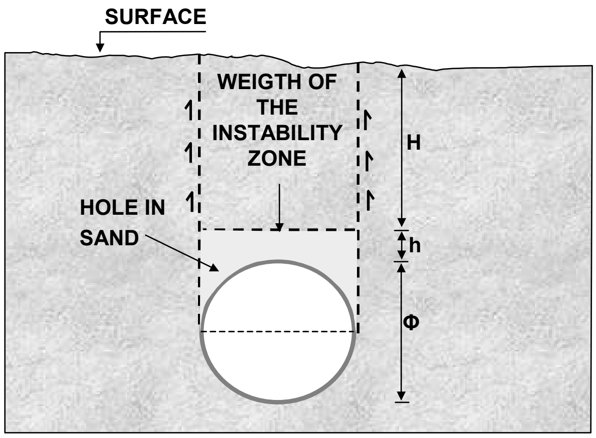

Figure 5. Geometrical hypotheses to analyze the dorsal instability.

thickness H, with a certain cohesion, C_a', and internal friction φ'. The stability condition according to the scheme mentioned above, is:

$$D \cdot L \cdot H \cdot \gamma_{ap} = 2H \cdot (L + D) \cdot \tau \tag{1}$$

where γ_{ap} and τ are the apparent density and the shear strength of the ground above the cavity $\left(\tau = K_o \sigma_v' \cdot tg\varphi' + C_a'\right)$ (2)

From this it is deduced that:

$$L = 2 \cdot D \cdot \tau / (D \cdot \gamma_{ap} - 2\tau) \tag{3}$$

In Madrid soils, for the usual depths and geotechnical properties, τ can be permitted to vary between 0.5 H + 1.5 and 0.8 H + 2.0 (in T/m^2), with which L becomes:

$$L = \begin{Bmatrix} D \cdot (0{,}5H + 1{,}5)/(D - 0{,}5H + 1{,}5) \\ D \cdot (0{,}8H + 2{,}0)/(D - 0{,}8H + 2{,}0) \end{Bmatrix} \tag{4}$$

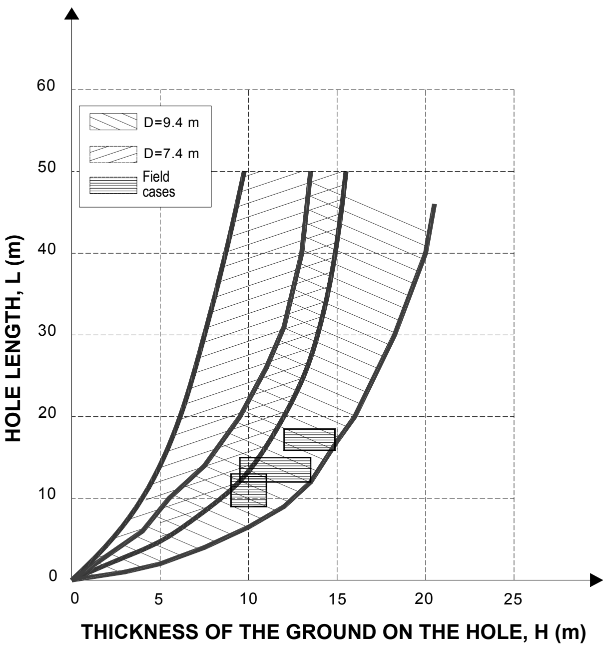

Figure 6. Comparision between analytical results and field situations.

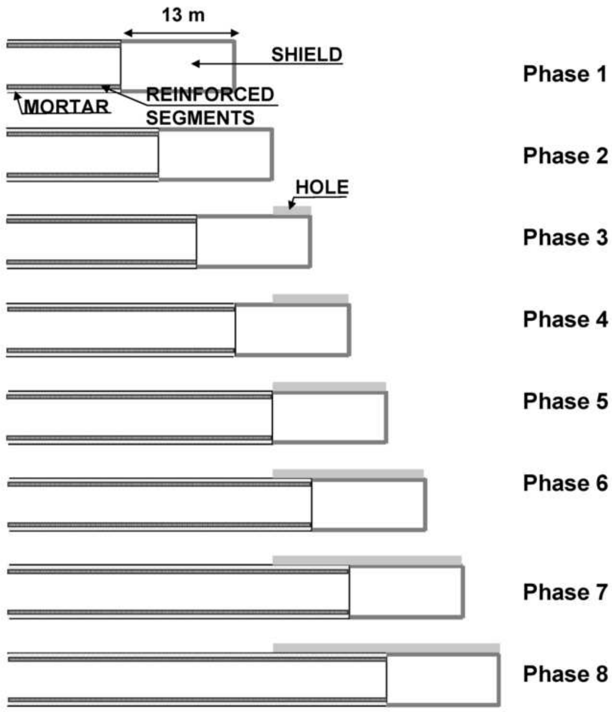

Figure 7. Theoretical simulation of the tunnel advance and dorsal instability (PLAXID-3D analysis).

These results are shown graphically in Fig. 6, applied to the diameters of the tunnellers used in the cited cases. Also shown are the values corresponding to real cases in which cave-ins have occurred. As can be seen in Fig. 6 the fit between the theoretical model and reality is sufficiently good: the instability takes place when the cavity has a length of the order of a diameter and a half of the tunneller.

The FEM (Version PLAXIS-3D) has also been used and a simulation has been conducted on the advance by phases, creating a cavity above the keystone (Fig. 7). Various cases

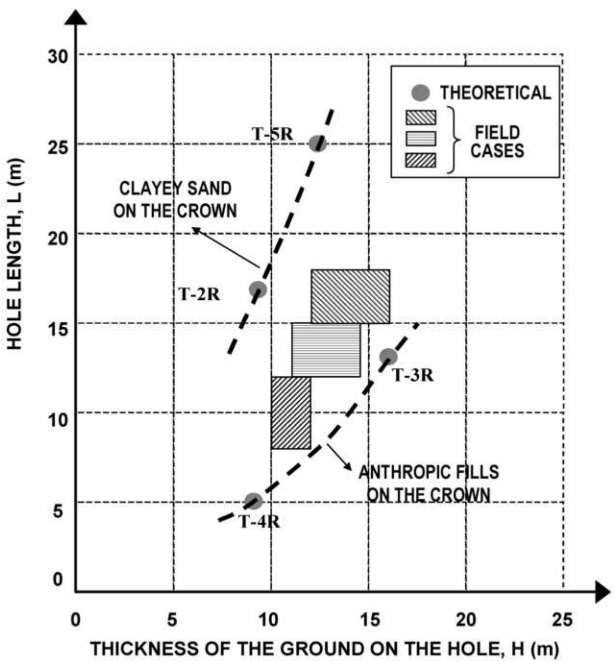

Figure 8. Comparison between PLAXIS-3D results and field situations.

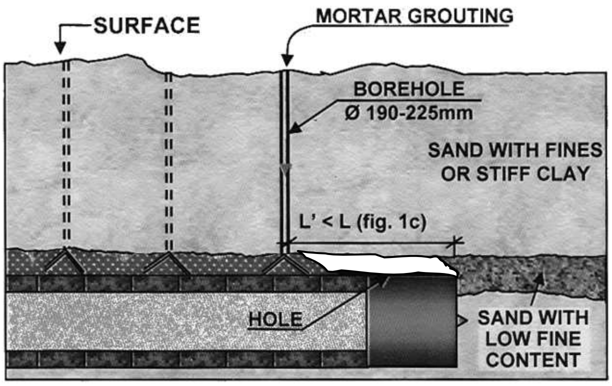

Figure 9. Example of the ground treatment from the surface with mortar (Arnaiz and Melis, 2003).

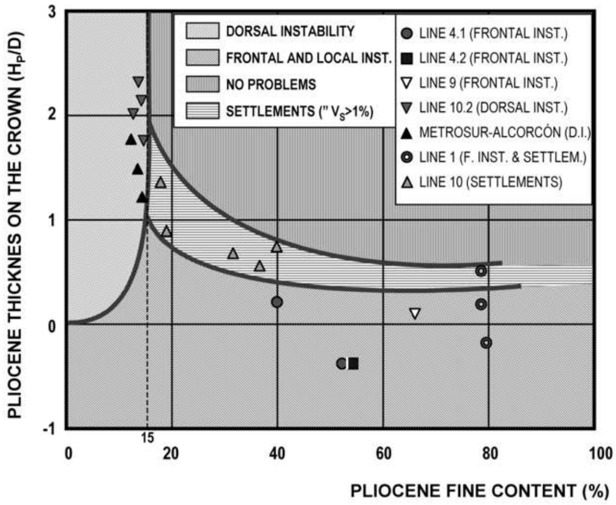

Figure 11. Inestability problems criteria for the Madrid Ground and E.P.B. excavation.

have been analysed, at all times with 2 m of sand without fines above the crown: a) Clayey sand (35 % of fines) above that sand (with thickness 9 m); b) With anthropic fills (thickness 16 m) above the sand. With these conditions the problem was considered to be demarcated.

Fig. 7 shows that instability was reached in phase 8 and the excavation could not be continued with (case of clayey sand). In Fig. 8 the values of L that are obtained can be seen: the real values lie between those corresponding to clayey sand and those for anthropic fill above the keystone, which also indicates that the problem has been reproduced sufficiently well.

4 SOLUTIONS

With the problem of dorsal instability, preliminary measures needed to be established in order to prevent or mitigate the problem and, above all, its affect on the surface and nearby installations. In general, the system was resorted to of trying to fill in the cavern that was being produced before breakage of the ground took place. Some drillings were sunk from the surface, of Ø 190-225 mm, and fluid mortar was poured in, in order to fill the cavity that was being induced (Fig. 9) These drill-holes were made 4-5 m from the shield so that the mortar would not have any influence on it. The sequence of holes was to drill one every 3 concrete rings, with some intermediate holes being drilled later on in the event of the amount poured in being greater than 15-20 m^3. In one of these situations (passage beneath a road) the average consumption of mortar was 10 m^3/ml.

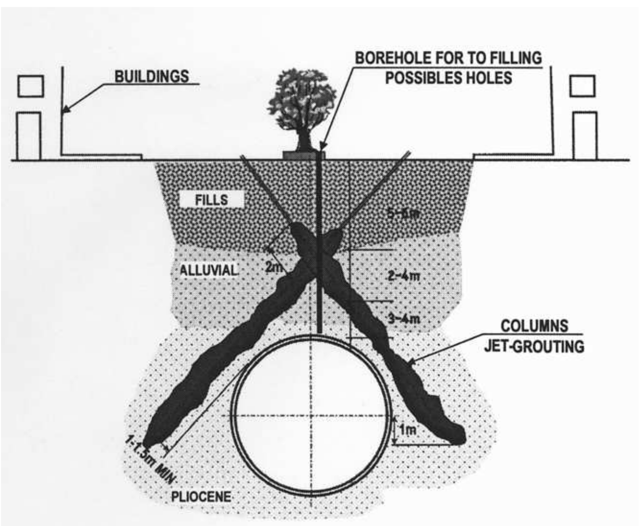

Figure 10. “Canadian tent” solution for frontal and dorsal tunnel instability (Oteo, 2003).

In areas where it was not possible to do this from the vertical, or serious repercussions were feared on nearby buildings, the “Canadian tent” treatment was used, with columns of jet-grouting (Fig. 10).

5 CONCLUSIONS

– In the case of layers of sand without fines (< 15 %) above the crown of a TBM, cavities are produced due to over-excavation. When the hole has a length of 1.5 to 2.0 times the diameter of the tunnel, dorsal instability is produced.
– In Fig. 11 a yardstick has been included for distinguishing the possible problems of instability in tunnels in Madrid (Spain), as a function of the granulometry of the Pliocene ground and its thickness above the crown.

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