Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (eds)
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Pore pressure generation and equalization around a circular tunnel in soft clays

G. Urciuoli & C. Russo
University of Naples Federico II, Italy

A. Desideri
University of Rome 'La Sapienza', Italy

L. Picarelli
Second University of Naples, Italy

ABSTRACT: This paper is devoted to a 2D-FD analysis of the process of pore pressures equalization induced by a circular unlined excavation in a saturated homogeneous clay. The influence of the constitutive laws of the subsoil and of the hydraulic boundary conditions introduced by the hole has been investigated.
The results of the analysis allow to point out some peculiar aspects of the soil behaviour, which should be considered for a proper design of the lining and of the related phases of construction.

1 FOREWORD

In 1981, Atkinson and Mair pointed out that the basic principles of modern Soil Mechanics apply very well to the analysis of tunnels in soft clays. Despite this apparently obvious consideration, they are not always applied in common practice.

Following the classical approach of Soil Mechanics, in tunnel design the undrained and the drained conditions should be both considered. In many cases the stability analysis may be limited to the undrained condition; for other aspects of the design, such as the evaluation of ground settlements, tunnel convergence and soil-lining interaction, the transient condition between the two extreme undrained and drained situations, must be taken into account.

Surprisingly, until now the transient condition, which in turn depends on pore pressure generation and dissipation, has been analysed in very few papers (Cividini et al., 1985; Seneviratne and Gunn, 1985; Mair and Taylor, 1992; Samarasekera and Eisenstein, 1992). The discussion of some aspects concerning this question is just the aim of this paper.

2. THE ROLE OF INDUCED STRESSES

The unloading caused by tunnelling produces significant changes in the geostatic stress field: first of all, a generalized rotation of the main stress axes occurs around the hole (Lee and Rowe, 1989), where variable and complex stress paths are generated (Ng and Lo, 1985); in addition, depending on size and depth of the hole, on mechanical properties of the soil and technological aspects of the excavation and lining construction, a soil ring around the tunnel may eventually yield. Moreover, even if generally small, the induced mean stresses are of opposite sign in different zones of the soil domain: being strictly related to this change of stress, in undrained conditions the excess pore pressures are positive in some zones and negative in others.

In this process, the coefficient at rest plays an important role, controlling the position of zones where positive and negative pore pressures are generated.

The role of induced stresses should be carefully considered in the selection of the soil parameters for tunnel design (Picarelli and Urciuoli, 1993), especially if, in addition, the induced and inherent anisotropy of the soil is taken into account. As an example, the coupled effect of induced stress paths and anisotropy controls both undrained stiffness and cohesion (Atkinson et al., 1990; Topolnicki et al., 1990), thus local stress level and induced strains.

The process of equalization affects the evolution of the displacements with time as well as the soil-lining interaction. The evaluation of both of them is not easy considering the complex initial distribution of excess pore pressures, which are responsible for local consolidation and swelling phenomena.

Many aspects of the soil behaviour affecting effectiveness of tunnelling are hence related to the stress field induced in the subsoil.

The paper will discuss some questions concerning pore pressure generation and dissipation; this will be done with the help of numerical analyses carried out with the Finite Differences program FLAC.

The examined problem is a very simple one, regarding a circular unlined excavation, either pervious and impervious, in plane strain condition. The subsoil is characterized with a coefficient at rest k_0=0.7 and is treated with both the elastic and the elasto-plastic Mohr-Coulomb constitutive models and the vertical and horizontal boundaries of the soil domain considered in the analysis are pervious.

The undrained excavation of the tunnel is simulated reducing to zero the stiffness and the stresses in the removed zones. No displacement fixties are applied on the boundary of the hole.

Since the main interest is to study and compare the process of dissipation of excess pore pressures induced by the excavation for different hydraulic boundary conditions introduced by the opening itself, the analysis has been performed with initial pore pressures equal to zero everywhere (Samarasekera and Eisenstein, 1992).

Although the case of unlined tunnel has been studied, the results obtained can be used to evaluate the qualitative interaction between soil and lining.

The size and location of the hole and the adopted soil parameters are reported in fig. 1.

3. PORE PRESSURES INDUCED BY TUNNELLING AND THEIR EQUALIZATION

3.1 The undrained condition

In plane strain conditions, the excess pore pressures practically depend on the balance of changes in radial stress (which decreases) and circumferential stress (which increases) around the hole; their sign (positive or negative) is variable from zone to zone, depending on the value of k_0. For a cylindrical hole in an infinite isotropic elastic medium under plane strain conditions, the classical solution (Jaeger and Cook, 1976) shows that if $k_0=1$ the mean stress does not change and the pore pressure remains unchanged.

In figure 1 are reported the excess pore pressures calculated for the two cases examined in this paper.

In the elastic medium (fig. 1a) the well known arch effect is clearly revealed by the increase of pore pressures in the zone of the walls; the point of maximum value is located on the horizontal axis, just on the hole contour. This zone of positive pressures extends in quite a wide area practically reaching the soil surface. In other zones, especially above and below the tunnel, the excavation gives rise to a pore pressure reduction.

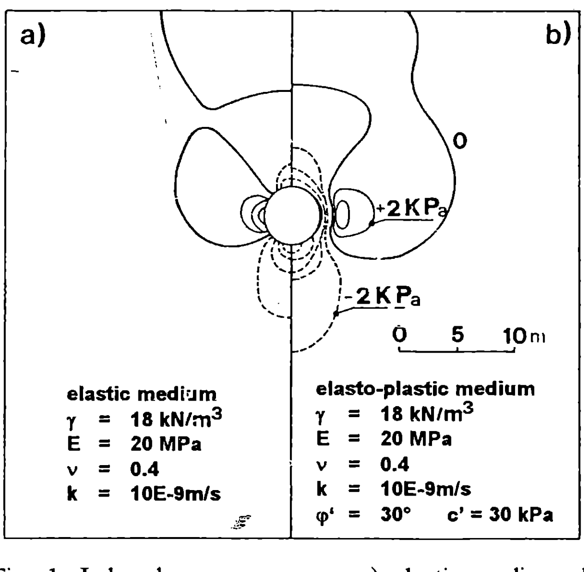

Fig. 1. Induced pore pressures: a) elastic medium; b) elasto-plastic medium

In the elasto-plastic medium (fig. 1b) the positive pore pressures due to the arch effect involve a zone located at some distance from the tunnel, whereas all around the hole the pore pressure is negative. This is a consequence of the plastic strains that develop in an annular soil ring surrounding the excavation, where the soil is not able to sustain an increment of circumferential stresses greater than a limit value determined by its shear strength: the stress redistribution following yielding produces the effects shown in the figure.

In a strongly overconsolidated soil characterized by a k_0 value greater than one, a similar behaviour can be observed, but the position of zones subjected to positive or negative pore pressures is reversed.

Similar analyses have been carried out by Samarasekera and Eisenstein (1992), who have published a number of normalized diagrams covering different situations. The results of the analyses reported here agree with them.

3.2 The transient condition

The analysis of the transient condition is frequently neglected in the design of tunnels in saturated clay, despite it being a crucial question, especially in urban areas, where the evolution with time of settlements following the excavation should be evaluated.

The problem is not simple since the distribution of induced pore pressures is rather complex and depends on several interrelated factors, such as the geometry of the hole, the value of k_0, the soil properties, the boundary conditions and the method of excavation.

Some aspects of the equalization process following the excavation are presented in figure 2.

In figure 2a are reported some lines of zero pore pressure at different times after the excavation, calculated for a sealed hole in an elastic medium. Position and size of the zones subjected to positive

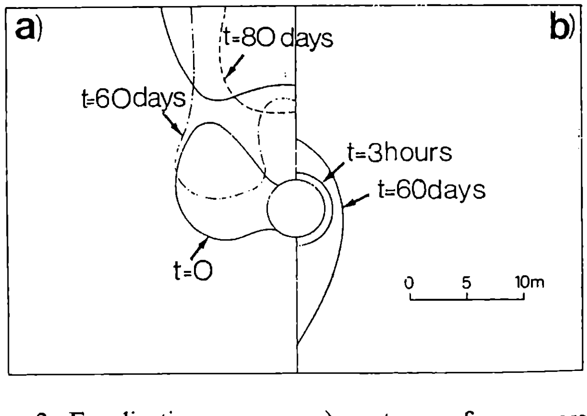

Fig. 2. Equalization process: a) contours of zero pore pressure for an impervious hole in an elastic medium; b) zones subject to a water flow from the pervious hole in elasto-plastic medium at different times

or negative pore pressures evolve as a consequence of equalization: in particular, during the process, the size of positive zones decreases and in a short time after the excavation the pressures are everywhere negative. This occurs also for an elasto-plastic soil and has clearly shown also by Seneviratne and Gunn (1985) and by Samarasekera and Eisenstein (1992).

In this situation, the direction of the flow lines is very complex and continuously changes. In the case of unsealed hole and plastic soil, in the zone immediately around the excavation the water flows from the hole towards the surrounding soil. The extension of this soil domain at two different times is represented in figure 2b.

Looking in detail at the process of equalization, in this zone it is strictly dependent on the draining boundary constituted by the pervious hole contour and is of course very quick. Far from the hole, the pore pressures induced by the excavation are negative and very small: the process of equalization is here slow, depending on the position of the point, and the presence of the hole does not play a relevant role. In an intermediate domain, zones subjected to either positive or negative pore pressures are initially present: in this situation, the line of zero pore pressure acts as an internal drainage contour. As a consequence, in the first phase of the process, the rate of equalization is much more controlled by the internal redistribution of water content than by drainage towards the external pervious contours (hole and lateral boundaries): the length of the drainage paths is then rather short and the equalization rate is quicker than it could thought to be; in the final phase, since in the entire domain the pore pressures have become negative, the process is controlled only by the external drainage contours and its rate slows down.

Further data clarifying this complex phenomenon are given in figure 3 where the evolution of pore pressures in some points located at a variable distance from the hole is reported; to simplify the diagram, the pore pressures have been normalized with respect to their initial values.

Figure 3a shows the influence of the hydraulic condition on the hole contour, in the case of elasto-plastic soil. For point A, located at a distance of only 0.1d from it (d=diameter), the equalization time clearly depends on this hydraulic condition, being shorter in the case of unsealed hole. In point B, located at a distance of 0.5d, in a zone of initially positive excess pore pressure, in the first 3-4 days the evolution of pore pressure substantially does not depend on the presence of the hole, because the strong hydraulic gradients in this zone control the equalization phenomenon much more than the drainage across the tunnel contour: just for this reason, the rate of the process is comparable with that featuring point A, closer to the pervious hole. Only in the later phase, when the pore pressure become negative and the hydraulic gradients are significantly smaller, the role of the external draining boundaries is recognizable. In point C, located in a zone of small hydraulic gradients at a distance of a diameter from the hole, the equalization is slower: in this case, the influence of the external draining boundaries is intermediate.

Figure 3a also indicates that in some cases the trend of pore pressure evolution can temporarily change: in point C, for instance, the pore pressure initially decreases, then increases towards the final zero value. This is a consequence of the complexity of the flow, whose direction can change in relation to the local variation of pore pressures.

In figure 3b are compared the solutions obtained for the two adopted soil models, referring to points located in a zone of initially positive pore pressure, at a distance of respectively 0.5d and d from the sealed hole. In the case of the elasto-plastic medium, point B is located in a zone of strong hydraulic gradients, thus the pore pressure dissipation is quicker than in the elastic medium. In point D, where hydraulic gradients are smaller, the process is irrespective of

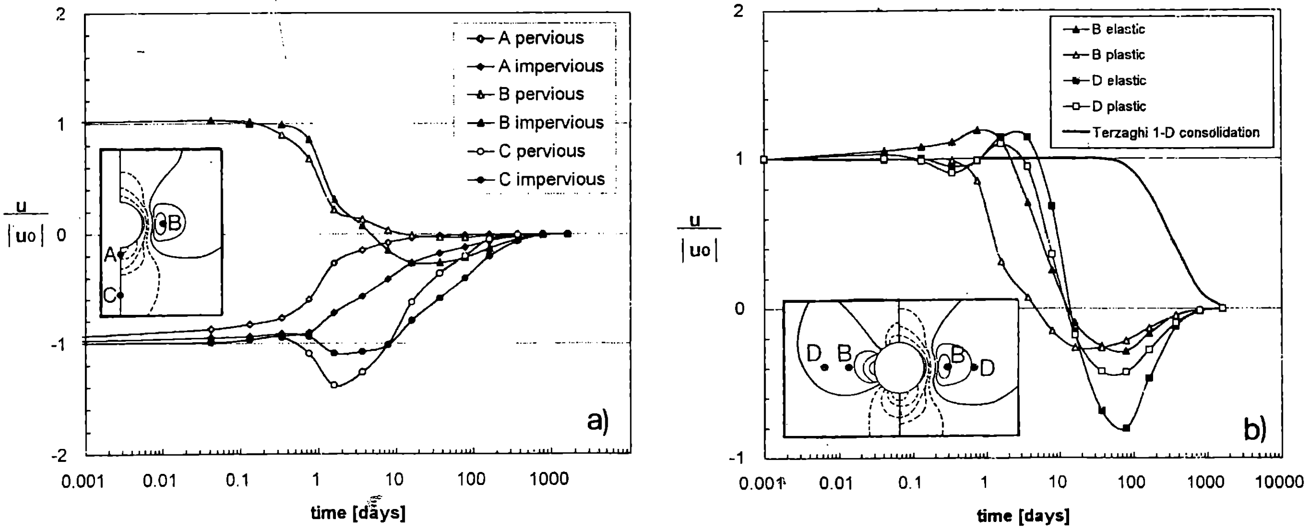

Fig. 3. Pore pressure evolution in some points around the hole: a) influence of the hydraulic condition on the hole boundary; b) influence of the soil model

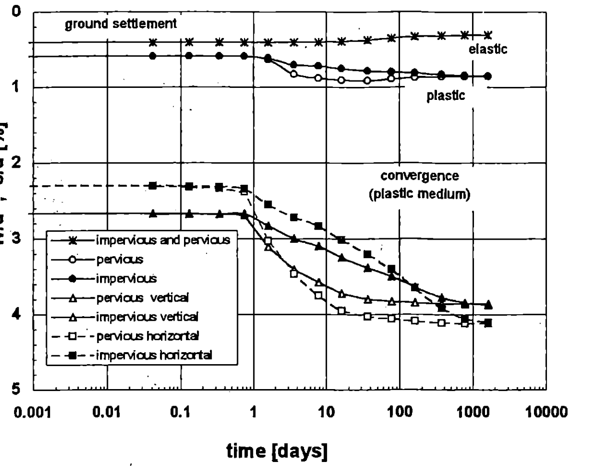

Fig. 4. Settlement (w) of the ground surface and convergences (c) of the hole

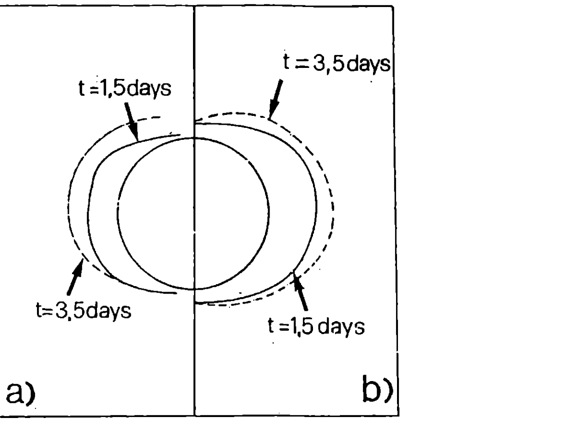

Fig. 5. Contour of yielded zones at different times: a) impervious hole boundary; b) pervious hole boundary

the model. Then, as concerns the equalization phenomenon, the influence of the model seems limited to the initial distribution of pore pressures.

In all cases the pore pressure becomes negative 5-10 days after the excavation: the successive phenomenon of dissipation slows down since it is governed by the external boundary condition. If point B is considered in the elastic soil, the time required for a complete equalization is similar to that obtainable from a theoretical analysis in the case of monodimensional consolidation (Terzaghi solution), for an initial rectangular isochrone. The most relevant difference due to the presence of a tunnel is that most of the pore pressure equalization takes place in the first days after the excavation, thanks to the peculiar initial pore pressure distribution: in particular, after 80 days the residual excess pore pressure is negative and of about the 30% of the initial value, whereas in the absence of tunnel, it is still about 100%.

In figure 4 are reported the ground surface settlement and the convergences versus time. The comparison with figure 3 gives an idea of the global engineering consequences of the excavation, disregarding the local different situations, and pointing out the role of both boundary conditions and soil model.

In the case of elastic medium, the undrained 2D settlement is a great percentage of the final one; thus, also in a 3D situation, the lining, even if placed very soon, may not be able to avoid some effects of the excavation on the structures present on the ground surface or at small depth. After a period of very small displacements, the subsoil slowly raises as a consequence of the swelling that involves the entire soil domain: however, the vertical displacement is quite small, because the pore pressures are small. The curves related to sealed and unsealed hole are practically coincident, showing that the permeability of the hole contour plays a negligible role on the global phenomenon, which is mainly controlled by the other draining boundaries.

The elasto-plastic model shows some peculiar aspects of the soil behaviour, that have not been revealed by the elastic analysis. Once again the time of global equalization is practically independent on the permeability of the hole contour, but the settlements are much greater than in the elastic soil and the final ground surface raising observed in that case is here absent or negligible, although in the last phase here also the entire soil domain is dissipating negative pore pressures. This situation may be explained if we consider that in the elasto-plastic medium plastic shear strains are induced when the yield curve is locally attained. During the equalization process both volumetric and deviatoric strains are induced: volumetric strains are a direct effect of the pore pressure equalization, whereas deviatoric strains are mostly due to yielding, caused by the increase of the stress level in zones initially subjected to negative pore pressures. The balance between these components of strain determines whether the ground surface settles or raises in the last phase of the process. In the case of pervious hole, close to it the dissipation of pore pressures is quicker, causing a quicker yielding: hence, in the very last phase of the process swelling prevails. In the case of impervious hole, the equalization around the hole is slower, then plastic shear strains develop more slowly, hiding the effects of swelling.

These considerations are supported by figure 5, showing the progressive extension of plastic zones in the subsoil. Obviously the settlement depends on the extension of plastic zones.

An useful engineering information regards the convergence of opposite points of the tunnel; the so called *ground loss* as well as the pressure of soil against lining are both related to this datum. The evolution of the convergence on the vertical and horizontal axes of the excavation are also reported in figure 4. Once again the influence of soil model is shown.

In principle, this diagram could be used to select the appropriate time for the installation of the lining.

In the case here considered, most of the variation in diameter length takes place immediately. After 3-4 days only 15-25% of the final value still has to be completed. Part of this further deformation will close the gap between soil and lining: thus, in this 2-D frame the load that the permanent lining will sustain should be limited. On the opposite, since only when the heading is sufficiently far from the considered section the strain field becomes really 2-D, it must be considered that in a first phase the convergence develops in 3-D mode and is far smaller than that calculated by a plane strain analysis.

4. SUMMARY AND CONCLUSIONS

The pore pressures generated by tunnelling in soft saturated clays and their successive equalization depend on a number of strictly interrelated geometrical, mechanical and technological factors; so, each case has a different solution.

To point out some peculiar aspects of this problem, the analysis of a circular tunnel in plane strain condition has been carried out, with the aim of investigating the influence of the constitutive laws of the subsoil and of the drainage conditions along the contour of the hole.

The analysis shows that around the tunnel the process of equalization is initially very rapid, because the consolidation in zones close to the walls supplies the swelling in the remaining zones: after only a few days since the excavation the local pore pressures decrease to a small percentage of their initial value; then the equalization rate declines since the positive pore pressures caused by the arch effect disappear and become negative.

In the case of an elasto-plastic medium, a soil ring around the hole is entirely subjected to negative pore pressures, so it swells during the transient process. In such circumstances, looking at the internal drainage condition, the pervious hole contour is quite a theoretical situation because, even if the lining were absent, the boundary would be really draining only if a water film were continuously available on it: this appears rather unlikely, mainly for the crown and the walls. For this reason it appears more realistic to consider the hole contour always impervious. However, the analysis shows that the influence of the hydraulic boundary conditions is significant only in the last phase of the process, when the lining has been by now placed and the strains to be still induced are very small.

In the considered example, a great percentage of the final predicted convergence is mobilized in a few days. This observation may be helpful in addressing the tunnel design and indicates that the short length of time generally selected for lining installation may be in some cases sufficient to avoid great earth pressures against the tunnel. Obviously, this is not true in high plasticity clays, characterized by a very low permeability and exhibiting great viscous strains (Urciuoli, 1992).

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