DISCUSSION

Loads on leaking and watertight tunnel linings, sewers and buried pipes due to groundwater

J. H. ATKINSON and R. J. MAIR (1983). *Géotechnique* **33,** No. 3, 341–344

Dr O. Hungr, *Thurber Consultants Ltd, Vancouver*

The Authors presented a simple analysis of the loads on leaking tunnel linings due to groundwater seepage forces. The substance of their conclusion is that, if the tunnel is deep and causes negligible drawdown, such seepage loads equal static groundwater pressures that would act on a similar watertight lining, i.e. there is no difference between watertight and leaking linings in such cases. This would be an important practical outcome, if it were proven. Unfortunately, the Authors' proof and explanation are not convincing.

Equation (1) of the Note states that the total radial pressure on a leaking lining equals the sum of the effective soil pressure, groundwater pressure and 'seepage stress'. The effective soil pressure can be calculated using the Authors' earlier stability equation in terms of effective stresses. The groundwater pressure is zero for sufficiently permeable leaking linings. The seepage stress is calculated with equation (10), which is the integral of the seepage stresses along the full length of a flow line between the water-table and the tunnel crown. With no drawdown, this is equal to the static groundwater pressure at the crown.

The analysis should account for the fact that seepage forces are not transmitted directly into the lining as assumed in equation (1). They are transmitted into the soil at all the points of the flow net. The soil skeleton then takes a part of these forces to the lining but absorbs a large part by means of its remaining strength. Seepage stress is a misleading term in an effective stress analysis. Seepage forces are not stresses, but body forces analogous to gravity, although variable in both magnitude and direction.

The Authors point out that only a small fraction of overburden stress reaches a flexible lining in a frictional soil. Similarly, it would be expected that only a fraction of the total seepage stress along a flow line reaches the lining in such soil. How large the part taken up by soil strength may be is to be shown, but it is probably not as large as for overburden stress because, unlike gravity, seepage forces increase closer to the lining. It is certainly not negligible, however. In view of these considerations, it would be ill advised to discount lining drainage as a means of total load reduction without conducting a more refined analysis similar to that presented by Curtis (1976) for the elastic case.

The analogy presented in Fig. 4 is incomplete. If the side of the container in Fig. 4(b) had friction, as a result of soil arching, the total stress on the base would be reduced.

REFERENCE

Curtis, D. J. (1976). Discussion of Muir Wood (1975). *Géotechnique* **26,** No. 1, 231–237.

Dr M. J. Gunn, *University of Surrey,* **and Dr R. N. Taylor,** *University of Cambridge*

We agree with the Authors that the most rational way to examine the loads acting on tunnel linings is through a consideration of the effective stresses and pore pressures in the soil surrounding the linings. In this discussion we shall make a few detailed points about the Authors' Technical Note and shall present the preliminary results of some finite element calculations which give a new insight into the mechanisms involved in the time-dependent build-up of load on tunnel linings.

In equation (1) the Authors appear to be rewriting Terzaghi's effective stress equation. They introduce a stress σ_g' which they call 'the effective radial stress in the ground': however, this differs from the normal definition of effective stress in that seepage stresses (i.e. σ_i') have been subtracted. This definition could be misleading: suppose for example that it is necessary to determine whether the soil is in a state of plastic failure. Clearly the soil effective stresses must be considered which are $\sigma_g'+\sigma_i'$ rather than just σ_g'. We believe that it is conceptually more straightforward to interpret the effect of drag forces due to seepage flow as increasing the effective stresses in the ground rather than as causing a separate seepage stress.

We note that the Authors have superposed the stability solutions for surface loading and self-weight (equation (3)). The validity of this superposition needs to be verified theoretically or otherwise.

In considering the effect of seepage on tunnel lining loads it is convenient to perform finite element analyses incorporating soil consolidation. The analyses reported here were based on the following assumptions: equilibrium of total stresses, the effective stress principle, continuity of porewater flow and volumetric strains and Darcy's law. Effective stresses were related to soil strains through an elastic–plastic stress–strain law with soil yielding governed by the Mohr–Coulomb criterion. The various soil parameters used in the analysis are listed in Table 1.

Table 1

Drained Young's modulus	E'	5000 kPa
Drained Poisson's ratio	ν'	0·33
Drained angle of friction	ϕ'	26°
Drained cohesion	c'	0
Permeability	k	10^{-9} m/s
Bulk density of water	γ_w	10 kN/m^3
Angle of dilation	ψ	0°

The tunnel was idealized as an axisymmetric cavity as shown in Fig. 1. This thick cylinder analogy is often used to simplify the tunnel problem so that basic phenomena can be examined in detail (e.g. the Authors' use of an axisymmetric flow net). A total stress of 200 kPa and a pore pressure of 100 kPa initially acted throughout the cylinder. During the analysis the stresses acting on the outer boundary of the cylinder remained fixed at these values. The process of tunnel excavation was modelled by reducing the total stress acting on the inner boundary from 200 kPa to 50 kPa. The insertion of a structural lining was then simulated by fixing the position of the inner boundary so that it was restrained from further movement while excess pore pressures dissipated during the remainder of the analysis. This procedure is equivalent to the erection of an infinitely stiff lining with no initial gap between the lining and the soil.

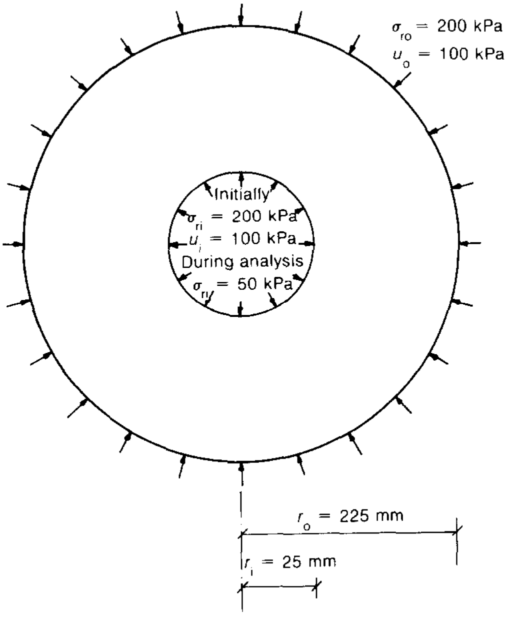

Fig. 1. Thick cylinder analogy of tunnelling

Two separate analyses were performed. In the first it was assumed that the tunnel lining remained impermeable and the pore pressures eventually returned to their initial values throughout the soil. In the second the lining was assumed to be permeable and the pore pressure on the inner boundary was fixed to have a value of zero after the insertion of the lining. The pore pressure head of 100 kPa between the outer and inner boundaries eventually established steady seepage towards the cavity.

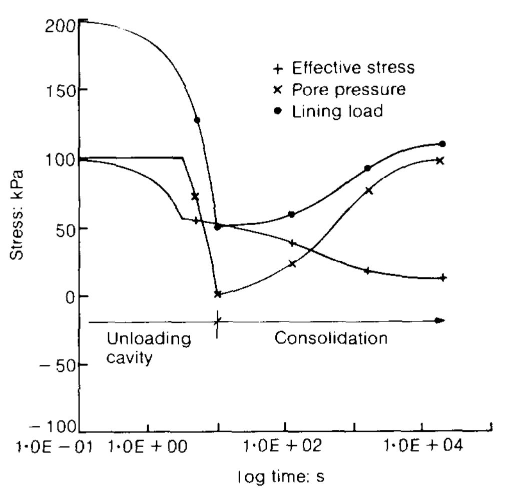

Fig. 2. Results of finite element analysis (impermeable lining)

Figures 2 and 3 show the variation with time of the total stress acting on the inner boundary, and the pore pressure and effective radial stress at a point in the soil close to the inner boundary. The reader's attention is drawn in particular to the predicted total stresses which are equivalent to the loads carried by the tunnel lining. Two main points can be made. First, there is a significant build-up of lining stress during consolidation for the impermeable lining. This type of build-up is often taken as evidence of viscous or creep behaviour of the soil or the lining. Here, however, only time-independent plasticity and primary consolidation have been assumed. Second, the magnitudes of the lining loads are very different for impermeable and permeable linings. This is in contrast with the Authors' simpler approach to the problem in which it was suggested that the lining loads should be identical. The reason for this discrepancy is that the Authors only considered equations of equilibrium whereas we (in our finite element analyses) have also taken account of soil strains.

It must be emphasized that the results presented in Figs 2 and 3 have been obtained on the basis of a set of soil properties and geometric dimensions appropriate for comparison with one particular laboratory experiment (not yet performed). No claim is being made for the general application of these results to practical tunnelling. A number of other factors will need to be considered before general conclusions can be drawn from analyses such as these. These factors include the magnitude of the temporary support pressure, the existence of a gap between the lining and the soil, the lining stiffness, the soil properties, dimensions and depth of the tunnel as well as the truly three-dimensional nature of the tunnelling operation. One factor which influences the predictions of lining load in this type of calculation is the time at which the lining starts to leak. If this happens a considerable time after the tunnel has been constructed then the predictions can be expected to be closer to the Authors' analysis.

Authors' reply

The stress changes that occur in the ground around tunnels during and after construction are complex, and these directly affect the long-term loading acting on tunnel linings. Dr Hungr, and Dr Gunn and Dr Taylor have raised a number of important points relating to this.

Both contributions state that our use of the concept of seepage stress to explain the difference in loading acting on watertight or permeable linings may be misleading, and they argue that seepage stresses should not be considered separately. Many engineers, however, intuitively feel that the total stress acting on a tunnel lining must be substantially reduced if it is permeable rather than watertight, because the water pressure acting on the lining is then zero. The purpose of our Note was to demonstrate that this may be an erroneous conclusion, particularly if the transition to steady state seepage does not cause significant strains in the soil around the lining. To emphasize this point, and in an attempt to clarify the argument, we chose to separate the component of effective stresses arising only from seepage stresses from the component of effective stresses arising only from gravitational forces. By doing this we believed that the difference was highlighted between a permeable lining, where seepage occurs, and an impermeable lining, where there is no seepage.

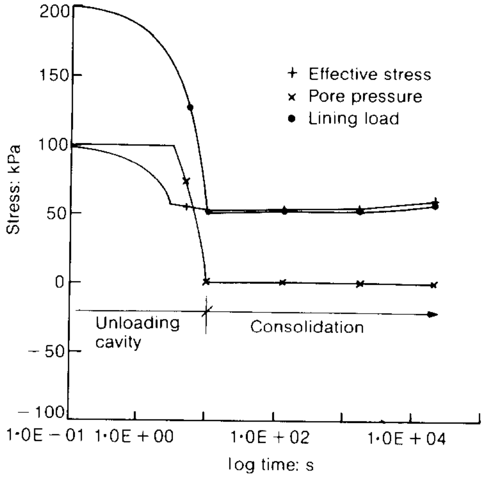

Fig. 3. Results of finite element analysis (permeable lining)

We remain of the opinion that the concept of seepage stress is useful to explain how the radial effective stresses in the soil close to a permeable tunnel lining are increased by seepage. Both the seepage stresses and the component of effective stresses due to gravitational forces can be considered together; indeed this becomes necessary in the more complicated case where soil strains caused by seepage are significant, as demonstrated by Gunn and Taylor.

Hungr states that 'seepage forces are not stresses, but body forces analogous to gravity, although variable in both magnitude and direction'. We cannot see the justification for his objection to our use of seepage stress. If gravitational accelerations acting on soil masses producing forces on soil grains can be interpreted as vertical stresses, hydraulic drag causing forces on grains can correspondingly be interpreted as seepage stresses acting in the direction of flow. Effective stresses may arise from a number of causes, such as gravitational acceleration (self-weight), earthquake or dynamic accelerations, or hydraulic drag forces; the directions of the stresses arising from each of these are determined by the directions of the accelerations and the seepage. For the problem considered in our Note, σ_g'

and σ_i' are both radial and hence could be simply summed.

An important assumption stated in our Note was that no significant soil strains occur close to the lining after its installation. In many soft ground tunnelling operations, relatively large ground strains generally occur during excavation and before installation of the lining, but thereafter further ground strains are usually much smaller. In clay, negative excess pore pressures are generated close to the tunnel by the process of tunnel excavation; these dissipate with time and, if the lining is permeable, steady state seepage develops. Generally, however, except perhaps in very soft clays, only relatively small strains are caused by this dissipation of excess pore pressures and subsequent steady state seepage; any arching effect due to these strains is then also small. Our Note argued that, in these circumstances, the total load acting on the lining will be almost the same irrespective of whether it is leaking or watertight. (We agree with Hungr that any arching effects would anyway be less for seepage stresses than for self-weight stresses, because seepage stresses build up rapidly close to the tunnel—unlike self-weight stresses.)

Gunn and Taylor present a very interesting example of finite element analysis predicting behaviour of a soft clay around a tunnel. In their example, the strains caused by dissipation of the excess pore pressure generated by excavation (but subsequent to lining installation) are *not* small. Analyses such as these are particularly valuable in improving the understanding of the effective stress changes in yielding soil around a tunnel opening and are especially relevant to problems of time-dependent deformations during excavation (known as squeeze to tunnelers). The undrained shear strength of the clay in their example is not stated, but it is understood that the stability ratio (Broms & Bennermark, 1967; Davis, Gunn, Mair & Seneviratne, 1980) is approaching a critical value, so that when excavation is simulated the tunnel is close to collapse; a substantial annulus of clay around the tunnel would then immediately be in a plastic state of failure. Moreover, a Young's modulus E' of only 5000 kPa has been assumed; even if only elastic behaviour occurred around the tunnel, this would indicate strains of about 2% for effective stress changes of the order of 100 kPa (in fact, substantial plastic behaviour was evident). Relatively large soil strains must therefore have occurred subsequent to tunnel excavation, and the resulting substantial increase in arching has the effect of reducing lining loads, as clearly shown by Gunn and Taylor. They show the final total stress on the lining to be 110 kPa and 60 kPa respectively for impermeable and permeable linings. These lining stresses correspond to 55% and 30% of the total overburden pressure.

The example of Gunn and Taylor shows that the radial effective stress (σ_g' as defined in our Note) drops to about 50 kPa in both cases. However, if there were no further significant soil strains after lining installation, we would suggest that for the impermeable lining σ_g' would remain at about 50 kPa and the pore pressure would return to its original value of 100 kPa; for the permeable lining the pore pressure would remain at zero, but seepage stresses would increase the radial effective stresses by 100 kPa, so that the combined radial effective stress would approach 150 kPa. In both cases, the total lining stresses would be about 150 kPa, which is 75% of the total overburden pressure. As we remarked in our Note, this value is more in accord with field observations of long-term stresses acting on tunnel linings in clays; these indicate stresses approaching full overburden pressures, despite the likelihood that most lined tunnels in clay act as permanent drains (Peck, 1969; Ward & Pender, 1981). We suggest that the reason for this is principally that the soil strains are relatively small after installation of the lining. Only in tunnelling in clays with high stability ratios might the long-term lining stresses be substantially less than 75% of the overburden pressure, and even then long-term creep effects (subsequent to complete dissipation of all excess porewater pressures) might reduce the arching.

We believe that the present criterion generally assumed by tunnel designers that full overburden pressure is transferred to linings in clay soils is prudent. Possibly this criterion might be over conservative in very deep tunnels. We remain firmly of the opinion that caution should be exercised by designers who might argue that significantly lower stresses are transferred to linings if they are permeable. There is clearly a need for more field measurements of long-term stresses in tunnel linings, particularly those in clay soils, and of porewater pressures in the ground around the linings.

Finally, we agree with the point raised by Gunn and Taylor regarding equation (3) in our Note. Superposition of surface loading and self-weight effects needs to be validated.

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