The drill-and-notch procedure has several advantages in blasting the contour of a tunnel:

1. Drilling costs should be reduced. Langefors and Kihlstrom (2) recommend s/D ratios of 16 and 8 for smooth blasting and presplitting respectively. Increasing the s/D ratio to, say, 50 will reduce the number of boreholes required on the contour by factors of 3 and 6 respectively.
2. Relatively few cracks will be produced in the wall that remains after excavation. This should improve its strength and stability and thus minimize the need for auxiliary support such as rock bolts, shotcrete, and frames.
3. Control of the fracture plane should reduce the possibility of overbreak and underbreak. Thus, the costs associated with scaling forms and concrete should be greatly reduced.
4. There will be a cost savings since the relatively low-density charges of 0.03 kg/m for 3.8-cm diameter (0.02 lb/ft for 1.5-in diameter) specified for use with notched boreholes require less explosive than the more highly loaded 0.12 kg/m for 3.8-cm diameter (0.08 lb/ft for 1.5-in diameter), smooth-blasting rounds. In addition, since low explosives may be used instead of high explosives, further cost reductions for explosives may be achieved.
5. Fracture control used in the hexagonal opening cut reduces the time required for opening the heading. The major advantage is the elimination of the very expensive, large-diameter dummy hole. In addition, the number of smaller holes is reduced, and the tolerance on the drilling pattern can be relaxed.
6. Finally, in both contouring and opening, using reduced and highly cushioned charges will greatly reduce ground vibration and thus reduce the number and frequency of complaints about blasting in heavily populated urban areas.

ACKNOWLEDGMENTS

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Improvement of Ground-Support Performance by Full Consideration of Ground Displacements

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A conceptual description of the ground behavior around a tunnel and a quantitative analysis of the effects of the more important factors that influence tunnel support loads are presented. Axisymmetric finite element models of the advancing tunnel were used for the quantitative analysis. The variables considered in the investigation were the relative stiffness of the ground and the support, the constitutive behavior of the ground, and the delay of support installation. The conclusions of the study are that decreasing the relative stiffness of the support or increas-

Figure 1. Tunnel conditions before excavation.

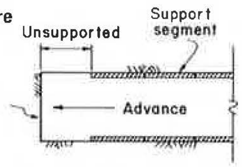


Figure 2. Ground movement and load redistribution resulting from tunnel excavation.

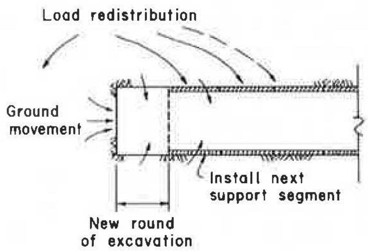
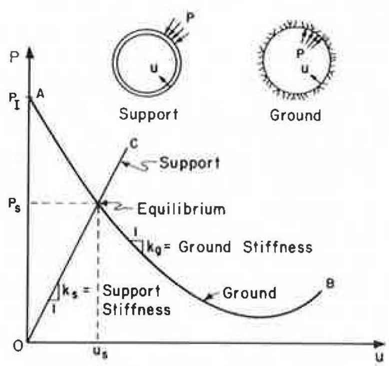


Figure 3. Ground and support characteristic curves.



ing the delay of the support installation generally reduces the forces in the tunnel support but at the same time may induce greater amounts of detrimental yielding in the ground mass. Comments on the optimization or minimization of tunnel support loads are also included.

Tunneling excavation creates a complex pattern of movements in the ground mass around the tunnel. These displacements, a significant portion of which occur in the region ahead of the advancing tunnel face, cause the shearing resistance of the ground to be mobilized and can result in substantially reduced support loads. Unfortunately, however, the exact magnitude of the ground movements near the face and the quantitative effect that these movements have on support loads are generally unknown. Because the relations between ground characteristics, near-face movements, and resulting support loads have not been adequately established by field measurements and analytical studies, no rational model of the mobilization of ground resistance or of corresponding support loads is possible.

The purpose of this paper is to improve the understanding of this ground-support interaction by investigating the effects of several ground and support parameters on tunnel performance, i.e., on ground displacements and support loads. Three major variables were considered in the investigation: (a) the unsupported length between the face of the tunnel and the point of support installation, (b) the ground behavior around the tunnel (elastic and inelastic), and (c) the relative stiffness of the support to the ground. Analytical finite element models were used in these studies since they permit one to examine easily and inexpensively a range of ground and support parameters. The results of these finite element analyses are not intended to represent the behavior of any particular real tunnel but can be used as guidelines for improving the efficiency of tunnel supports.

QUALITATIVE BEHAVIOR OF GROUND AND SUPPORT

The behavior of the ground around a tunnel as it interacts with the support is extremely complex; loading and unloading, fracture and plastic yielding, postfailure strength and stiffness deterioration, seepage, creep, consolidation, or swelling can all occur around a tunnel. Many of the factors that influence the behavior are interrelated, and separating their effects is difficult. However, the conceptual description presented in this section will provide a better understanding of this behavior and the various factors that affect it and will form a basis for the interpretation of the results of the quantitative analytical study.

Only those aspects of interaction behavior that are relevant to this analytical study are described here. A more complete treatment of this topic is given by Einstein and others (4).

Ground-Structure Interaction

A good overview of the patterns of stress changes and ground movements that occur around an advancing tunnel may be gained by considering a typical cycle in the tunnel construction sequence. Figure 1 shows the conditions that exist in the tunnel immediately before a new round of excavation. The tunnel support has been installed up to a point a short distance behind the face. (The exact details of the support conditions at the face depend, of course, on the ground type and on the details of the construction procedure.) The changes that occur after an advance are shown in Figure 2. The removal of ground at the face induces a change in the stress field or a redistribution of load around the tunnel. Most of the redistributed load is transferred to the tunnel support—both to the support already in place and to the newly installed segment—but a significant portion is also transferred to the unexcavated ground ahead of the face. Concurrently, this redistribution of load causes a pattern of movements within the ground mass. Behind the face, predominantly radial deformations toward the tunnel occur around the excavated section while, in the region immediately ahead of the face, the combination of the increase in stress caused by redistribution of load and the removal of lateral support (the excavated ground) up to the new face results in both longitudinal and radial ground displacements. The radial displacements ahead of the face are particularly significant since they may be a sizable fraction (20 to 30 percent or more) of the eventual total radial ground movement around the tunnel.

The load redistribution around an advancing tunnel will produce failure in the ground mass when the shear stresses that result from the excavation exceed the shear strength of the material. In other words, failure occurs when the difference between the major and minor principal stresses exceeds some maximum allowable value. In an unlined tunnel, the largest difference in principal stresses occurs at the tunnel wall where the radial stresses approach zero.

The primary purpose of the tunnel support is to provide a counterstress to the ground mass around the tunnel to maintain the stability of the opening at an acceptable level of deformation. The unloading of the ground mass that follows excavation results in the loading of the tunnel support; this relation can be seen most easily by using the conceptual tool of characteristic curves. Figure 3 shows the characteristic curves for both the ground

Figure 4. Effect of support delay on support loads.

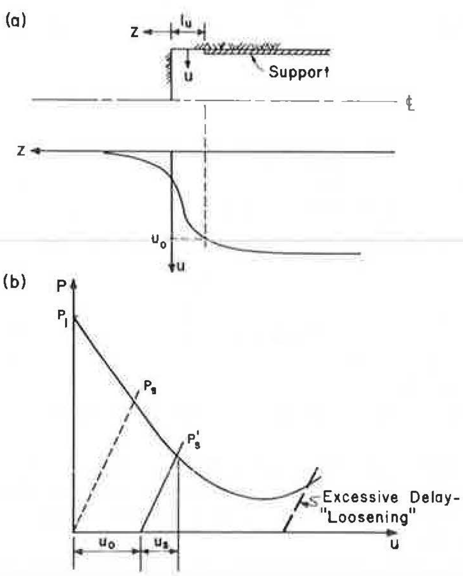


Figure 5. Effect of ground yielding on support loads.

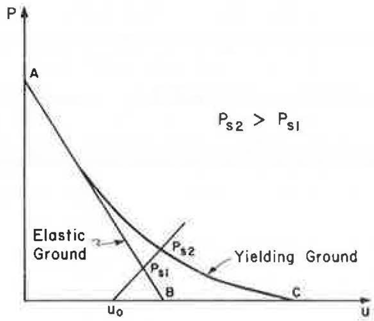
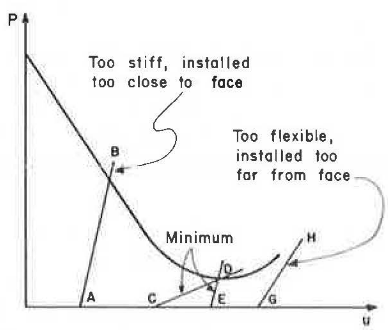


Figure 6. Minimization of support loads.



and the support. In this highly idealized situation, the excavation of the ground corresponds to a decrease of the internal tunnel pressure along curve AB. The support is assumed to be in place before any excavation starts, and thus any excavation (i.e., unloading of the ground) immediately results in a loading of the support along curve OC. The intersection of the two curves is the equilibrium point: P_s is the tunnel support load and u_s is the corresponding inward radial displacement at equilibrium. Of course, the support characteristic curves need not have the idealized linear shape shown in the figure; the curves should represent the actual load-displacement characteristics of the support [Lombardi (5) gives examples of nonlinear support systems].

The development of support forces as the support deforms with the ground and the concurrent restraining effects these forces have on further ground movement is the ground-structure interaction around the tunnel. The essential feature of this interaction phenomenon is that the support and the ground mass are in contact and deform together. This can happen in two ways: (a) The support is installed so close to the face that further advances of the tunnel result in additional ground movements and support deformations, and (b) the ground and support movements continue after the support has been installed because of a variation in the ground properties with time. In reality, both types of interaction often occur simultaneously as soon as the in situ state of stress in the ground has been altered by the excavation. However, for the purposes of the present discussion, only the time-independent, or instantaneous, interaction is considered.

The instantaneous ground-structure interaction is greatly affected by any ground movements that occur before the support is constructed. The magnitude of these ground movements depends to a large extent on exactly how far behind the face the support is installed. If the support is installed right at the face, the presupport ground movements will be very small, substantial additional movements will take place as the excavation proceeds, and the eventual support loads will be relatively large. On the other hand, if the support is installed farther behind the face, more ground movements will have already occurred, less interaction will take place between the ground and the support, and consequently smaller support loads will develop (provided no detrimental ground loosening occurs).

The effects of support delay (the spatial lag of support installation behind the face) on the ground-structure interaction and on the resulting tunnel support loads are shown in Figure 4. As shown in the upper part of the figure, the radial ground movements begin at approximately one to two tunnel radii ahead of the face and increase very rapidly near the face. By the time the support is constructed, the ground has already deformed by an amount u_0. This movement corresponds to a partial unloading of the ground mass before support; any further movement of the ground will cause deformations and internal forces in the tunnel support. Preexcavation support of the tunnel (i.e., the support is somehow installed before excavation) would give an equilibrium support pressure equal to P_s; the one-radius support delay would result in the reduced equilibrium pressure P_s' (6). In general, increasing the support delay decreases the support loads if the support delay is not too large. An excessively large delay allows the ground to loosen and leads to larger support loads (Figure 4).

In addition to the delay of support installation, another factor that has an extremely important effect on ground-structure interaction and the resultant support loads is the relative stiffness of the ground mass and the support. This can be seen conceptually by considering the ground-structure interaction as a sharing of load by two dissimilar but intimately connected structural elements much in the same way as load is shared between steel and concrete in a reinforced concrete column. The stiffer element (the steel in the reinforced concrete column) carries a proportionately larger share of the load; increasing the stiffness further increases the load on the element. Similarly, increasing the stiffness of the tunnel support relative to the ground mass results in larger support loads if all other factors are held constant. As Figure 3 shows, the stiffness of the ground and the support are directly related to the slopes of their characteristic curves (6).

The effect on the tunnel support loads of ground yielding or failure is shown in Figure 5. The straight line AB represents the elastic ground behavior, and curve AC is the ground characteristic curve when yielding occurs.

Table 1. Cases analyzed.

Case	Description of Ground	Ground Properties[a]				Support Properties[b]			
		E/P	ν	ϕ	c/P	E_ℓ/P	ν_ℓ	t/R	C^*[c]
1A	Dense sand, badly fractured rock	180	0.30	35°	0.0012	37 440	0.30	0.0358	0.134
2A	Undrained clay	60	0.48	0	0.200	37 440	0.30	0.0358	0.052
2B	Loose sand, drained silty clay, very badly fractured rock	60	0.30	25°	0.0012	37 440	0.30	0.0358	0.044
SS	Massive soft rock (e.g., sandstone)	24 000	0.30	-	-	37 440	0.30	0.0358	17.9
LLE[d]	Drained soft ground	60	0.40	-	-	24 000	0.15	0.1	0.028
LEP1[d]	Drained soft ground	60	0.40	30°	0.168	24 000	0.15	0.1	0.028
LEP2[d]	Undrained soft ground	60	0.40	0°	0.168	24 000	0.15	0.1	0.028

[a] In situ ground stresses: $\sigma_v = \sigma_h$ = 575 kPa (12 000 lbf/ft²); corresponds to a depth of approximately 30 m (100 ft).
[b] R = 3 m (10 ft) in all cases.
[c] $C^* = [ER(1 - \nu_\ell^2)]/[E_\ell t(1 - \nu^2)]$ = measure of stiffness of ground relative to support.
[d] From Ranken and Ghaboussi (7).

Table 2. Summary of analysis results.

Case	Type of Analysis	Support Delay (lu/R)	Finite Element			Closed Form (T/PR)
			u/R	T/PR	Z_p/R[a]	
1A	Elastic	0	0.001 1	0.77	-	0.91
1A	Elastic	0.5	0.002 2	0.51	-	0.91
1A	Elastoplastic (ϕ = 35°, c/P = 0.0012)	0	0.001 1	0.75	0.25	0.91
1A	Elastoplastic (ϕ = 35°, c/P = 0.0012)	0.5	0.002 2	0.50	0.25	0.91
2A	Elastic	0	0.003 8	0.84	-	0.97
2A	Elastic	0.5	0.006 2	0.61	-	0.97
2A	Elastic	1.0	0.015	0.25	-	0.97
2A	Elastoplastic (ϕ = 0, c/P = 0.200)	0	0.009 4	0.65	1.75	0.97
2A	Elastoplastic (ϕ = 0, c/P = 0.200)	0.5	0.014	0.45	2.0	0.97
2A	Elastoplastic (ϕ = 0, c/P = 0.200)	1.0	0.029	0.35	2.0	0.97
2B	Elastic	0	0.002 6	0.83	-	0.97
2B	Elastic	0.5	0.004 6	0.58	-	0.97
2B	Elastoplastic (ϕ = 25°, c/P = 0.0012)	0	0.002 8	0.81	0.75	0.97
2B	Elastoplastic (ϕ = 25°, c/P = 0.0012)	0.5	0.004 9	0.64	0.50	0.97
SS	Elastic	0	0.000 048	0.054	-	0.074
SS	Elastic	0.5	0.000 051	0.030	-	0.074
LLE[b]	Elastic	0	0.002 8	0.88	-	0.98
LLE[b]	Elastic	1.0	0.015 3	0.29	-	0.98
LEP1[b]	Elastoplastic (ϕ = 30°, c/P = 0.168)	0	0.002 8	0.88	0.50	0.98
LEP1[b]	Elastoplastic (ϕ = 30°, c/P = 0.168)	1.0	0.017 7	0.30	0.60	0.98
LEP2[b]	Elastoplastic (ϕ = 0, c/P = 0.168)	0	0.004 1	0.80	1.5	0.98
LEP2[b]	Elastoplastic (ϕ = 0, c/P = 0.168)	1.0	0.018 8	0.45	1.8	0.98

[a] Z_p = extent of yielded zone ahead of face. [b] From Ranken and Ghaboussi (7).

The same support system (stiffness, strength, installation delay) is used in both cases, but in the case of ground yielding the equilibrium support pressure and displacements increase. This increase may be viewed conceptually by considering the effective stiffness of the ground in the two cases. As yielding occurs, the ground within the failed zone becomes plastic and considerably less stiff. The stiffness may even become negative (at least theoretically) in severely strain-softening materials. This decrease in stiffness in the failure zone in turn causes a reduction of the effective stiffness of the ground mass as a whole or, in other words, a decrease in the stiffness of the ground relative to the support. The support loads must, as a consequence, increase.

Minimization of Support Loads

It has been shown that the load sustained by the support in a tunnel is not a fixed quantity. The support pressure can be varied over a moderate range by suitably adjusting factors such as support stiffness and delay of installation. Obviously, then, these factors should be adjusted in such a way as to minimize the support loads or, stated in another way, to mobilize the maximum strength of the ground mass without exceeding maximum admissible displacements from the viewpoint of stability or operation.

Minimizing the support load is conceptually nothing more than an attempt to intersect the ground characteristic curve at its lowest point. Figure 6 shows this minimum and some typical nonminimum cases (curves AB and GH); it also shows that more than one support system can produce the minimum support load for any given tunneling situation (curves CD and ED). This conceptual framework puts the following analytical study of the factors that influence the ground-support interaction into its proper context.

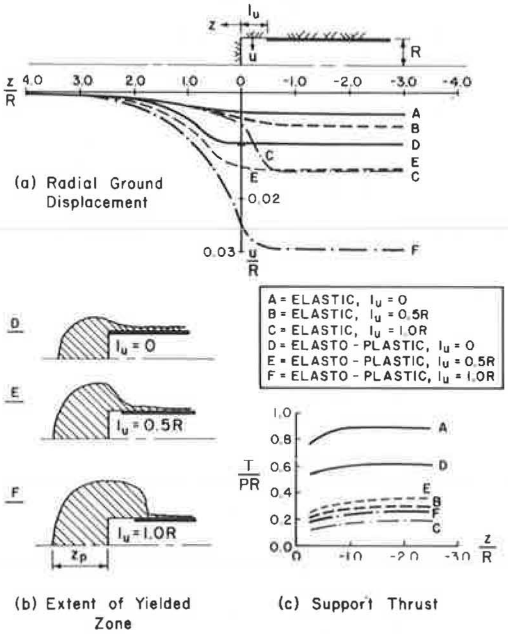
ANALYTICAL STUDIES OF GROUND-SUPPORT INTERACTION

Purpose

Some of the factors that most influence ground-support behavior around a tunnel—ground properties (strength and deformability), the relative stiffness of the support and the ground, and the delay of the support installation—have already been described conceptually. It has also been shown to be possible, at least qualitatively, to adjust these factors to yield a minimum support load. However, in practical tunnel design it is necessary to assign quantitative values to these factors, and that is the purpose of this analytical study. In this study, the major factors are varied to investigate which ranges of their values are most important in optimizing the design of tunnel support. However, the investigation is not intended to be a detailed parametric study.

Two sets of analytical studies were used. The first set consists of the finite element analyses reported in the literature by Ranken and Ghaboussi (7), who used the GEOSYS program (1). The studies in the second set are the finite element analyses that we conducted under the

Figure 7. Analysis results for undrained clay (case 2A).



sponsorship of the U.S. Department of Transportation. The computer program ADINA (2, 3) was used in these analyses. Details of these studies are given below.

Description

The analytical studies were conducted to study the effects of three major factors that influence ground-support interaction: (a) the delay of the support installation (it should be recalled that delay refers to a lag in space rather than time)—installation of the support either right at the face, half a tunnel radius behind the face, or one full radius behind the face; (b) the ground behavior—either linearly elastic, frictional elastic and perfectly plastic ($\phi \neq 0$), or purely cohesive elastic and perfectly plastic ($\phi = 0$); and, to a lesser extent, (c) the relative stiffness of the support and the ground. The idealized tunnels are all 6 m (20 ft) in diameter at a centerline depth of 30 m (100 ft). The in situ vertical and horizontal ground stresses are both 575 kPa (12 000 lbf/ft^2), i.e., K = 1. In nearly all cases, the ground properties are characteristic of soft ground—either soil or badly fractured or shattered rock. One intact rock case was analyzed to determine better the effects of the relative stiffness of the ground and the support. The support properties in the cases we analyzed were based on typical dimensions for precast concrete liner segments; the support properties used in the analyses performed by Ranken and Ghaboussi correspond to 30-cm (1-ft) thick concrete liner. Complete details of all of the cases, including those of Ranken and Ghaboussi, are given in Table 1 (E = modulus of elasticity, c = cohesion, and C* = compressibility ratio).

Because of the assumption of uniform in situ ground stresses (i.e., K = 1), two-dimensional axisymmetric finite elements can be used to analyze the behavior near the tunnel face. Sequential excavation of the initially stressed ground and the installation of the liner elements are simulated by deactivating or activating elements at appropriate stages of the calculations. Fourteen excavation-installation steps were used in most of the analyses that we performed.

The details of the finite element analyses performed by Ranken and Ghaboussi are described in their original report (7).

Results

The pertinent data from the analyses performed for this study are summarized in Table 2. The results of most interest are u/R, the normalized radial ground displacements at the tunnel wall, and T/PR, the normalized support thrust (P = overburden pressure and R = tunnel radius). Also given in the table is Z_p, the extent of the plastic zone ahead of the tunnel face, and a reference value for the normalized support thrust obtained from a closed-form elastic plane strain solution (4).

Some important trends can already be discerned in the data presented in Table 2. All of the cases except SS (the intact rock case) have roughly similar values for T/PR independent of the ground type or the ground strength parameters. Only the delay of the support installation has an important influence. When the support is installed right at the face (l_u = 0), T/PR varies between 0.6 and 0.9 (and in most cases between 0.75 and 0.88); when the support is delayed (l_u = 0.5R or 1.0R), T/PR ranges from 0.25 to 0.65.

If the intact rock case SS is compared to the other cases, the effect of the relative stiffness of the ground to the support loads becomes apparent. The compressibility ratio C* (defined in Table 1) varies between the narrow limits of 0.028 and 0.134 for all cases except case SS. In contrast, case SS has a compressibility ratio two to three orders of magnitude higher (C = 17.9) and a much lower thrust coefficient (T/PR = 0.054 for l_u = 0). Thus, the intact rock, which is much stiffer than the soft ground of the other cases, carries a proportionately larger share of the load around the tunnel, which leaves little to be sustained by the tunnel supports. This is exactly the result predicted qualitatively earlier.

The variation of ground displacements and support thrusts with distance from the tunnel face is shown in Figure 7 for case 2A, a purely cohesive soft ground (ϕ = 0) (the data for the other cases are not presented but are similar in nature). The results for both elastic and elastoplastic fully supported and partially supported (support installed at a distance l_u behind the face) analyses are presented. In all of the cases, the radial ground movements begin approximately three to four tunnel radii ahead of the face. Nearly all of the ground displacement around these partially or fully supported tunnels occurs ahead of the face; the installation of the support and the rapid development of the support thrust quickly arrest further ground movement. Plane strain equilibrium conditions for both the displacements and the support thrusts are reached one to two radii behind the face in all cases.

The extent of the yielded zone for the elastoplastic analyses of case 2A is also shown in Figure 7. Yielding occurs principally in the region immediately ahead of the face, and the partially supported cases (l_u = 0.5R - 1.0R) generally exhibit more yielding than the fully supported cases (l_u = 0). The counterstresses applied to the ground mass by the tunnel support reduce the extent of the yielded zone around the support in the plane strain region. This "collapse" of the plastic zone, which was found in all of the cases we analyzed, is somewhat different from the findings obtained by Ranken and Ghaboussi (7); in their elastoplastic analyses, installation of the support prevented any further increases in the extent of the yielded zone but did not reduce its size in the region of plane strain. From conceptual considerations, however, a decrease in the extent of the yielded zone would be expected after the support is installed. Excavation causes a radial unloading and tangential loading of the ground

Figure 8. Effect of support delay on final radial ground displacement.

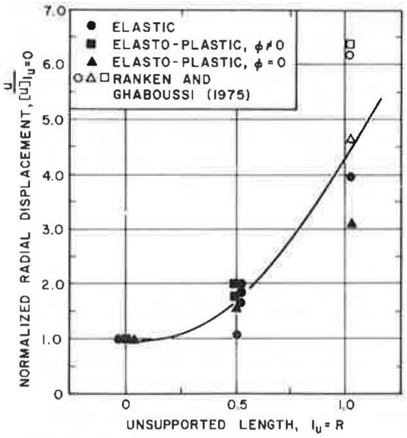
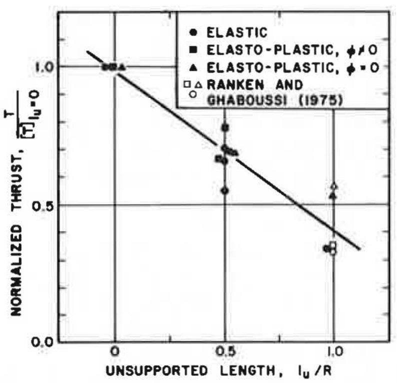


Figure 9. Effect of support delay on support thrust.



near the tunnel wall; interaction with the support reverses the sense of this loading and should therefore cause a partial return to elastic behavior.

The effect that the delay of the support installation has on radial displacements is shown in Figure 8. The final radial ground displacements have been normalized by dividing by the equivalent displacements for the fully supported cases (l_u = 0); thus, the figure shows the percentage increase in ground displacements that results only from the support delay. A delay of 0.5R yielded a 70 percent average increase in radial ground displacements; further increasing the delay to 1.0R increased the ground movements 350 percent above the fully supported cases. Whereas the elastic and frictional ($\phi \neq 0$) elastoplastic analyses yielded similar percentage increases in ground movements, the increases for the purely cohesive (ϕ = 0) elastoplastic analyses were smaller, possibly because of the absence of postfailure dilatancy in the ϕ = 0 analyses.

Figure 9 shows the corresponding effect that support delay has on support thrust. In this figure, the support thrusts obtained from the finite element analyses have been normalized by using the thrusts calculated from the closed-form, plane strain solution (Table 2). As expected, based on the qualitative behavior described earlier and on Figure 4, delaying the support installation substantially reduces the support forces: A delay of 0.5R yielded a decrease in thrust of about 30 percent. Further increasing the support delay to 1.0R had a variable effect on support thrust. The increase in delay reduced the support thrust for the

Figure 10. Effect of ground yielding on final radial ground displacement.

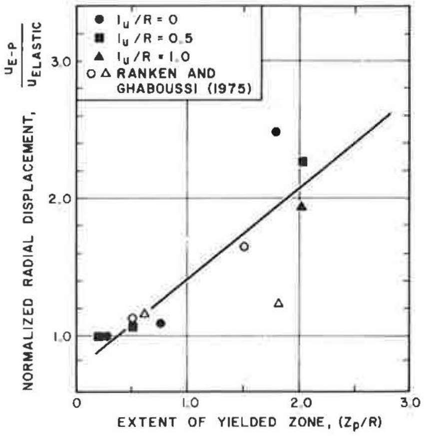
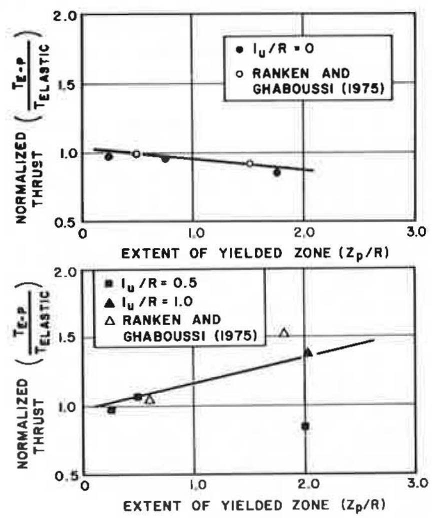


Figure 11. Effect of ground yielding on support thrust.



elastic cases by another 30 percent; however, in the elastoplastic cases the thrust decreased only slightly as the delay was increased from 0.5R to 1.0R. The additional yielding in these elastoplastic cases appears to have counteracted any benefits of the longer support delay.

The last factor considered in this study was the effect of failure in the ground mass on ground displacements and support forces. As expected, based on the earlier qualitative prediction and on Figure 5, ground yielding or failure should increase ground displacements and support forces. Figure 10 shows the increase in ground displacements obtained from the analyses. The vertical axis represents the final radial displacements in the elastoplastic cases divided by the equivalent elastic displacements, and the horizontal axis represents the amount of ground yielding measured by the extent of the plastic zone ahead of the face (Z_p). There is considerable scatter in the data, but the general trend is an increase in displacements with increased yielding.

The effect of ground yielding on support forces was inconclusive. As shown in Figure 11, increased ground yielding in the fully supported cases (l_u = 0) slightly decreased support thrusts. In the partially supported cases (l_u = 0.5R and 1.0R), however, increased yielding in the ground mass did increase support forces but by an unexpectedly small amount. An interaction appears to take place in which the detrimental aspects of ground yielding are counteracted by the beneficial effects of support delay. Yielding of the ground mass increases the distance between the tunnel support and the unyielded, stiffer ground regions ahead of the face and results in what might be called an increase in the effective unsupported length. In some instances, this effect might lead to a net reduction in the support thrusts. This is one possible explanation for the slight decrease in support thrust that occurred in the fully supported tunnels as the extent of the yielded zone increased.

CONCLUSIONS AND RECOMMENDATIONS

This study has attempted to show the following effects that support delay, ground yielding, and relative support stiffness have on the ground displacements around a tunnel and on tunnel support loads:

1. Support delay—Out of the three major variables considered in this study, delay in the support installation had the most dramatic effect on tunnel performance. Delaying the support installation to a point one tunnel radius behind the face increased the average radial ground movements by 350 percent and decreased the average support thrust by 60 percent. These findings agree well with the qualitative predictions.
2. Ground behavior (yielding or nonyielding)—The results of the finite element analyses were inconclusive on this point. Yielding in the ground mass increased radial ground movements in all cases, but it decreased the support thrusts in the fully supported cases (support installed at the face) and increased the thrust in the partially supported tunnels (support installed one-half to one radius behind the face). Qualitatively, ground yielding should increase both ground displacements and support thrusts in all cases. There appeared to be some interaction between the detrimental aspects of ground yielding and the beneficial effects of support delay. In some cases, ground yielding might be considered to increase the total distance between the support and the stiff, unyielded ground ahead of the face or, in other words, to increase the effective support delay.
3. Relative stiffness of ground and support—Increasing relative stiffness (as measured by the compressibility ratio) by over two orders of magnitude reduced support thrusts by nearly 1700 percent. However, radial ground movements depended primarily on the absolute ground stiffness rather than the stiffness of the ground relative to the support.

The forces in the tunnel support can be reduced by delaying the support installation or by decreasing the stiffness of the support relative to the ground. However, this reduction may be offset by the accompanying increase in ground yielding (especially if the ground is strain-softening). The radial movements of the ground increase with increasing support delay and decrease with increasing ground and support stiffness. The optimum combination of support delay and support stiffness that minimizes the support loads depends also on the amount of yielding in the ground mass. Although further investigations are required to assess the full effect of ground yielding (particularly for strain-softening ground behavior, which was not considered in this study), this study does show the beneficial effect of small support delays (unsupported length = 0.5 to 1.0 radius) and moderate reductions in support stiffness on tunnel support loads.

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