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Soft ground tunnelling

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Mr A. W. Shilston, Consulting Engineer

In a 'state of the art' paper set against the background of the conception, design and construction of a length of hypothetical tunnel driven under a road in a city (and therefore a built-up area with buried services below the carriageway above the tunnel) there is a significant gap in an otherwise comprehensive review of soft ground tunnelling procedures. Something ought to be said about grouting, grummetting, caulking and timbering in the context of the type of tunnel described.

82. The Greathead type boogee (grout) pan still seems to be in use after more than 100 years. The alternatives appear to be the Mono pump or possibly the double acting Cementation grout pump. In the early days lias-lime grout was used: neat ordinary Portland cement or rapid hardening Portland cement are now usually employed, perhaps with PFA admixtures. Overbreak grouting is sometimes carried out using pea gravel in conjunction with a boogee pan. The primary role of grouting in a clay tunnel is to fill the overbreak space; it is doubtful whether there is a great deal of merit in grouting a gravel tunnel from the cavity filling standpoint.

83. Views seem to differ on the role of grouting from the aspect of tunnel lining watertightness. Back grouting is often done in an attempt to improve watertightness. Grouting a tunnel lining in gravel is hardly an item of work that a contractor can be expected to price in a tender bill of quantities: yet it appears in some bills that contractors are required to price for grouting and making watertight against the superficial measurement of the tunnel extrados.

84. The Authors make no reference to the types of grummetting and caulking available and the role of these in the finished tunnel. It would add comprehensiveness to the Paper if they would say something about the interrelated operations of grouting, grummetting and caulking in the context of the type of tunnel described.

85. Finally, reference is made in the Paper to timbering and boarding. Ought the younger engineers for whom the Paper was written to assume that axiomatically the use of wood is involved? If not, perhaps some indication should be given whether other materials can or ought, in some situations, to be used.

Mr D. A. Howells, Consulting Engineer

The Authors, referring to the paper by Donovan,[1] note that 'like so many of the best papers on the subject, his contains no mathematical formulae'. It would be difficult, though, to carry out the analyses referred to in §§ 21–27 without reference to some of the other best papers on the subject: those which do contain some mathematical formulae.

87. Stability of the lining requires an adequate factor of safety against failure in the mode which will produce the lowest factor of safety. This failure mode may be investigated by either an upper bound or a lower bound approach.

88. The upper bound approach may for engineering purposes be identified with the definition of that collapse mechanism, which might be a roof fall for example, having the lowest factor of safety. Then the forces between the ground and the lining

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can be assessed and the idea of loads acting on the lining becomes a valid one. However both the data and the theoretical structure relating them to the proportions of the collapse mechanism are in a very primitive state, so that large factors of ignorance have to be incorporated in any formulation. Many contributions to the upper bound approach are discussed by Szechy[2] though he does not classify them as such.

89. The lower bound approach can, again without necessarily being rigorously submitted to the logic of applied mechanics, be regarded as much the same thing as a stress analysis approach. A purely elastic analysis stops too far short of the lower bound to be very helpful. The step by step penetration of the non-linear range is a recent development. It depends very much on a successful understanding of the other variables, such as volumetric strain, which enter into the stress/strain relation. The basic tunnelling operation occupies a finite time, as does the progressive falling of individual lumps from the roof, and this can be represented by what Zienkiewicz and his colleagues[3] call a 'fictitious' time. In all this lower bound approach the state of stress in the ground is modified by the construction of the tunnel and the modified stresses are shared between the lining and the ground depending upon their relative stiffness in relation to different kinds of deformation, so that any idea of loads upon the lining is quite inappropriate.

90. It might be thought that with an upper bound and a lower bound to collapse, the stability of a tunnel lining could be assessed with some confidence, but in practice this is not so. The upper bound approach is found to be appropriate to shallow tunnels and the lower bound approach to deeper ones. In fact the criterion is not the depth itself, but the non-dimensional ratio of the overburden pressure to the shear strength of the ground. This arises partly because the roof fall mechanism, which predominates for shallow tunnels, may not be the determining collapse mechanism at greater depths and partly because for shallow tunnels the in situ stresses are so small.

91. Design and analysis are two facets of one engineering process and should not be confused. Design is a matter of choice: analysis a matter of assessing the effect of a choice. Many analyses based on seemingly unrealistic assumptions can help the designer reach a decision provided he never loses sight of the assumptions. 'Direct design', where the choice of a particular dimension follows directly from the analysis, is less common than many young engineers imagine and to accept it as valid in a particular circumstance is itself a design decision. In tunnelling there is still much to learn before it can become acceptable.

92. Will the Authors please give a definition of 'empirical' as they use it in the phrase (§ 24): 'Empirical and semi-empirical methods of design generally make basic assumptions about the ground loadings . . .'. In the usual Baconian meaning 'empiricism' is incompatible with the making of basic assumptions.

Mr D. W. Smith, Lecturer, University of Dundee

The most important comment to be made on this excellent Paper is that many more such are needed. Not only the younger engineer, but also university teachers and their students, any engineer, however experienced, who wishes to be informed outside his own speciality, and eventually, in fact, the whole profession, would benefit from a more abundant supply of good review papers which summarize current practice in a branch of civil engineering. In a lively and developing technology it is inevitable that textbooks are, for the most part, either too purely scientific, or soon out of date. There will always be a gap to be filled by papers such as this, written in terms that can be understood by beginners and by engineers from all branches.

94. In the limited space available to them, the Authors clearly had to be selective, leaving a number of questions unanswered; and not all the material could be descriptive of the present state of the art as against permanent background facts. The reader would welcome much fuller discussion of the pros and cons of various decisions.

95. For example, just enough is said about tunnels with and without shields and

about shields with and without tails (§§ 32–35) to whet the appetite. In ground where a tail is unnecessary, what conditions demand the presence of the shield? What considerations lead the engineer to select bolted and grouted lining before the question of the shield-tail has been settled?

96. Another area where further information would be valuable concerns costs, and speed of progress in tunnel construction. Of course these vary widely with circumstances, but some very rough indication of the most and the least expensive, and the quickest and slowest construction, would be helpful, especially if backed up by a brief statement of the reasons leading to each.

97. Finally, it would be of interest to hear the Authors' views about the potential value of tunnel engineering as a subject for undergraduate teaching. All too frequently the noises from industry that penetrate academic circles as to what should be included in an overcrowded degree course concern fringe subjects and beyond. It is good to have tunnelling affirmed as mainstream civil engineering (§ 2). Should it, then, be part of mainstream teaching, and if so, how large a part?

Messrs Bartlett and King

Mr Shilston raises questions of grouting, waterproofing and timbering. Grouting to fill the annular void left between the excavated perimeter of the ground and the outside of the tunnel lining is generally essential, except for linings which are expanded against the ground. The grouting serves two main purposes: it ensures that the lining is properly embedded in, and thus supported by, the surrounding ground, and it reduces ground movement into the annular void, which could result in undesirable settlement of the ground surface. In soft ground tunnels, grouting is normally carried out as Mr Shilston describes. Where the restraint of ground movement is particularly important, the timing of the shield advance and the injection of grout must be controlled carefully; in sands and gravels which tend to ravel onto the tunnel crown very rapidly, it may not be possible to prevent all movement, but in this case early embedment of the shoulders of the tunnel lining is essential if distortion is to be avoided. In future it is to be hoped that new grouts and improved sealing arrangements around the tail of the shield will allow grout to be injected as the shield advances, whenever desirable.

99. This type of grouting clearly assists in obtaining watertightness but must be differentiated both from deeper injection to fill ground fissures and from grout treatment carried out in advance of tunnelling. These operations may be used specifically to promote watertightness, and various materials are employed. Shortage of space precludes dealing with the subject in detail here.

100. Caulking is carried out to waterproof the joints between the segments of bolted tunnel linings where a watertight tunnel is required. Lead, or an asbestos cement compound, is forced into a caulking groove in the joint using special tools. The caulking material is held in position by exerting pressure on the sides of the groove. Lead is the more expensive material, but is used, in conjunction with cast iron linings, where high water pressures are expected or where some movement of the tunnel lining is expected after caulking has been carried out. In the latter event, the lead can be reworked in the caulking groove to re-seal the joint. Grummets are used to seal the bolts to the tunnel lining, and consist of a ring of hard PVC, or hemp impregnated with silica gel placed round the bolt, under each washer and forced hard down onto the segment and into the bolt-hole as the bolt is tightened up.

101. On Mr Shilston's final point, general practice is to use timber for securing a tunnel face. It is a comparatively cheap material, light to handle and easy to secure, and simple to cut and shape. In shields employing forward-acting rams to retain the tunnel face, built-in steel face boards are sometimes employed. Steel may also be used in large tunnels for main support members spanning the full face, and as headboards to support the arched top of the excavation for each ring but timber is still the most common material.

102. **Mr Howells** is helpful in his definition of upper and lower bound approaches, and he confirms the complexity of the problem facing a designer. To carry out an analysis which would be considered reasonably representative of the actual tunnelling process and the behaviour of the ground may be a very lengthy and complex operation, and might not be justifiable where, in the engineer's judgement, sufficient experience is already available to show how the ground and lining will behave. The methods of analysis used for design in such cases are, indeed must be, justified by actual observation of the lining behaviour in equivalent circumstances. However, it has not usually been practicable in the past to observe ground stresses and deformation directly, only the behaviour of the lining itself being observable. Several simplified methods of analysis, which can give satisfactory results if properly applied, do not treat lining and ground as a continuum, but analyse the lining only, with various loadings and restraints representing the role of the ground. Thus

(*a*) assumptions must be made about ground loadings, since these are not directly observable;
(*b*) observation may be used as the basis of defining lining deformation.

103. To answer Mr Howell's point; in the context of simple lining design, empirical methods may be considered as those which are based on observation of lining behaviour; nevertheless, for a workable method of analysis, a variable and non-observable parameter, such as ground loading, may need to be invoked.

104. **Mr Smith** treats the Authors lightly on the amount of material which has been left out of the Paper. The subject is not easy to summarize: tunnelling does not conform readily to simple categorization or rules. Every tunnel presents new problems, but this is part of their fascination for an engineer. To answer the question on shield tails very briefly: a tail is required where, during a shield drive, ground may be encountered which will not stand unsupported behind the shield long enough for a ring of the tunnel lining to be erected. Such ground generally precludes the use of expanded linings, which must be jacked out against the ground and rely for their integrity on complete, even embedment. The ground must be cut by the shield to a smooth profile. In some ground conditions, for instance where layers of hard claystone are present in a clay face, it may not be possible for a smooth profile to be cut: in this case, although a shield tail may not be required, a grouted rather than expanded lining may be needed. Of course many types of soft ground may be tunnelled without a shield; other means of ground support may then be necessary, and the choice is generally an economic or practical one; the latter since alternative methods of support often require miners who are highly skilled in traditional techniques, and are as scarce as other such craftsmen.

105. Both costs and rates of advance vary over a very wide range indeed, and depend on many factors. One hesitates to give examples, since these may not mean much out of the very specific context of a single tunnel. Ground conditions, groundwater level, tunnel depth, working access, drive length, type of lining, final use, finishings and many other factors have a profound influence even for tunnels of the same size. Some costs for road tunnels in the UK have been published[4] and show costs for 10 m dia. tunnels varying between about £2000 and £10 000/m at 1970 prices; this variation is due largely to ground and groundwater conditions. At the other extreme, 1·5 m dia. sewer tunnels may, in favourable ground conditions, cost as little as £150/m. For 10 m dia. tunnels rates of progress, when work is proceeding smoothly, may vary between 5 and 20 m/week, depending on tunnelling conditions. For medium sized tunnels, particularly those of 3–4 m dia. which are large enough for mechanical equipment to be accommodated and serviced efficiently, very high rates of progress exceeding 100 m/week have been achieved in suitable strata.

106. For a given size of tunnel constructed under similar conditions with a shield, the cost per metre will initially decrease as the length increases, since the fixed costs of sinking the shaft, installing winding gear, erecting and launching the shield, installing

the materials handling equipment on sledges behind the shield (in stages), together with the gradual build-up of efficient production (learning curve) will then be spread over a greater amount. In very long tunnels, however, distance from the point of access brings its own cost penalty in due course.

107. For hand driven tunnels without a shield, the costs of the heavily timbered excavation for the first two rings (known as the 'break-up') together with the installation of these rings and the slow progress until full production conditions can be established similarly affect the cost per metre driven.

108. The higher speeds of progress achievable with a shield (especially one equipped with mechanical excavators or tunnel lining erectors) may justify the use of a shield in perfectly good ground not otherwise requiring the provision of a shield.

109. Finally, Mr Smith raises the question of education at undergraduate level. Tunnelling is coming more to the forefront of civil engineering, particularly for transportation and services applications: in the 5 year period from 1970 to 1974, over 400 km of tunnels, with a value of about £350 million at 1976 prices, were built in the UK (which is better equipped with earlier tunnels than most countries). This suggests that universities could play a significant part through equipping young engineers to take up, and contribute to, this discipline at an earlier stage.

110. The difficulty of introducing tunnelling into a first degree syllabus is partly because the subject lacks a rigorous and universally accepted theoretical framework on which the problem-solving approach to teaching can build. The simpler design methods have gained acceptance by giving the 'right' answer, and the ability to judge this rightness is likely to be gained only by sustained practical experience. More complex design methods are not necessarily more apposite, and are probably outside the scope of a first degree. Nevertheless, two possible approaches might be considered. First, some of the concepts of ground behaviour and ground control during tunnel construction could be brought into a soil mechanics syllabus; secondly, tunnelling could be treated as a general subject, with only a small theoretical content, linking together several other engineering disciplines.

111. A tunnelling contract requires an unusually high degree of detailed planning, practical supervision, quick and accurate setting out under adverse (and often exasperating) conditions, an understanding and feeling for complex mechanical equipment, coupled with an ability to judge and manage a robust and somewhat independent labour force.

112. All tunnelling work is carried out from a minimum number of shafts or adits to the surface. In urban areas, one such shaft may be the only access to underground workings the size of a reasonably large construction site. If the conception and planning of the way the contract is to be carried out is wrong at the start, efficiency will deteriorate as work progresses away from the focal point. It would be true to say that a knowledge of the history of tunnelling alone would be of great benefit to the young engineer who finds himself underground for the first time.

113. Nevertheless, taking a broad view, tunnelling is and will remain a small sector of civil engineering and cannot claim an important part of any normal first degree syllabus. A university student will perhaps have to be satisfied with some background and historical information on the subject. If he is well grounded in the mechanical sciences he will understand tunnelling after some practical experience, and may then benefit from a post-graduate course in one or more of the associated fields such as soil mechanics, hydraulics or the chemistry of grouts.

References

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