Discussion

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Discussion: Effect of soil models on the prediction of tunnelling-induced deformations of structures

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The authors present an interesting study (Giardina *et al.*, 2020) that compares the results of testing a model tunnel in dry sand in a geotechnical centrifuge with the results of numerical analysis using three different constitutive models. The results are relevant to two questions facing the designers of tunnels constructed by pressurised tunnel-boring machines (PTBMs).

(*a*) Question 1: What magnitude of surface volume loss (settlement trough unit volume) is acceptable during tunnelling, considering the effect on buildings, utilities, roads and other structures near the tunnel alignment?
(*b*) Question 2: What is the appropriate range of operating pressures that should be applied to achieve the target volume loss while avoiding unacceptable heave?

In the context of this discussion, 'operating pressures' refer to the pressures applied at the tunnel face, along the TBM skin and during grouting in the tail void.

It is common in major tunnelling contracts to specify limiting values of surface volume loss. Different limiting values for volume loss may be specified along the tunnel alignment, depending on the sensitivity of the nearby or overlying civil infrastructure. Limiting surface volume loss values have tended to reduce as experience has been gained with PTBMs, and it is now common for a general limit of 1% volume loss to be required, with local limits of 0.5% or 0.75% in sensitive areas; Wan *et al.* (2020) give an example of such an approach. It is the appointed contractor's task to plan and apply the appropriate operating pressures to meet the contracted limits for volume loss. This approach utilises the potential for modern PTBMs and the TBM operators to limit ground movements at source, and generally avoids recourse to ancillary building protection measures such as underpinning or grouting. The approach does, however, rely on the ability of the contractors and their designers to define accurately what can be a very narrow range of acceptable operating pressures, based on the available geotechnical information along the tunnel alignment.

The available guides to establishing operating pressures – Golder Associates (2009), CEDD (2014) and DAUB (2016) – support the calculation of operating pressures at intervals along the tunnel drive, in advance of tunnelling. The spacing of calculation sections depends on the variability of the ground and groundwater conditions. Examples of highly variable ground conditions would include Hong Kong and Singapore, where deep tropical weathering, erosion and more recent deposition results in face conditions that can change rapidly from rock to saprolite to soft clay or sand, or Toronto where the glacial soils can result in the face changing quickly from hard clayey glacial till to uniform, saturated glaciolacustrine sand. The calculation of operating pressure ranges is a design deliverable, although subject to verification and appropriate adjustment on an observational basis during tunnelling. The guides quoted above give various options for establishing the design pressure range, from simple limit equilibrium calculations to using the results of model tunnel tests and/or numerical analysis.

While the paper focuses on the first design question listed above, there is information relevant to the second question. The authors provide in Figure 7(a) a comparison of centrifuge test results based on Farrell (2010) and finite-element (FE) analyses using three soil models. The results are presented as normalised pressure plotted against volume loss. In the critical 0.5–1% volume loss range, the difference between the results of the centrifuge modelling and the numerical analysis is stark: the the linear elastic model with a Mohr-Coulomb failure criterion (MC) and the kinematic hardening model based on Dafalias and Manzari (2004) (DM) models results indicate that the support pressures required are 30% to 70% higher than those from the centrifuge model at the same value of volume loss. The power law elasticity model (PL) is, maybe just by coincidence, approximately correct at 0.5% volume loss, but severely underestimates the required support pressure at 1% volume loss.

The authors note a significant difference in the distribution of initial stresses around the tunnel between the centrifuge testing and the FE analysis. They also warn that the comparison is qualitative rather than quantitative. However, the case studied involves simple two-dimensional plane-strain convergence around the tunnel in dry sand based on the membrane model, literally in the case of the model tunnel. For real tunnels, the problem is three-dimensional with the potential for ground loss at the face, along the TBM skin and at the tail void. Commonly, sand at tunnel level is saturated. The presence of groundwater introduces complications, both in terms of altering the normalised pressure–volume loss relationship compared with dry sand (Franza *et al.*, 2020) and because the pressure applied to the support medium can alter the groundwater pressure (Broere, 2003). The membrane model may not apply, if the support medium penetrates into the face (DAUB, 2016). The potential for local failure in a face composed of granular soil also needs to be considered (Broere, 2015). Establishing the appropriate pressure range for an actual tunnel is therefore significantly more complex than the relatively simple example studied in the paper.

The results in Figure 7(a) of the paper can be used to illustrate general relationships that have been observed in practice. From the results of the centrifuge tests, it can be seen that a very small increase in the normalised support pressure is required to reduce the volume loss from 4% to 2%. However, an increasingly large support pressure is required to reduce the target volume loss below 2%. Golder Associates (2009) provide a simple, semi-empirical method for estimating the support pressure required for 1% volume loss. Such a method would not apply below 1% volume loss and this illustrates the need for more refined approaches to assess the support pressure required to achieve the low values of volume loss that are now commonly specified. The paper also demonstrates the limitations in some of the commonly used methods of numerical analysis.

The centrifuge model tests to which the authors refer were carried out more than ten years ago. Although there have been published examples of more recent testing of plane-strain convergence in sand (e.g. Franza *et al.*, 2019; Iglesia *et al.*, 2013) there have been few centrifuge model tests related directly to face support (e.g. Chambon and Corte 1994; Chen *et al.*, 2013; Idinger *et al.*, 2011) and fewer still of either case in saturated sand (e.g. Lee *et al.*, 2004; Plekkenpol *et al.*, 2006). The published results from centrifuge tests on model tunnels in sand are limited in scope and insufficient to provide an adequate reference framework for the designer faced with this issue in practice.

Referring to the FE analyses carried out by the authors, the paper concludes that ‘the PL model performed reasonably well across the entire range of predictions’ (i.e. tunnel and surface volume losses of as much as 4%) ‘but particularly at lower volume losses’ (Giardina *et al.*, 2020; p. 395). Although this conclusion reflects a satisfactory comparison between numerical and experimental surface volume loss (settlement) relationships as examined in the published two-dimensional study, the pressure–volume loss relationship of the PL model appears to be entirely unrealistic. At volume losses greater than about 0.5%, Figure 7(a) suggests that negative pressures are required at tunnel level in the PL model to produce the large surface volume losses. Figure 7(b) further suggests that dilation significantly mitigates (halves) propagation to the surface of large volume losses at tunnel level. Yet practical experience and other model testing of face losses (cited above) or large losses around a lining (e.g. tail seal failure) suggest that large losses of granular soils at tunnel level propagate directly to the surface in flowing or running ground failure behaviour. If a PL numerical approach were to be used to estimate the operating pressures, the results could suggest that no support pressure would be required at tunnel level to meet a surface volume loss criterion of 1%. Conversely, if very large volume losses were to occur (on the order of 4%), forensic evaluations using a PL model could come to the erroneous conclusion that radial support pressure control at tunnel level was not required and that some other factor was the principal cause of large settlements.

The authors state that unrealistic tensile radial stresses were an acceptable solution for simulating surface volume loss and that no attempt was made to reproduce the stress distribution around the tunnel. However, Figure 7(a) and the authors' conclusions could readily be misconstrued to suggest that numerical simulations using a similar PL model might produce reliable results for estimating surface settlement. Fundamentally, why should such a model be considered useful or reliable for one subset of behaviours when it is based upon an unrealistic forcing of the model conditions?

While the numerical and physical experiments provide useful information about the consequential surface displacement conditions and their effects (question 1), the research does not address the basic needs of those tasked with answering question 2 and could, potentially, be misunderstood or misused without additional clarification.

Based on current trends, the specification of incrementally lower and lower limiting values for volume loss as the primary or only means of limiting damage to buildings is likely to continue. This trend changes the primary focus of concern from assessing the impact of ground movements on buildings and other urban infrastructure to the need to identify the precise range of acceptable pressures that will meet the settlement limits while also controlling the risk of unacceptable heave.

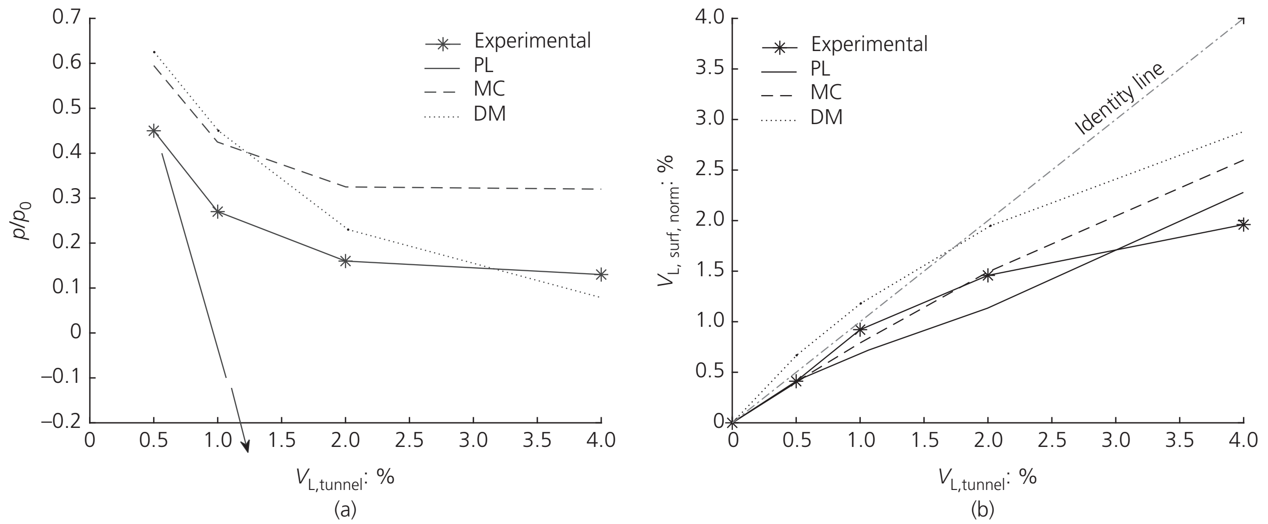

Figure 7. Relation between volume loss at the tunnel and (a) normalised pressure; (b) normalised volume loss at the surface (greenfield test)

Designers will also be faced with ever more extreme problems in terms of tunnel size and cover-to-diameter ratio; in extreme cases the allowable pressure range becomes very narrow. These trends reflect the proper exploitation of the opportunities provided by modern pressurised TBM technology. However, from the information presented in the paper, the discussion contributors question whether there is currently a sufficiently secure basis for the analyses that will be required to justify the target operating pressure ranges for tunnelling in saturated sand at very low specified values for volume loss. Would the authors agree that further centrifuge testing of model tunnels in saturated sand, together with the assessment of the most appropriate approach for numerical analyses to match the results, could provide an appropriate basis for future analytical needs?

Authors' reply

The authors thank the discussion contributors for their interest in the paper, and for their valuable comments. The aim of the paper was to improve on current practice of tunnelling-induced damage assessment by investigating the predictive capability of different soil constitutive models. The focus is on providing more information to allow efficient simulation of realistic ground movements combined with detailed building response (Giardina *et al.*, 2020). The discussion contributors argue that by showing the relationship between the tunnel volume loss and the normalised pressure needed to obtain the corresponding volume loss for each of the analysed constitutive models (Figure 7(a)), the reader could wrongly deduce that such pressures represent realistic operating values.

The authors' simulations were based on computationally efficient methods of simulating a given design surface volume loss, hence allowing for equally efficient prediction of building damage due to soil–structure interaction. Thus, the focus was on achieving realistic surface settlement profiles for improved assessment of expected building damage. The issue of assessing the operating pressures to achieve acceptable volume loss values was not covered in the investigation. As stated in the paper, the stress reduction prescribed at the tunnel boundary, with respect to the initial stress state, should simply be regarded as a fictitious perturbation employed to obtain a realistic displacement field close to the ground surface. As the source of such a perturbation is relatively far from the surface – that is, the tunnel is relatively deep – the actual way of simulating tunnel excavation has a limited importance in this case. The relevant objective is to obtain acceptable numerical results in relation to the soil–structure interaction, and in the authors' case these results have been validated by comparing them to centrifuge data. In fact, even an arbitrary displacement field applied at the tunnel boundary might work for the purpose of the authors' research (e.g. Boldini *et al.*, 2018, 2021; Losacco *et al.*, 2014). In this case, stress reduction was chosen owing to the resemblance to the actual device employed to generate the volume loss in the centrifuge set-up.

Hence, in no way should combining the results shown in Figures 7(a) and 7(b) be interpreted as a guideline to relate the volume loss to the operating support pressure exerted at the tunnel face or boundary in real tunnel excavations. As far as the non-linear elastic 'PL' constitutive model is concerned, despite the fair predictive capabilities shown in the paper, the reader is warned that unrealistic, non-physical, tensile stresses need to be applied at the tunnel boundary to obtain large volume loss when using this model. Again, this means that even the simple PL model, if properly calibrated to match the soil displacements expected close to the ground surface in greenfield conditions, might be used for a quick preliminary assessment of the effects of soil–structure interaction. But the authors agree with the discussion contributors that it is certainly not suitable to obtain a realistic volume loss starting from a prescribed, operating pressure applied at the tunnel boundary. The authors agree that future centrifuge simulations to simulate face pressure could be useful, although realistically simulating the spatial distribution of soil properties remains a challenge.

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