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Closure to "Discussion: Greenfield tunnelling in sands: the effects of soil density and relative depth" by Andrea Franza, Alec M. Marshall, and Bo Zhou

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The Authors would like to thank Dr Boone and Mr Shirlaw for their insights relating to some of the current challenges facing tunnelling engineers and for their comments on both the usefulness and limitations of the centrifuge test outcomes presented in Franza *et al.* (2019). The submitted discussion is a valuable contribution from the perspective of practitioners and supports the need to move towards more sophisticated reduced scale centrifuge testing, something the Authors wholeheartedly agree with. The Discussion provides an excellent overview of where new developments in research could provide a direct impact on the tunnelling industry.

SOME CONTEXT TO THE RESEARCH

In Franza *et al.* (2019), the use of dry sand and plane-strain conditions was in part related to an impetus to extend the data set from Marshall *et al.* (2012) on tunnelling-induced settlements in dense sand to include medium-dense and loose sands, whilst also discussing ground reaction curves, deformation mechanisms, and arching. The PhD research project conducted by A. Franza focused predominately on tunnel-pile and tunnel-piled building interaction (Franza & Marshall, 2018, 2019a). For this testing, the use of dry loose sand allowed for simple, relatively quick, and repeatable test preparation. For the interpretation of the outcomes of these tests, the need to better characterise loose sand behaviour under greenfield conditions arose. Furthermore, for the tunnel-pile and tunnel-building interaction experiments, a more simple 2D model was adopted to reduce uncertainties that generally worsen with the complexity of an experimental set-up. Therefore, plane-strain tunnelling in dry sand was considered to be appropriate, which was also consistent with other recent research (Farrell *et al.*, 2014; Ritter *et al.*, 2017; Marshall *et al.*, 2010).

It may also be of interest that the experimental set-up used in Franza *et al.* (2019), originally developed by (Zhou *et al.*, 2014), was designed to perform tests on saturated soils; future works will deal specifically with aspects highlighted by the Discussion relating to the effect of water. In addition, we agree with the Discussion that centrifuge investigation of three-dimensional tunnelling would be of great interest and practical use; these will also have significant benefit for the study of tunnel-structure interaction problems. It is encouraging that three-dimensional tunnelling systems have been developed for centrifuge testing by using independent ground loss systems (Boonyarak & Ng, 2015) and model tunnel boring machines (Nomoto *et al.*, 1999); more work in this area is certainly warranted.

TUNNEL AND SOIL VOLUME LOSS

To the Authors' knowledge, design values of soil volume losses $V_{l,s}$ often range between 0.5 and 2%. We referred to $V_{l,t} = 1, 2, 3$ and 5% as low, medium, high and extremely high volume losses, respectively, and included the high and very high values to relate to cases where tunnel boring machines do not achieve the target design soil volume loss, as reported in the Discussion. Related to this, Franza & Marshall (2019b) characterised greenfield ground movements (both vertical and horizontal) from centrifuge test results up to tunnel volume losses $V_{l,t} = 4 - 5\%$ with empirical and semi-analytical

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methods; empirical formulas to estimate (from the considered centrifuge test results) the relationship between $V_{l,s}$ and $V_{l,t}$ as a function of soil relative density I_d and tunnel cover-to-diameter ratio C/D were also provided. Building on what is presented in the Discussion, we would like to emphasise the importance of predicting both surface and subsurface soil volume losses; whilst shallow foundations may interact predominately with near-surface movements, buried infrastructure and deep foundations interact with subsurface movements. Surface and subsurface soil volume losses for relative depths of $z/z_t = 0, 0.25, 0.5$, where z_t is depth to tunnel axis, were reported in both Franza *et al.* (2019) (Figure 9) and Franza & Marshall (2019b).

The Discussion highlighted that, for routine design, engineers are interested in the relationship between soil and tunnel volume losses mainly in the range of $V_{l,t} < 2\%$. To support this, the data from Figure 9 of Franza *et al.* (2019) is reproduced here in Figure **??** for $V_{l,t} = 0.5 - 2\%$ and soil relative density $I_d = 0.3$, 0.5, and 0.9; the observed trends agree with the comments within the Discussion. Note that information such as that provided within Figure **??** can be used alongside data on the relationship between $V_{l,t}$ and LF (such as those from the Discussion or presented here in Figure 2) to evaluate soil volume loss at various depths based on a given value of LF.

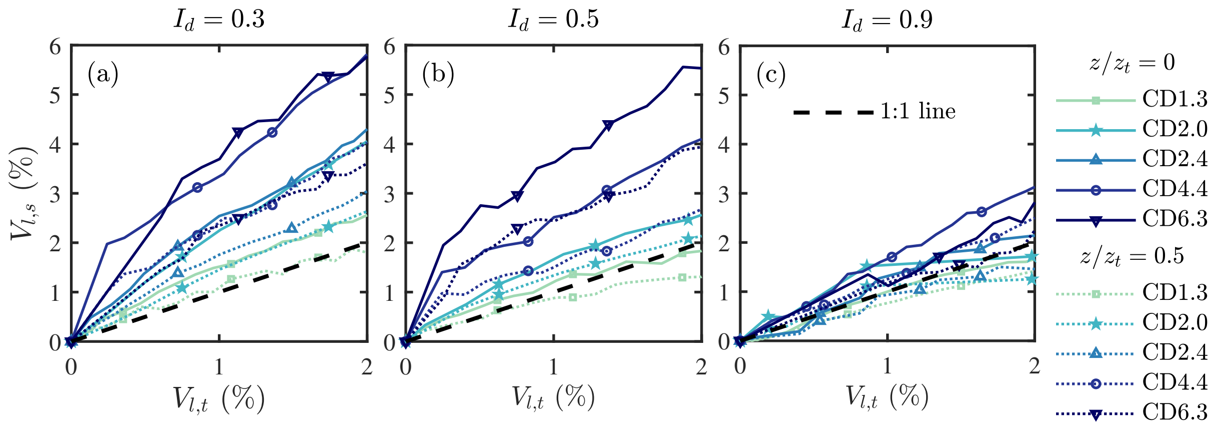

Fig. 1. $V_{l,s}$ plotted against $V_{l,t}$ up to 2% for $z/z_t = 0$ and $z/z_t = 0.5$.

LOAD FACTOR

An effective framework for assessing the relationship between tunnel support pressure and surface/sub-surface soil volume loss is certainly needed. We are pleased that our research is able to contribute to this goal in some way. Among others, theoretical research recently published by Mo & Yu (2017) and Vu *et al.* (2016) has provided the relationship between tunnel support pressure and volume loss for plane-strain and three-dimensional conditions.

We would like to add several comments related to the load factor concept provided within the Discussion. First consider that the theoretical normalised pressure at the tunnel axis level σ_{norm} is:

$$\sigma_{norm,0} = \frac{\sigma_{t,0}}{\gamma D} = \frac{\sigma_{v,0}}{\gamma D} = \frac{C}{D} + \frac{1}{2} \tag{1}$$

where $\sigma_{v,0} = \gamma\left(C + D/2\right)$ is the vertical stress in the soil at the level of the tunnel axis, γ is soil unit weight, D is tunnel diameter, C is ground cover from the surface to the tunnel crown, and the subscripts t, v, and 0 refer to tunnel, vertical, and initial value (prior to volume loss), respectively.

Second, the selection of the tunnel pressure at failure/collapse σ_c (labelled P_c in the Discussion) should be discussed. To calculate load factor LF from the data in Franza *et al.* (2019), the Discussion assumed σ_c as the tunnel internal pressure σ_t at a tunnel volume loss $V_{l,t} = 5 - 8\%$. This value is likely not a true reflection of the collapse pressure from the experiments. For $C/D = 2.4$ and $I_d = 0.9$, Marshall (2009) provided data which indicated that collapse was likely reached for $V_{l,t} = 15 - 20\%$ with experimental values of normalised collapse pressure $\sigma_{norm,c} = \sigma_c/\left(\gamma D\right)$ within the range 0.18 - 0.08. This collapse value is notably lower than the initial $\sigma_{norm,0}$ based on Equation (1) and smaller than the tunnel support pressure σ_{norm} for $V_{l,t} = 5 - 8\%$ used within the Discussion. The impact of this feature on the narrative and figures within the Discussion is secondary; the conclusions drawn from the interrogation of the Franza *et al.* (2019) data within the Discussion are entirely appropriate.

As discussed above, $\sigma_{norm,c}$ is much less than $\sigma_{norm,0}$. Considering this, the Authors would like to suggest a first (non-conservative) estimate of the load factor LF as LF^*, which does not require the tunnel collapse pressure, σ_c:

$$LF^* = \frac{\sigma_{v,0} - \sigma_t}{\sigma_{v,0}} = \frac{\sigma_{t,0} - \sigma_t}{\sigma_{t,0}} = 1 - \frac{\sigma_t}{\sigma_{t,0}}; \quad LF = \frac{\sigma_{v,0} - \sigma_t}{\sigma_{v,0} - \sigma_c} \tag{2}$$

By definition,

$$\frac{LF^*}{LF} = \frac{\sigma_{v,0} - \sigma_c}{\sigma_{v,0}} = 1 - \frac{\sigma_c}{\sigma_{v,0}} = 1 - \frac{\sigma_{norm,c}}{\sigma_{norm,0}} < 1 \tag{3}$$

For instance, for the test with $C/D = 2.4$ in dense sand ($I_d = 0.9$), $\sigma_{norm,0} = 2.9$ and $\sigma_{norm,c} = 0.18$ while $LF^* = 0.94LF$. Thus, LF^* provides a somewhat non-conservative estimate of LF with an error of 6%. As mentioned in the Discussion, engineers are interested in prescribing a rational limit for the load factor and LF^* may provide a useful reference for this in cases where there is uncertainty regarding the collapse tunnel pressure. It is worth noting that Franza *et al.* (2019) reported $\sigma_t/\sigma_{t,0}$ against tunnel volume loss, which is equivalent to the relationship between LF^* and volume loss (refer to Equation 2).

Third, to complement the Discussion, we have provided here in Figure 2 the normalised ground reaction curves of the entire available data set; results for medium dense sand ($I_d = 0.5$) were not included in Franza *et al.* (2019) due to space restrictions. Figures 2a-c and d-f show the normalised pressure $\sigma_{norm} = \sigma_t/\left(\rho g N D\right)$ and the relative tunnel pressure $\sigma_t/\sigma_{t,0}$, respectively, against tunnel volume loss. Considering that most of the performed greenfield tunnelling experiments were not taken to a state of full collapse (hence there is uncertainty regarding the value of σ_c), the values of LF^* are used in Figures 2g-i rather than LF. As mentioned in the Discussion, a rather brittle response is obtained for the dense sands, in which the $V_{l,t} - LF^*$ curves show a vertical asymptotic trend after a certain critical LF^*. A brittle tunnel volume loss versus LF^* trend is also observed for the shallow tunnels $C/D = 1.3 - 2.0$ with medium dense sand ($I_D = 0.5$). On the other hand, because of the hardening behaviour of loose sands, the increase of $V_{l,t}$ with LF^* is more gradual in the loose sand tests. In all cases, the centrifuge data illustrate that increments of $V_{l,t}$ above 3% are associated with minimal increases in LF^*, confirming the risk related to unexpected large tunnel volume losses above a critical value of load factor.

Fourth, we would like to point out that for model tunnels pressurised with water (as for Franza *et al.* (2019)), there is a gradient of internal tunnel pressure across the depth of the tunnel due to the self-weight of the water. As discussed by Farrell (2010), particularly for shallow tunnels, the minimum support pressure at the tunnel crown may lead to a localised collapse in the area around the crown. The impact of this issue on the conclusions provided by the Discussion is likely insignificant, however we mention it here for the sake of other researchers who are considering centrifuge modelling for the purpose of developing load factor LF design charts.

Finally, it may be of interest that recent research has indicated that the relationship between $V_{l,t}$ and $V_{l,s}$ and, consequently, that between $V_{l,t}$ and LF, is not significantly affected by the presence of a building when compared to the influence of soil density (Ritter *et al.*, 2017).

CONCLUSIONS

Despite their limitations, plane-strain tests of greenfield tunnelling and tunnel-structure interactions provide a reliable and relatively straightforward way to investigate soil deformation mechanisms. They also provide valuable data for the calibration and validation of analytical and numerical models. However, we completely agree with the Discussion in that future research could provide significant benefits by investigating more realistic three-dimensional problems, in terms of improving our understanding of the relationship between load factor and tunnel volume loss, as well as the prediction of tunnel-structure interactions. We would like to emphasise the importance of continuous and open discussions between researchers and practitioners, and would again like to thank the authors of the Discussion for their insightful contribution which has provided guidance for the direction of our future research initiatives.

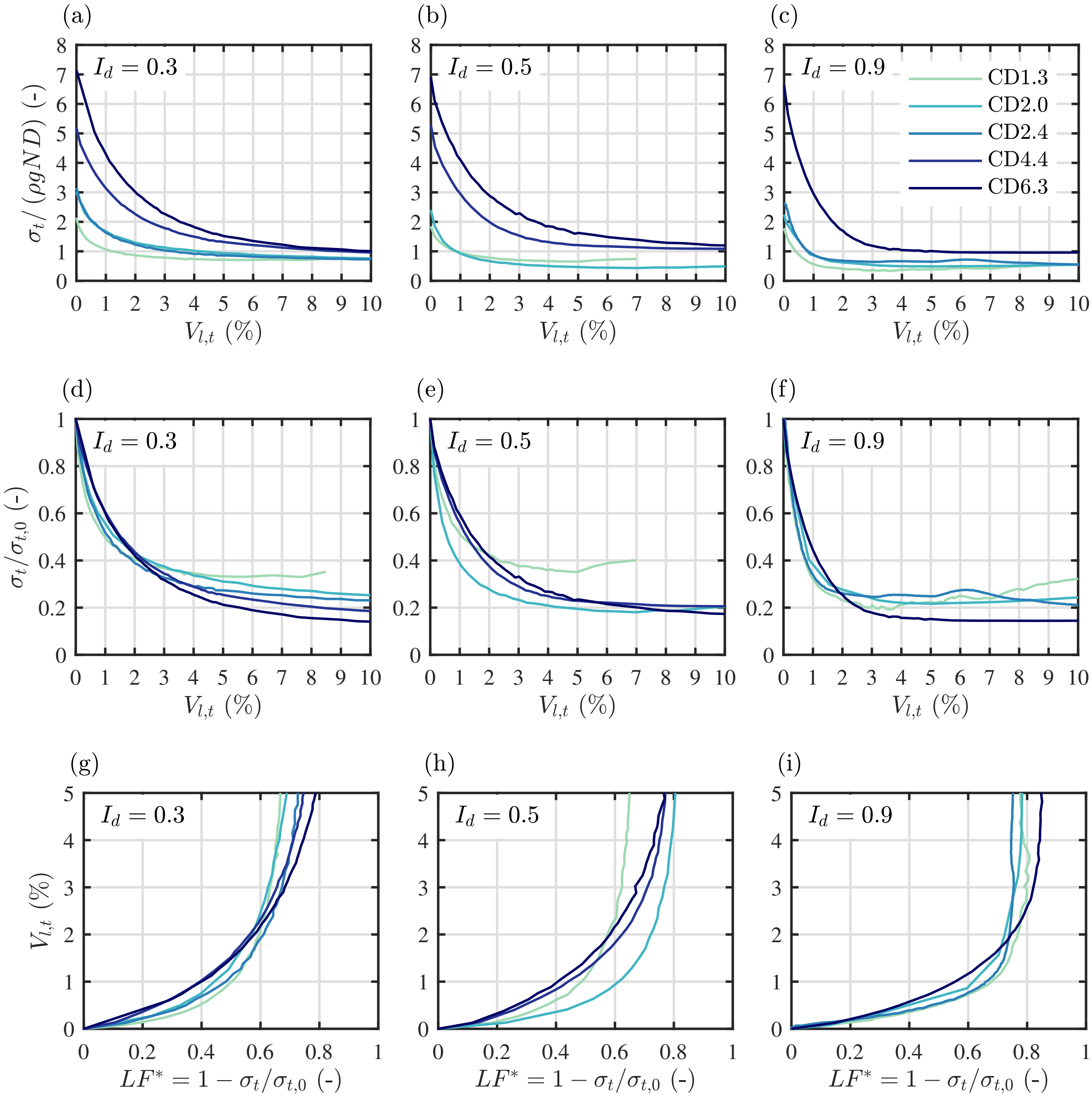

Fig. 2. (a) Normalised tunnel pressure; (b) relative tunnel pressure with tunnel volume loss; (c) tunnel volume loss against alternative form of load factor LF^*.

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