DISCUSSION

Uplift resistance of buried submarine pipelines: comparison between centrifuge modelling and full-scale tests


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The authors’ contribution is most timely, owing to the paucity of comparisons between centrifuge model data and their corresponding prototypes. The problem addressed is the uplift resistance of buried pipelines in granular soils. Owing to the strong similarities between the uplift resistance of pipelines, buried plates and the classic trap-door problem, a number of aspects of this problem have been addressed previously (e.g. Vardoulakis et al., 1981; Cole & Lade, 1984; Lade et al., 1988). This discussion concerns the scale effects reported by the authors, and is intended to confirm the hypothesis that any inconsistency in the conventional understanding of centrifuge tests is the result of the dependence of the mobilised shear stress across localisations (or shear bands) on the relative displacement across the localisation.

It has been previously proposed (Scarpelli & Wood, 1982; Muhlhaus & Vardoulakis, 1987; Stone & Wood, 1992) that this relative displacement is primarily a function of the soil grading (characterised by the mean particle size, $d_{50}$), and thus for small-scale modelling of problems involving discontinuous soil mechanics, it may be necessary to scale the particle size (or, more correctly, the grading curve) to ensure that: (a) the kinematics of the reduced scale model are compatible with those of the corresponding prototype; (b) the scale of the localisations themselves does not adversely affect the model response; and (c) the mobilised strength on localisations in the model is compatible with that which would be present in the corresponding prototype.

Consider a localisation or shear band propagating through a dense cohesionless soil from an induced boundary displacement, such as a buried plate or pipeline, as illustrated in Fig. 9(a).

The kinematics of the problem constrain the initial localisation to be inclined at the angle of mobilised dilation (initially a maximum, $\theta_{\max}$) to the major principal stress (assumed to be vertical). A section of the localisation can be idealised as a condition of direct shear, as is rather crudely replicated in a direct shear box test, as indicated in Fig. 9(b).

Typical shear box tests on dense sands of different uniform gradations (characterised by the $d_{50}$ value) but at the same initial void ratio and normal stress are shown in Fig. 10 (Stone & Wood, 1992). It is apparent from these tests that the relative displacement across the shear box (and hence across the shear band), which coincides with the peak and critical state friction angles, appears to be a function of the grain size. This is intuitively likely, as it would be expected that, for geometrically similar 50 mm and 5 mm diameter particles, the larger particles would require significantly more relative displacement to achieve corresponding peak critical state conditions.

Furthermore, as the ratio of the shear box dimensions to grain size increases, the measured peak strength reduces. This is consistent with the observations reported by Garnier (2002).

For the purposes of this discussion, it has been assumed that the degree of restraint provided by the shear box (i.e. the ratio of particle size to shear box dimensions) is such that only one shear band forms, aligned with the zero extension (horizontal direction). When less restraint is provided such that shear bands can form freely (i.e. with large particle size to shear box dimension ratios), complex shear band patterns can develop (e.g. Scarpelli & Wood, 1982).

The orientation of the localisation as shown in Fig. 9(a) is kinematically compatible only if the shear band is dilating at the maximum rate ($\theta_{\max}$). At some relative displacement across the localisation the dilation reduces to zero, and kinematics dictate that a new vertical shear band should form associated with zero dilation. However, formation of a new shear band results in fresh dilation, and the (new) vertical shear band itself is now kinematically inadmissible, possibly resulting in curvature of the propagating shear band. The above illustrates the potential complexity of the kinematics of shear band formation for problems of this type, especially where multiple shear bands can develop (e.g. Cole & Lade, 1984; Lade et al., 1984).

From the above it is apparent that, to achieve geometric similarity in patterns of shear band formation in a reduced scale model, the particle size should also be factored, strictly speaking by the model scale factor, but in practice this is not always necessary or realistic.

As the relative displacements (across a propagating shear band) required to mobilise peak and critical state, at model scales, are primarily a function of the grain size used in the model, then for the pipeline tests reported by the authors it would be expected that the mobilisation distance would be primarily a function of the grain size. This appears to be in disagreement with the plot of mobilisation distance against...
the grain size means that the localisation dimensions remain at prototype scale, and may have a detrimental effect on the observed model response.

For the ‘silt-sized’ material, several factors may contribute to the differences observed. First, there is the possibility that the soil response during the pipe uplift test was not fully drained, and even that suction could have developed behind the pipe. Pore pressure data from a transducer located in the pipe would be very useful to investigate this possibility. Second, if fully drained conditions did occur, then the potential for multiple shear bands to occur exists, and direct comparison with the sand tests becomes difficult.

Consideration of the model test kinematics should be included in the interpretation of any reduced-scale test where discontinuities form (both at 1g and in the centrifuge), and in particular it may be necessary to scale the particle size (or grading curve), if not by the actual model scale factor, then at least sufficiently enough to allow the full development of localisation patterns and the attainment of the correct values of mobilised friction at corresponding points on the model and prototype localisations. This confirms the authors’ hypothesis that mobilised shear stress across localisations depends on the absolute relative displacement across the localisation.

Authors’ reply
The authors thank the discussers for their interesting contribution.

We agree that it seems reasonable to suppose that, if the particles can be treated as rigid and inert, then in geometrically similar systems with localised deformation the displacements would have to scale with the particle size. That could be tested experimentally by comparing a conventional shear box test on sand with a test on gravel with a particle size 10 times larger (and as far as practicable the same mineralogy and particle shape), in a shear box itself scaled up 10 times. The same argument would in turn indicate that in a centrifuge test the soil ought itself to be scaled, so that in a 100g test at 1/100 scale the particle size distribution ought to be the prototype particle size distribution scaled downwards 100 times. However, obvious difficulties are that a sand or silt prototype would then be represented by a clay model, that clay has qualitatively different behaviour, and that clay particles interact with pore water in a more complex way than do particles of sand.

The opposite view, that the shape and mineralogy of a particular grading of material have a stronger influence on the response than the particle size, has been historically favoured by small-scale modellers, who have chosen to use the ‘prototype’ material. In element testing this view is rarely stated, but is always assumed. When stiffness measurements are reported from continuum deformation of high-quality intact triaxial samples, one never asks ‘Should the grains have been scaled down by the ratio of the sample height to the prototype zone of soil that the sample represents?’ When modelling continuum deformation such scaling is not considered necessary.

This contrast between the modelling of events that are governed by stress–strain and stress–displacement laws is not widely appreciated. We welcome increased interest in the formation and detailed structure and mechanics of shear bands, and further investigations following the pioneering work of Scarpelli, Wood and Garnier.

REFERENCES


