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Gravity Effects of Deformation Zones Induced by Tunnelling in Soft and Stiff Clays

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SUMMARY

We calculated gravity response of geotechnical models of deformation zones induced by tunnelling in two environments - soft clays and stiff clays. Approximately elliptic zones of deformation above the tunnels arise in both cases, but internal structures of the zones are different, and different are also theirs gravity effects. In soft clays, the deformation zone above the tunnel is actually zone of compaction and causes decrease of amplitude of gravity anomaly over the tunnel. In stiff clays a zone of dilatancy occurs next to the tunnel, but an overall gravity effect of deformation zone is insignificant and doesn't affect the amplitude of gravity anomaly measured above the tunnel at the surface.

Introduction

Existence of deformation zones above subsurface voids, e.g. tunnels, cellars, mining chambers and galleries, is known from both geotechnical modelling and in situ geotechnical monitoring. In gravity prospecting it is often generally assumed that the zones of deformation are zones of lower densities and a negative gravity anomaly over the void will be more intensive than an anomaly measured (calculated) for the void itself. Even if the estimated density difference between deformation zone and surrounding rocks is taken small in this presumption, it may form more than 50 % of anomaly amplitude above the void (Blecha, 2003; Blecha and Mrlina, 2001). This is caused by the fact, that the model of the deformation zone is several times higher than void itself and often reaches the surface.

In our contribution, we aimed to verify the concept of lower densities zones by exact computing the gravity response of geotechnical models including their complicated internal structure. We used tunnel as an example of the void and for the rock environment we selected two types of soils with different geotechnical properties – soft clays and stiff clays. The stiff clays occur in Tertiary sedimentary basins, for example. The soft clays are typical in areas of young marine sediments.

Geotechnical modelling

The problem analysed is a fictitious tunnel excavated by the New austrian tunnelling method. The tunnel width is 15.5 m and height 12 m, the tunnel roof is 20 m below the ground surface. The problem has been analysed by the Finite element program *Tochnog Professional*. The soil behaviour is characterised by the hypoplastic constitutive model for clays (Mašín, 2005). This is an advanced non-linear constitutive model, which takes into account the influence of void ratio (defined as a ratio of volume of voids vs. volume of mineral grains) on soil behaviour. The soil parameters have been taken over from Mašín (2005), the soft clay is modelled by initial distribution of void ratio that corresponds to the normally consolidated state, the stiff clay has an overconsolidation ratio OCR=5 and lower critical state friction angle φ_c. The density effects on the initial stress distribution have been neglected.

Gravity modelling

The distribution of void ratios calculated by the geotechnical model has been converted into wet bulk densities by assuming full saturation and density of mineral grains D_s=2650 kg/m^3. Gravity effect of rock environment has been calculated as 2-D model with *GM-SYS* profile modelling program. *GM-SYS* software allows calculating gravity effects of blocks with finite lengths (2.5 and 2.75-D models); in the case of a tunnel, however, 2-D modelling concept is suitable and satisfactory. For both stiff and soft clays, we calculated the reference model for a tunnel in homogeneous environment with density gradually increasing with depth and the geotechnical model, which considers change of soil density induced by tunnelling.

Results of geotechnical modelling

Geotechnical models of deformation zones (in terms of vertical displacements) in soft and stiff clays are in Figs. 1a and 2a. It can be seen that in both cases significant vertical downward displacements occur above the tunnels. The patterns of void ratios (densities) is in the two cases significantly different. In the stiff clays (Fig. 1b), looser zones with lower densities (higher void ratios) occur next to the tunnel, the soil is however densified above the tunnel in the vicinity of the ground surface. In the soft clay (Fig. 2b), significant densification occurs both next to the tunnel and above the tunnel.

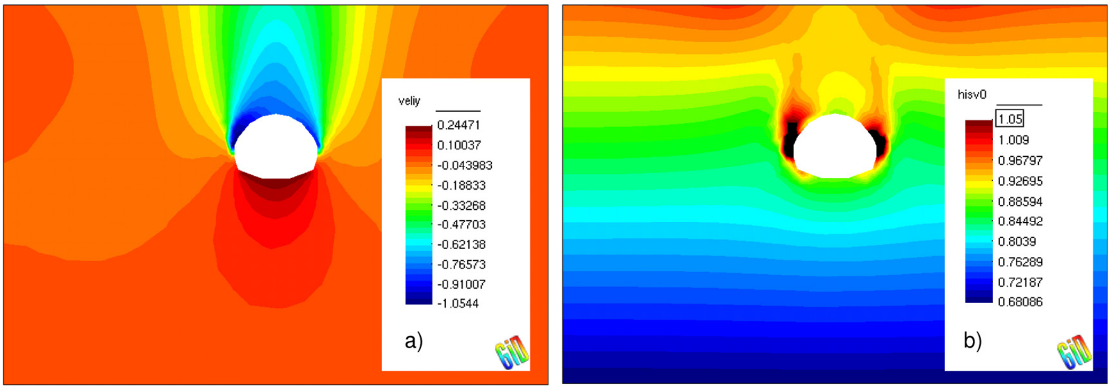

Figure 1. Results of geotechnical models of a tunnel in stiff clays. a) vertical displacements, b) distribution of void ratios.

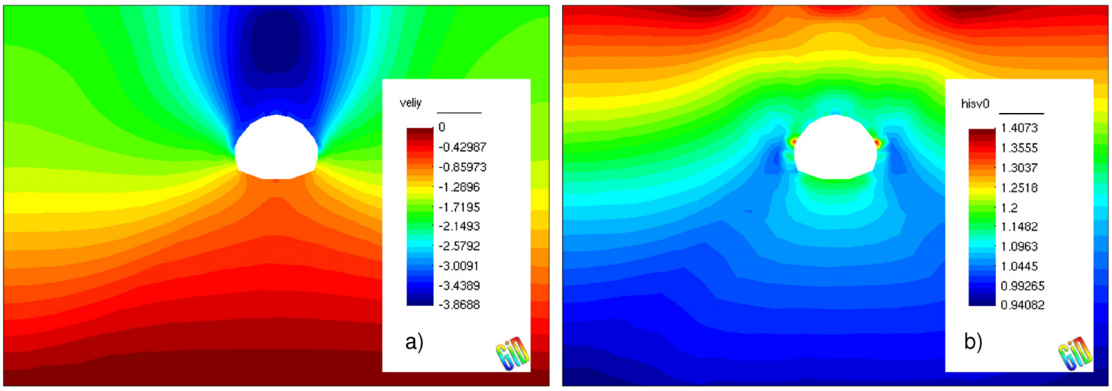

Figure 2. Results of geotechnical models of a tunnel in soft clays. a) vertical displacements, b) distribution of void ratios.

These predictions can be explained by considering the behaviour of soil subjected to shear deformation (Fig. 3). The void ratio of the stiff clay increases (the soil dilates) after the initial small contraction. Therefore, the region next to the surface in Fig. 1a is densified (small, but not negligible shear strains), the region close to the tunnel sides has higher void ratio (large shearing causes large dilatancy). In the case of the soft clay, even small shear strains cause volumetric contractancy, so significant compaction is predicted (Fig. 2a).

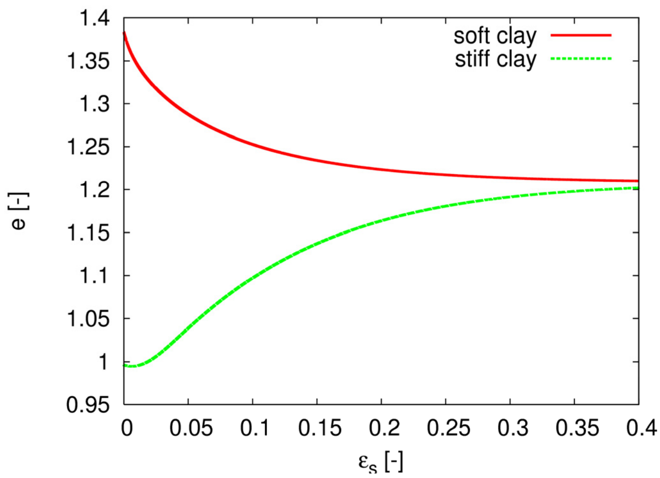

Figure 3. Change of void ratio e of stiff and soft clays with shear strain ε_s.

Results of gravity modelling

As an example of gravity modelling we show reference and geotechnical models of a tunnel in stiff clays – Fig. 4. The reference model is in Fig. 4a, the geotechnical model including the change of void ratio induced by tunneling in Fig. 4b.

Results of gravity modelling of deformation zones above the tunnel in both soft and stiff clays are summarized in Fig. 5. Deformation zone induced by the tunnelling in soft clays is a source of positive gravity anomaly with amplitude of 0.012 mGal. It means that if we will measure gravity over the tunnel in soft clays, we should receive less intensive negative anomaly than calculated for the tunnel itself. In the case of stiff clays, gravity effects caused by the deformation zone range between ± 0.002 mGal. This effect is too small even for most precise microgravity surveys. It means, that deformation zone above the tunnel in stiff clays doesn't affect the gravity anomaly caused by the tunnel.

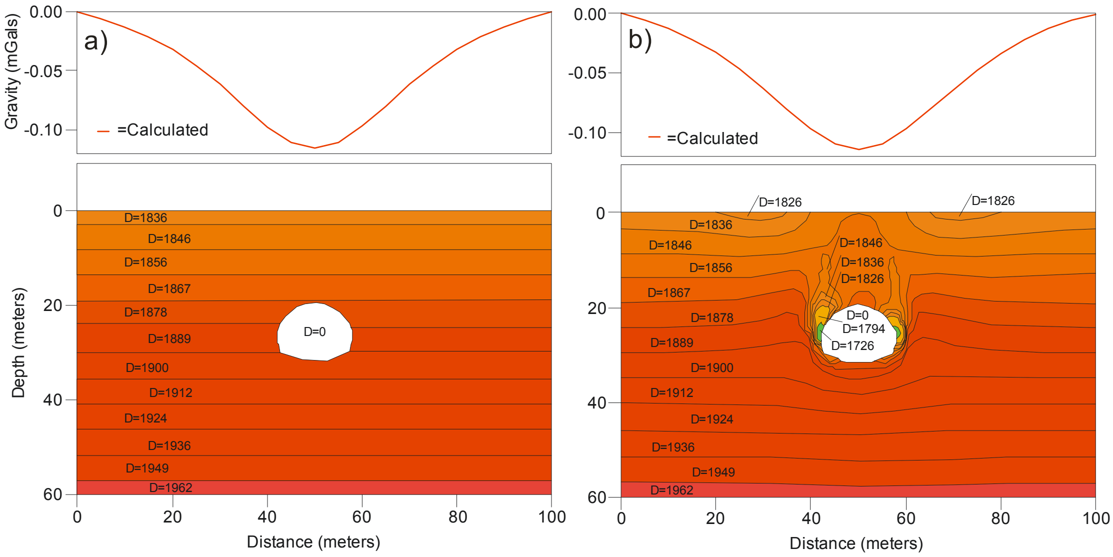

Figure 4. Reference a) and geotechnical b) gravity models of a tunnel in stiff clays. Densities *D* are in [kg/m^3].

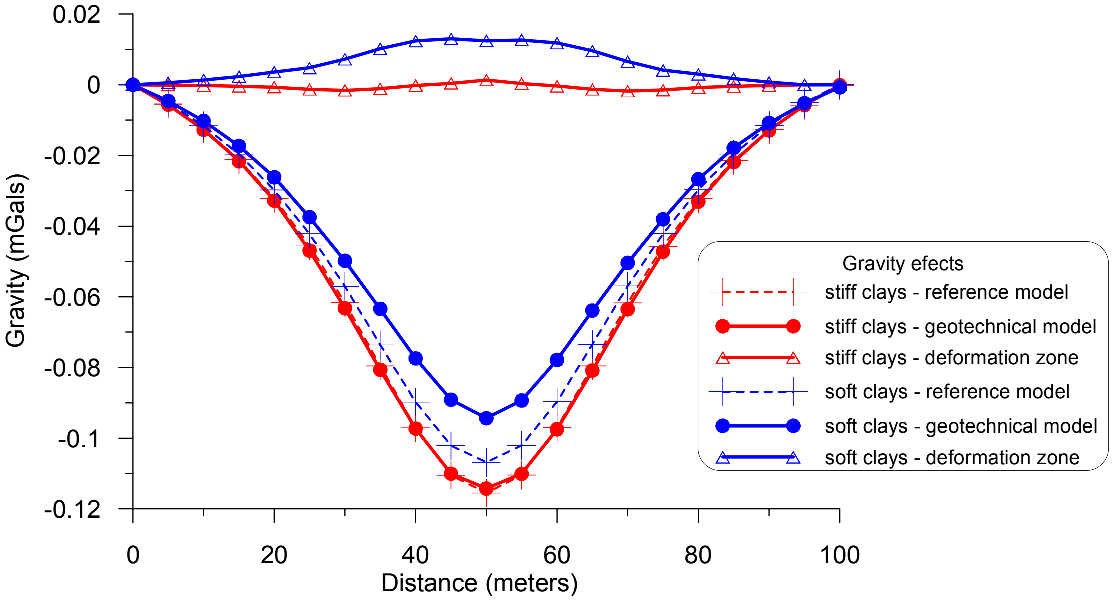

Figure 5. Gravity effects of tunnels in stiff and soft clays. Reference models are calculated for horizontally homogeneous environment and geotechnical models are for rock environment with deformation zone induced by tunnelling.

Conclusions

Results of our modelling show that deformation zones induced by tunnelling in soft and stiff clays are not sources of an additional negative gravity anomaly caused by the tunnel. In the case of soft clays the deformation zone is the source of positive gravity anomaly and causes decrease of amplitude of negative anomaly produced by the tunnel itself. In the case of stiff clays the overall gravity effect of deformation zone is negligible and doesn't affect the measured gravity anomaly over the tunnel.

It must be emphasized that the conclusions are based on geotechnical modelling of tunnelling in two specific environments, therefore the conclusions cannot be drawn in general. The research will continue with geotechnical and gravity modelling of other types of soils and rocks and with verification of calculated gravity effects in the field.

Acknowledgements

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