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The impact of small strain stiffness parameters on geotechnical numerical modelling: a case study in Budapest, Hungary

L'impact des paramètres de rigidité des petites déformations sur la modélisation numérique géotechnique: une étude de cas à Budapest, Hongrie

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ABSTRACT: Geotechnical numerical modelling has become a standard tool for analyzing complex geotechnical structures. However, determining small strain stiffness parameters presents challenges for engineers. The widely used HSSmall model requires estimation of the initial shear modulus (G_0) and shear strain parameter ($\gamma_{0.7}$), which significantly influence the behaviour. In this study, their impact was investigated on numerical modelling results using soil data from a site in Hungary. We compare the results of seismic CPT and MASW, which yielded slightly different results for shear wave velocity with depth. Plaxis 2D software is used to analyze the effects of parameters on different geotechnical structures. Additionally, we conduct a comprehensive parameter analysis to assess the influence of G_0 and $\gamma_{0.7}$. Our findings provide valuable insights into the significance of small strain stiffness parameters in geotechnical numerical modelling and highlight the need for accurate determination of these parameters for reliable predictions of structural behaviour. This research contributes to improving the understanding of the challenges associated with small strain stiffness parameters and their impact on numerical modelling and can aid geotechnical engineers in selecting appropriate parameter values for their projects.

RÉSUMÉ: La modélisation numérique géotechnique est devenue un outil standard pour l'analyse des structures géotechniques complexes. Cependant, la détermination des paramètres de rigidité pour les petites déformations représente un défi pour les ingénieurs. Le modèle HSSmall, largement utilisé, nécessite l'estimation du module de cisaillement initial (G_0) et du paramètre de déformation de cisaillement ($\gamma_{0.7}$), qui influencent considérablement le comportement. Dans cette étude, nous étudions leur impact sur les résultats de la modélisation numérique en utilisant les données du sol d'un site en Hongrie. Nous comparons les résultats de la CPT sismique et de la MASW, qui ont donné des résultats légèrement différents pour la vitesse des ondes de cisaillement en fonction de la profondeur. Le logiciel Plaxis 2D est utilisé pour analyser les effets des paramètres sur différentes structures géotechniques. En outre, nous effectuons une analyse complète des paramètres pour évaluer l'influence de G_0 et de $\gamma_{0.7}$ sur les résultats de la modélisation. Nos résultats fournissent des indications précieuses sur l'importance des paramètres de rigidité des petites déformations dans la modélisation numérique géotechnique et soulignent la nécessité d'une détermination précise de ces paramètres pour des prévisions fiables du comportement structurel. Cette recherche contribue à améliorer la compréhension des défis associés aux paramètres de rigidité des petites déformations et leur impact sur la modélisation numérique et peut aider les ingénieurs géotechniques à sélectionner les valeurs de paramètres appropriées pour leurs projets.

Keywords: HSS soil model; FEM; parametric study; small strain stiffness.

1 INTRODUCTION

Nowadays, more and more projects require a more accurate description of the complex behaviour of structures. To this end, in addition to the superstructure, two- or three-dimensional finite element modelling is also used to understand the expected behaviour of the soil environment to analyse the construction, renovation and restoration phases. Numerical modelling is becoming increasingly widespread and is now part of the design practice to deal with complex tasks and to find optimal technical and economic solutions.

Advanced material models of geotechnical finite element software are used to describe the soil behaviour, but the determination of parameters is a critical point in the process. Using advanced material models requires the study of parameters describing the complex – nonlinear, time-dependent – behaviour of soils. These can usually be determined by specific, targeted tests, but in their absence their value can only be estimated from other measurement data based on recommendations in the literature. Furthermore, the extrapolation of small sample test results and the scatter of measurement results, introduces uncertainty in the determination of parameters, and parameter analysis is therefore carried out in design practice to understand the impact of them.

The most widely used material model in Hungarian practice (both for design and research, Hübner and Mahler, 2020) today is the HSSmall (Benz, 2007, Plaxis, 2022), a double hardening material model that considers the higher stiffness of soils in the small strain range as well. The influence of two parameters describing the stiffness variation with strain level on the calculation results is analysed in this paper based on the results of investigations carried out at a specific site in Hungary for typical geotechnical structures.

2 EXAMINATION PROGRAM

In the framework of this study, we aimed to assess how much the calculation results differ in the case of parameters obtained by different measurement and estimation models, what effect the inherent uncertainty in the parameters has. For this purpose, we used measurement data from a site in Budapest, where, in addition to 10 large diameter boreholes and 4 CPT tests, 1 seismic CPT (SCPT) and a surface wave measurement (MASW) for research purposes (Szilvágyi et al, 2017) were also performed to record the shear wave propagation velocity profile.

The typical stratification of the area and the parameters that have been obtained based on the soil tests are summarised in Table 1.

Table 1. Soil parameters.

Soil layer	fill	sand	Danube sedim.	Mioc clay
depth, z [m]	0-2	2-7.5	7.5-14	14-
friction angle, φ [°]	28	31	38	26
cohesion, c [kPa]	0	0	0	80
unit weight, γ [kN/m^3]	18	19	21	21
oedemetric mod., E_{oed} [MPa]	8	12	50	15

To analyze the effect of the small strain parameters under investigation, three shear wave propagation profiles were investigated. In addition to the results of the two targeted tests, seismic CPT and MASW measurements, the evolution of the shear wave propagation velocity (CPT-R) was estimated from the CPT data according to Robertson (2009) (Szilvágyi et al, 2017).

The three resulting profiles are shown in Figure 1. The notation given here is later used for comparison. In the figure, it can be observed that in the upper 6 m thick soil zone the MASW measurement values are larger than the SCPT and CPT-R data series.

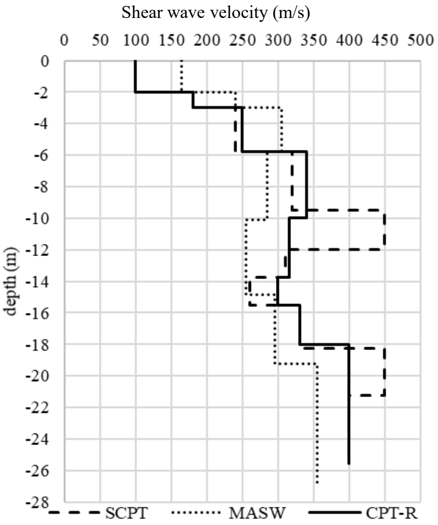

Figure 1. Shear wave velocity profiles.

The shear modulus at in situ stress state was estimated from the shear wave velocity (v_s) profiles and the soil density (ρ) based on the equation.

$$G_0 = \rho \cdot v_s^2 \tag{1}$$

Important to note, that the difference between the three shear-wave propagation velocity values based on each test appears squared in terms of shear modulus value.

The shear strain, where the shear modulus is 70% of its maximum value is estimated according to the recommendation of Plaxis (2022)

$$\gamma_{0.7} = \frac{1}{9G_0}[2c'(1+cos2\varphi') - \sigma_1'(1+K_0)sin2\varphi'] \tag{2}$$

All the input stiffness parameters were calculated for a reference stress of $p^{ref} = 100$ kPa using the Plaxis material model (Plaxis, 2022).

First, the impact of the three soil profiles on the calculation results was investigated. Second, a parameter analysis was performed to study the variation of the two input parameters over a larger range, for which the parameter values were modified – separately – based on the CPT-R profile as shown in the table below.

Table 2. Parameter study.

parameters	**modification multipliers**			
shear modulus, G_0	0.50	0.75	1.25	1.50
shear strain, $\gamma_{0.7}$		0.75	1.25	1.50

In the framework of the research, we investigated the use of Plaxis 2D software for strip footing, excavation support, slab foundation, combined pile-raft foundation and rigid inclusion. In the present paper, the results of these calculations are summarized for a back-anchored diaphragm-wall excavation support, a 40 cm thick slab foundation placed near the surface and a rigid inclusion foundation system with D = 60 cm diameter concrete piles distributed in a 2 m by 2 m grid. The structures investigated are illustrated in the following figures.

For the modelling of the excavation support, the calculation was carried out following the real construction phases, i.e. after the completion of the diaphragm wall, the soil was removed to the anchorage level in the first phase, the anchors were activated in a separate phase with the pre-stressing force, and the complete 10 m excavation was carried out in the last calculation step.

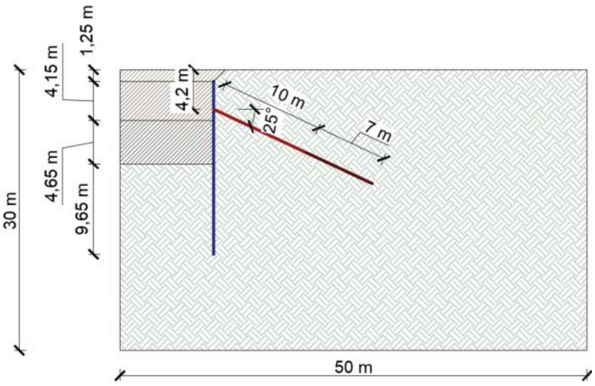

Figure 2. Cross section of diaphragm wall.

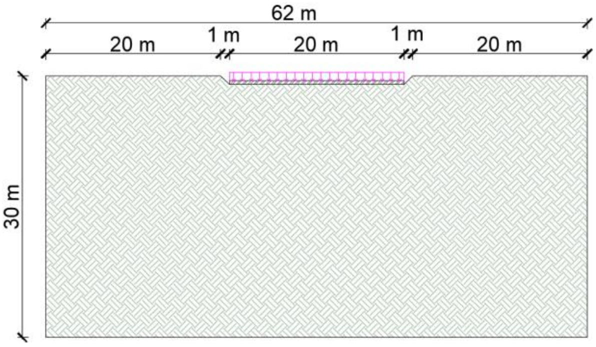

Figure 3. Cross section of slab foundation.

For the slab foundation and the rigid inclusion, a uniformly distributed load of 80-200-250 kPa was activated on the upper plane of the plate, and the resulting deformations and stresses were analysed.

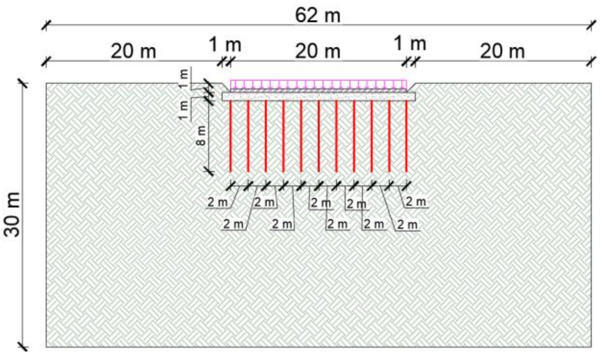

Figure 4. Cross section of rigid inclusion foundation system.

3 RESULTS

3.1 Excavation support

Of the results obtained with the soil models from the field measurements, the SCPT and CPT-R models gave almost identical results, and the MASW soil model showed a significant difference. This is illustrated in Figure 5, which shows the evolution of the bending moments at the end of the first excavation (red-FK2), anchoring (green-H) and full excavation (blue-FK3+V) phases.

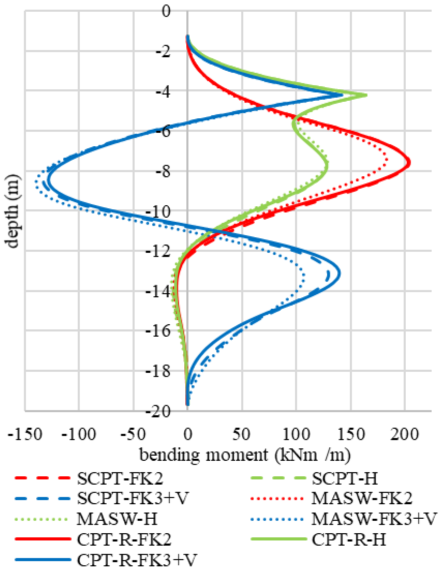

Figure 5. Bending moment of diaphragm wall.

This shows that in the final state, the difference between the maximum moments above the excavation plane is only 10%, which has no significant effect on the design of the structure. Below the excavation level, however, the MASW bending moment value is only 75% of the result obtained with the other two soil models. The differences start to develop from 5 m below the surface, where the MASW measurement shows that the stiffness is higher at small strain level. However, below the working pit level, in the confinement zone, the MASW recorded a lower shear wave velocity value, therefore there is less support stiffness, and thus the wall "moves out of the ground", and thus the stresses are slightly lower. There is little variation in displacement between the models.

The parameter analysis by varying the initial shear modulus showed significant differences in both structural stress and deformation. The effect of the initial shear modulus is largest in the final state (blue curves) (see Figure 6). At a depth of 8.5 m from the surface, the moment was 140% of the original value with the modulus halved and 67% with the modulus one and a half times the original value, with a difference of more than two times between the two extreme values.

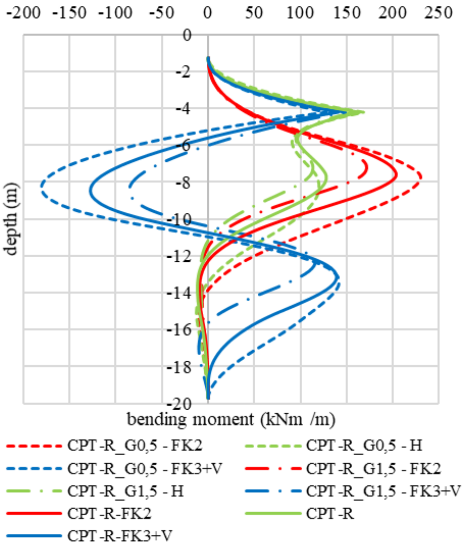

Figure 6. Bending moment of diaphragm wall, G_0 varied.

As shown in Figure 6, at the highest initial stiffness, the bending moment decreases rapidly below the excavation level, i.e. within a small distance, support of the structure is assured. As the modulus decreases, the stiffness of the supporting structure transmits the earth pressure of the background area to a deeper and deeper range, therefore the maximum stress in this range becomes larger and its decay reaches a greater and greater depth. With higher soil stiffness, no substantial stress is experienced in the lower support zone of the diaphragm, but with decreasing stiffness, significant stress is experienced. This is consistent with the calculated shear force distribution, which shows that at higher soil stiffness, the shear stress in the lower part of the diaphragm is small but increases with decreasing stiffness.

The change in the small strain shear modulus has no significant effect on the anchor force: the difference is only 3-4% compared to the baseline value, varying between 564-594 kN. Compared to the soil model estimated from the soil test, changing the small strain modulus without changing the moduli in the large strain range results in a difference in the peak displacement of almost the same proportion (see Figure 7). This is essentially due to the different support stiffness in the confinement range, with the higher part of the structure essentially rotating rigidly as a result of the different support.

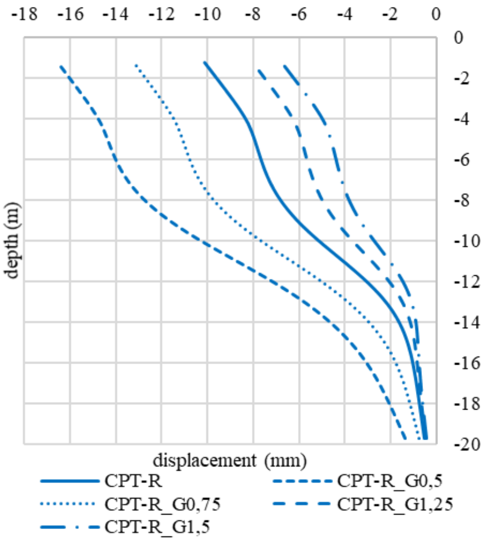

Figure 7. Displacement of the diaphragm wall, G_0 varied.

The sensitivity analysis of $\gamma_{0.7}$, which defines the shape of the modulus degradation curve, shows that its effect on the computed results is smaller than that of G_0, but the mechanisms show good agreement. In the intermediate construction phase, both the moments and shear forces vary nearly identically within a narrow range as a function of $\gamma_{0.7}$. Again, the largest deviations are in the final phase. As the reference shear strain decreases, the soil stiffness decreases more rapidly as the deformation level increases, with a consequent decrease in the support stiffness. Accordingly, as the value $\gamma_{0.7}$ decreases, a larger soil zone provides passive lateral support, whereas as it increases, a soil layer of smaller thickness is able to exert resistance. At the same time, the difference between the two extreme values is only about 15% in the maximum bending moment below the excavation level, and its position changes by only ~1 m.

3.2 Slab foundation

Figure 8 shows the variation of the bending moment in the slab as a function of the load and the soil profile recorded from the field measurements. In the figure, the line type indicates the soil model, and the colour indicates the load level. In general, it can be observed that the curvature of the plate is slightly reduced in the axis of symmetry, with the maximum curvature and hence the maximum moment occurring at ¼ length of the plate. This is related to the fact that the uniformly distributed load results in a shifted soil pressure towards the edges due to the stiffness of the plate, where it is higher. For all three load cases, the moment developed in the plate was almost identical for the SCPT and CPT-R models, but the MASW calculation showed a significant difference. Examining the ratio of moments at the maximum load location, at one quarter of the length of the plate, the value from the SCPT model was 1.5 times the MASW model's value for 80 kPa, 2.7 times for 200 kPa and four times for 250 kPa, so the difference increased with increasing load.

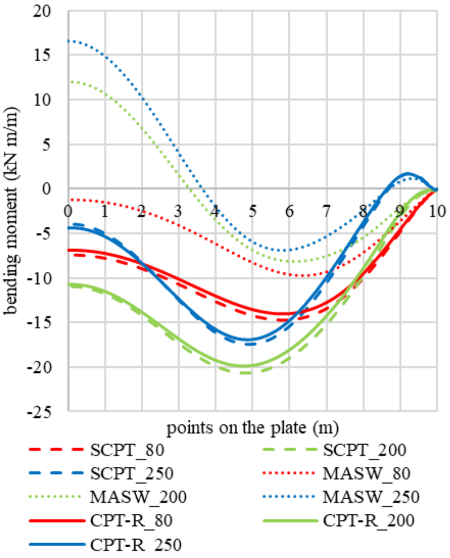

Figure 8. Bending moment along slab foundation.

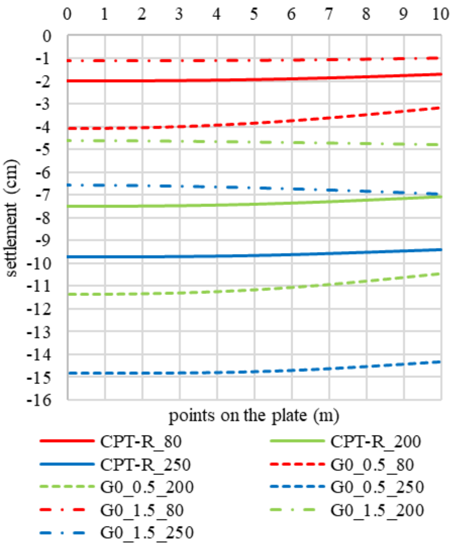

Figure 9. Settlement of plate foundation, G_0 varied.

The results of the parameter analysis regarding the small strain shear modulus and the value of $\gamma_{0.7}$ confirmed the previous findings. A larger change in the small strain modulus also had a significant effect on the range of deformation, and the change was almost directly reflected in the calculated settlement range (see Figure 9).

The deformation of the slab clearly shows that at high soil stiffness the central area of the slab curved in the opposite direction, i.e. tension appeared in the top of the slab. The change in the shear strain value has no such significant effect.

By reducing the reference value, the calculated settlement increased slightly, but the plate shape did not change. However, increasing the reference shear strain reduced the deformations, and in some cases the curvature of slab also switched.

3.3 Rigid inclusion

In the case of the 2D modelling of rigid inclusion soil improvement, the uncertainty inherent in the field measurements did not make a significant difference. Although the variation between the soil models is observed with increasing load, it is moderate. A similar trend to the slab was observed in the bending moment plot. The peak of the bending moment developed at about 2 m from the edge of the plate and tension appeared in the top of the section in the middle of the plate due to the high load (see Figure 10).

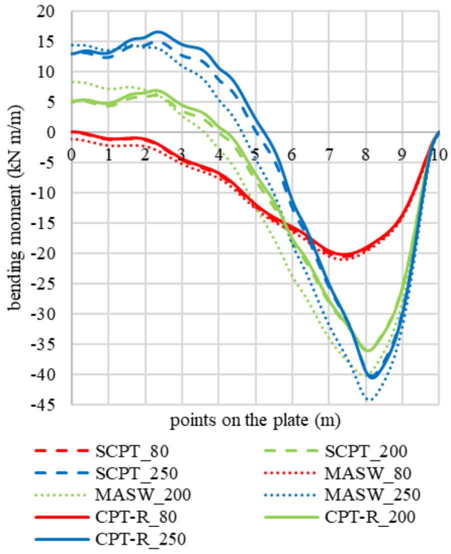

Figure 10. Bending moments in the plate on rigid inclusion.

Increasing the initial shear modulus by one and a half times along the entire length caused little change at all three load levels. At lower loads, the decrease in modulus increased the shear stress along the entire length. Under loads of 200 and 250 kPa, the moment at the plate edges was less sensitive to the change in shear modulus, but there was a significant difference at mid-plate, with tension appearing in the bottom section of the plate.

The effect of the change in the reference shear strain value was smaller for rigid inclusion than for pure slab foundation. For the smallest value, the displacements were 110% of the original value, and for the larger reference shear strain, the displacements were 80% of the original value.

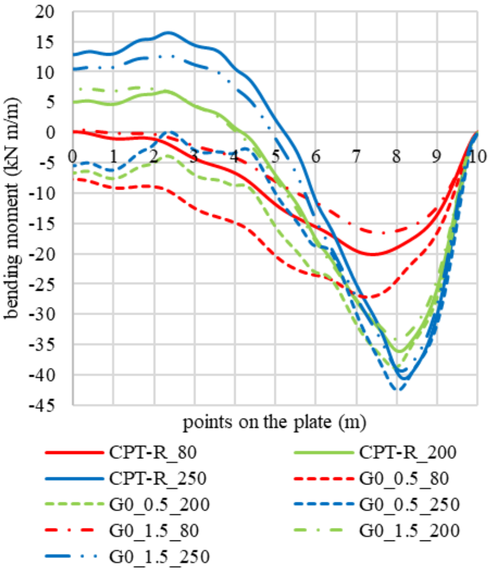

Figure 11. Effect of G_0 on bending moment in plate on rigid inclusion.

4 CONCLUSION

For numerical modelling, the determination of the material model parameters is of paramount importance, and the uncertainties inherent in them will appear in the computational results. In this paper, we investigate how small strain stiffness parameters affect behaviour of typical geotechnical structures.

We have shown, how different shear wave velocity measurements have a significant effect on calculation results for the slab, and a more moderate effect in the case of a diaphragm wall and a rigid inclusion foundation system. A significant effect of the small strain parameters has been identified in the case of the slab bending moments.

Next a parameter study showed, that changing the small strain shear modulus and the value of $\gamma_{0.7}$ over a larger range resulted in significant differences for all three structures. In the case of the excavation support, the change in the stiffness conditions of the embedment area also affected the deformations and bending moment distribution, with the structure being more sensitive to changes in the small strain shear modulus. The behaviour of the slab foundation was fundamentally influenced by the shear modulus, and the results varied substantially in proportion to it. Shear strain parameter had a minor effect also here. For the rigid inclusion, the effect of G_0 decreased with increasing load, as the near-surface layers, which determine the behaviour, were subjected to larger deformation.

Overall, the determination of the G_0 value has a greater impact on the structural behaviour, hence it should be determined by targeted field measurements as precise as possible. The estimation of the shear deformation parameter, which defines the shape of the degradation curve, has shown to have a moderate impact in the modelling of these structures.

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