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Comparison of various FEM approaches in analysis of passive earth pressures

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Passive earth pressure is an important element in integral bridge design. Due to the integral connection between bridge deck and abutments, the integral bridge expansion and contraction under temperature action causes abutments to move together with the deck. With temperature varying in time, this also causes varying earth pressures acting on the abutments. Abutments are generally being designed to withstand passive earth pressure because it is significantly higher than active earth pressure. However, by using the controlled yielding technique, these pressures can be considerably lowered. For this purpose, a few-centimeters-thick layer of easily compressible material is placed behind abutment, which provides a means to potential material saving. In this article, results from 2D and 3D FEM models of integral abutment are presented. Internal forces obtained in 2D and 3D analysis are compared between themselves, and influence of compressible layer thickness on internal forces is also presented.

Keywords: abutment, earth pressure, integral bridge, polystyrene.

1. Introduction

Integral bridges represent an alternative form of design in bridge engineering. They do not have bearings or expansion joints. Contractions and elongations of these structures, caused mainly by temperature, result in interaction with surrounding soil. Active earth pressure and earth pressure at rest have a significantly lower effect on abutment than passive earth pressure. Therefore, passive earth pressure is usually a decisive factor when designing such abutment. However, if abutment is high, this can lead to very robust design. Reduction of passive earth pressures can be achieved by various measures, one of them being the controlled yielding technique. This technique consists of placing easily compressible layer behind bridge abutment, as described for example in Pennsylvania Department of Transportation Design Manual [1]. In this article, various approaches of FEM modeling are compared between themselves, which will be calibrated to experimental results in future.

2. FEM model

2D FEM model was created using beam elements representing an abutment, and quad elements to represent a layer of expanded polystyrene (EPS) and surrounding soil. A nonlinear material model was used for concrete, reinforcing steel and EPS. However, for soil, only a linear material model was available, due to FEM program limitations.

3D FEM model was created using volume elements, except for the abutment in which quad elements with corresponding parameters were used instead. For soil, the Mohr-Coulomb and Drucker-Prager nonlinear material models were used.

The thickness of EPS layer was 0, 50, 100, 180 and 300 millimeters.

The connection between the abutment and soil was represented by springs, capable of transferring compression only, for both 2D and 3D model.

QUAD elements used have three unknowns in their four nodes – u_x, v_y, ϕ_z. ϕ_z was nullified in a 2D analysis, because every element was supported in the direction perpendicular to its plane, while in a 3D analysis this was not the case. In the 3D analysis tetrahedron elements were used. These elements have three unknowns in their nodes – u_x, v_y, w_z. BRIC elements of regular shape could not be used because mesh irregularity prevents their use for automatic meshing in the used software.

Visualisation of the model is shown in Fig. 1. For both models, SOFiSTiK FEM software was used [2]. Stress-strain diagrams are shown in Fig. 2, and selected material properties are listed in Table 1.

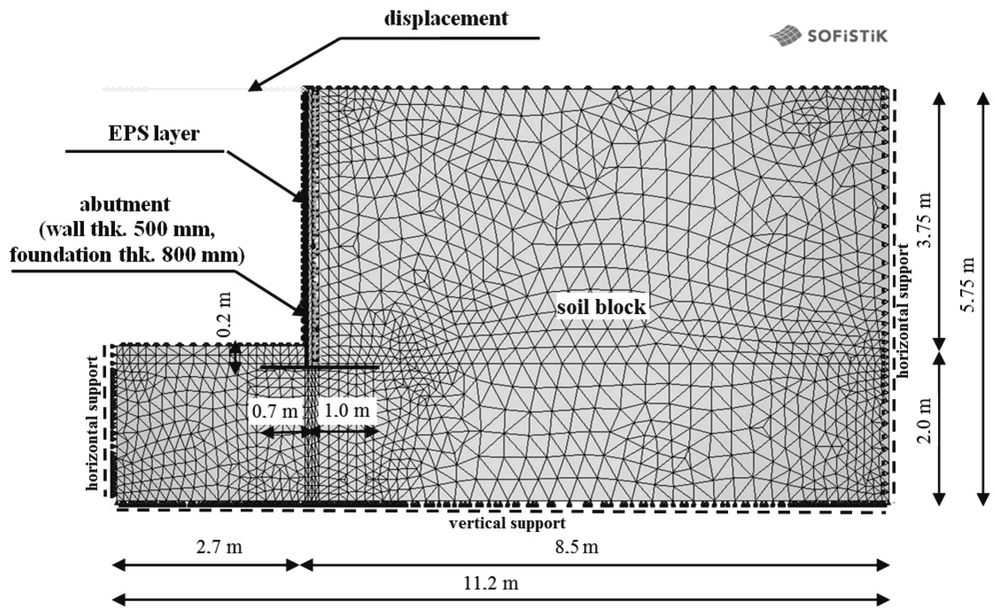

Fig. 1. Visualization of the model.

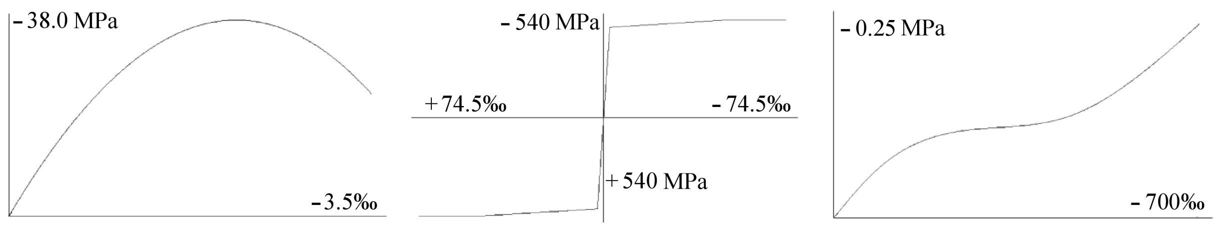

Fig. 2. Stress-strain diagrams (concrete/reiforcement/EPS).

Table 1. Selected material properties.

Material properties	Units	Concrete	Reinforcement	Gravel	EPS
γ	kN/m^{-3}	25.0	78.5	19.0	10.0
ν	–	0.20	0.30	–	0.00
E	MPa	32840	200000	130000	0.35
c	kPa	–	0.0	–	–
φ	°	–	30.0	–	–

3. Evaluation of results

When compressive layer was used, most of the deformations were concentrated in this layer. Only small percentage transferred to soil. Figure 3 depicts horizontal displacement for 10 mm deformation induced in the head of the abutment when no compressive layer was used, and Fig. 4 represents the case when 100 mm-thick EPS layer was used.

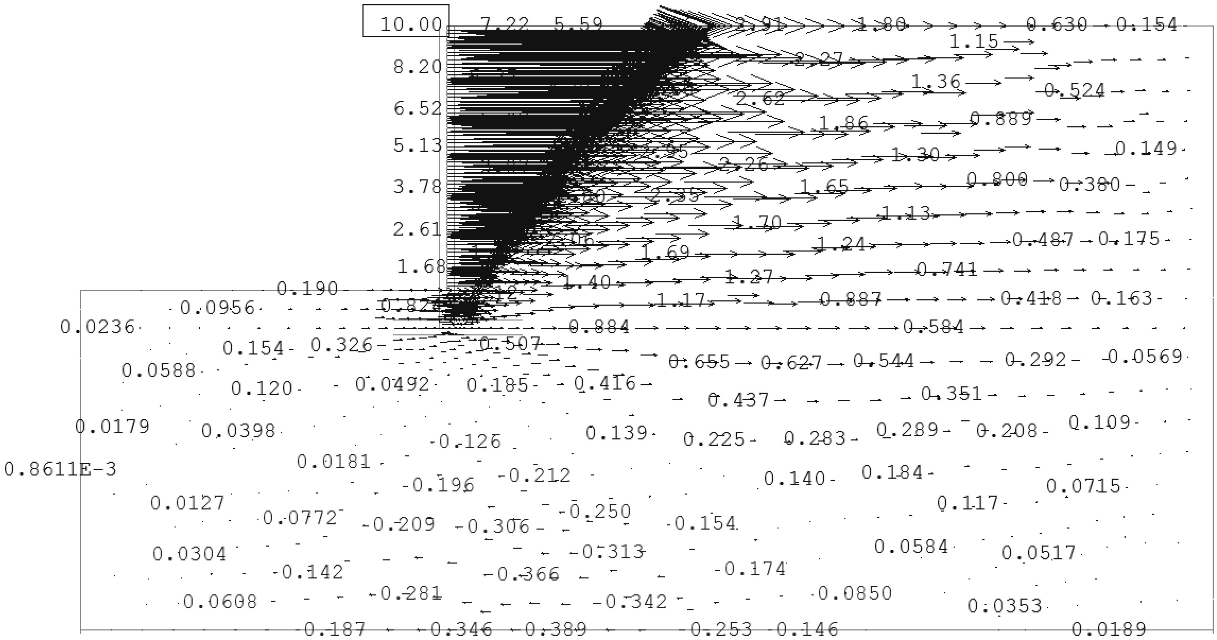

Fig. 3. Horizontal displacements without compressive layer [mm] – 3D model results.

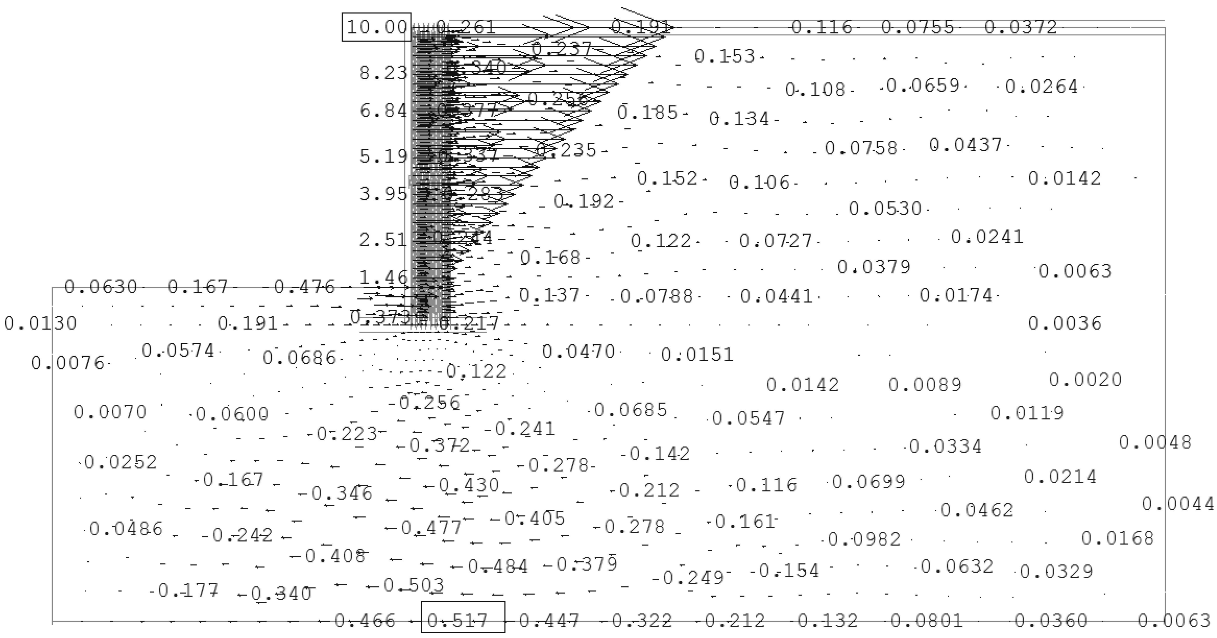

Fig. 4. Horizontal displacements with compressive layer [mm] – 3D model results.

Results showing bending moments and shear forces obtained from the 2D model are presented in Fig. 5. Bending moments from the 2D model with the EPS layer thickness of 100 mm and from

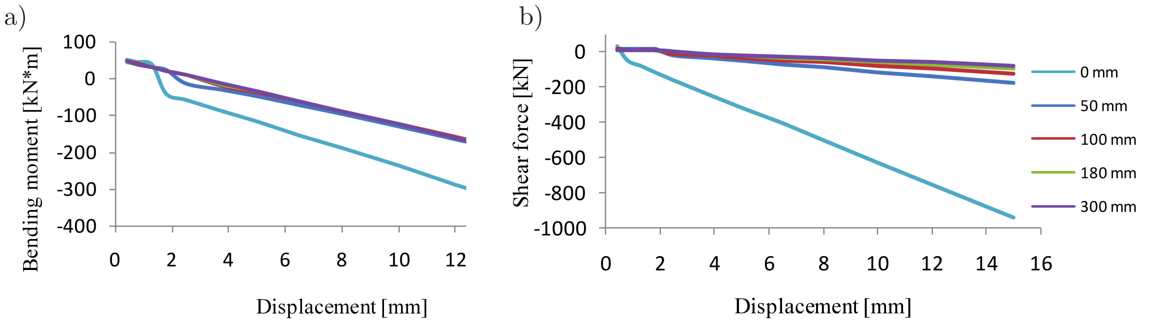

Fig. 5. 2D nonlinear analysis: a) bending moments, b) shear forces.

the 3D model using the Drucker-Prager and Mohr-Coulomb soil model are depicted in Fig. 6a and, analogically, for shear forces in Fig. 6b.

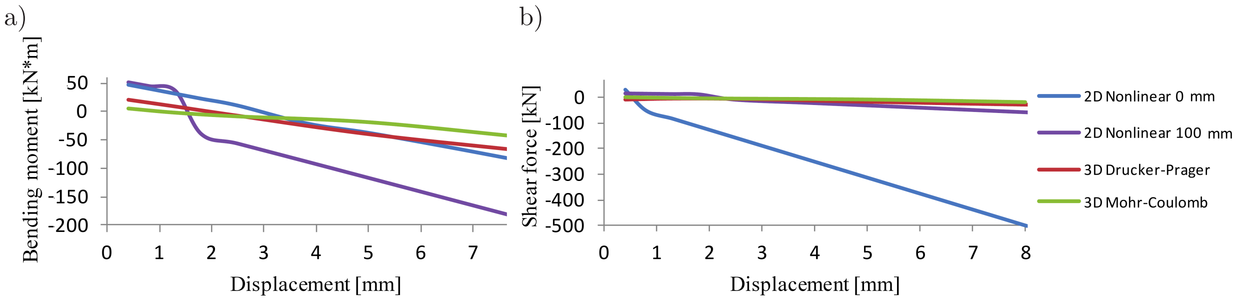

Fig. 6. 3D nonlinear analysis: a) bending moments, b) shear forces.

Results from 2D and 3D models are very similar to the results for shear forces and bending moments. Therefore, the influence of nonlinear soil behavior seems to be only of small impact on the results, which is also confirmed by negligible differences between results from the Drucker-Prager and Mohr-Coulomb model. The hardening soil material model proved to be ineffective in this case, as it did not meet convergence criteria even after the considerable amount of calculation time. In both cases (2D and 3D models), bending moments were reduced to less than 40% compared to the case when no compressible layer was used, which corresponds to similar results obtained in [3].

Influence of thickness of the compressible layer is shown in Fig. 7. In this case, even small thicknesses were adequate to rapidly decrease earth pressure acting on the abutment. Dependency between shear forces and EPS layer thickness appears to be of exponential nature.

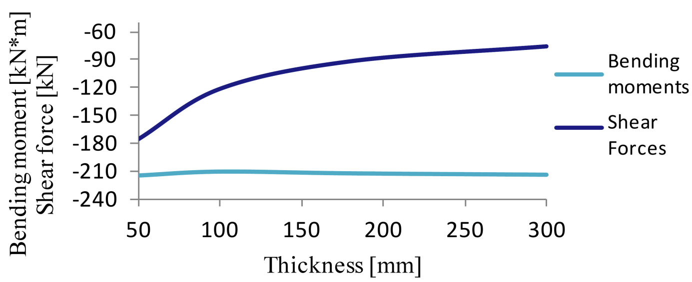

Fig. 7. Influence of thickness of compressible layer – 2D model results.

Probably the most important negative effect of using compressive layer is an increased settlement of soil in proximity to the abutment. This is caused by decreased interface friction between soil and EPS layer [4]. Figure 8 represents vertical displacements when no compressible layer was used, while Fig. 9 shows vertical displacements with the usage of EPS layer. The difference in settlement

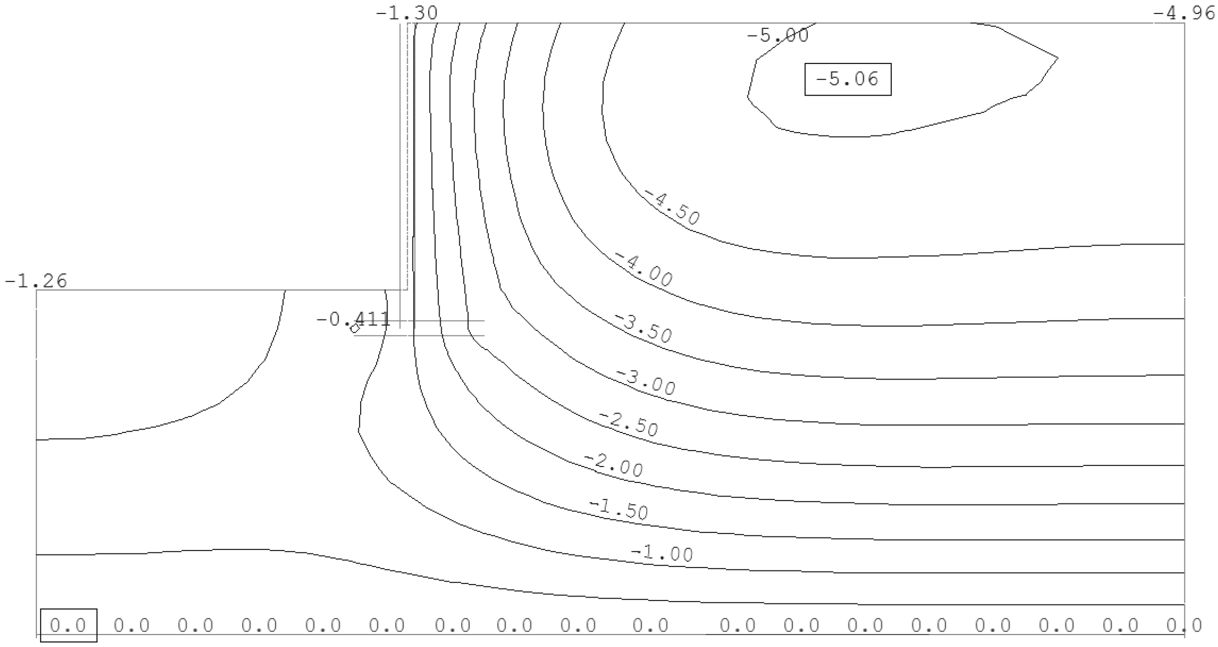

Fig. 8. Vertical displacements with no compressible layer [mm] – 3D model results.

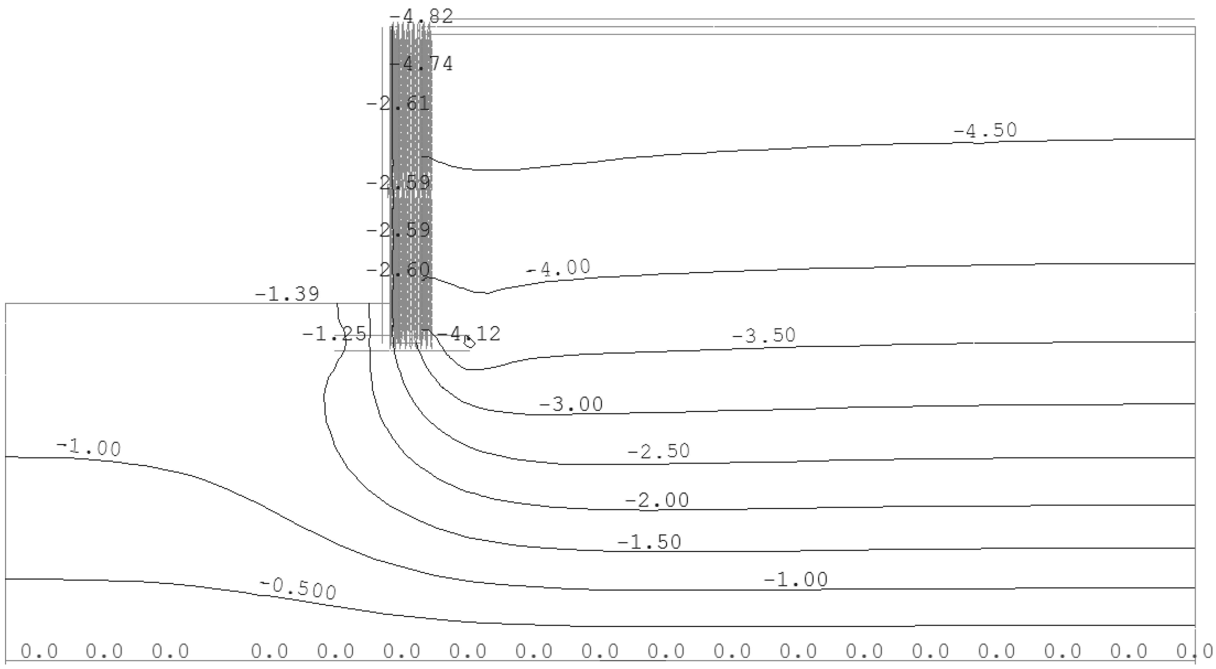

Fig. 9. Vertical displacements with a 100 mm thick compressible layer [mm] – 3D model results.

close behind the abutment is more than 3.5 times larger. However, this can be compensated with adequate design of transition slab.

4. Conclusions

Several conclusions can be drawn as a result of the numerical analysis performed in this study. Various thicknesses of the compressible layer were examined. Using layers with higher thicknesses resulted in roughly the same decrease of bending moments as in the thinnest variant of compressible layer examined. Therefore, it is anticipated that even a relatively small thickness (in this case 50 mm of EPS behind the 500 mm-thick abutment wall) of compressible layer is capable of significantly reducing bending moments caused by passive earth pressure acting on integral abutment (more than 50%), and high thicknesses of EPS layer are unnecessary for reducing bending moments.

The relationship between shear forces and thickness of compressible layer appears to be of exponential nature.

Influence of the nonlinear material model of soil seems to have a negligible impact on results, as most of the deformations cumulate in the compressible layer.

Settlement in proximity of abutment can increase significantly; in the examined case more than 3.5 times, thanks to low abutment-soil interface friction [4].

Acknowledgments

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