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IMPACT OF SOIL REPLACEMENT ON ROAD EMBANKMENT SETTLEMENT

Summary: This paper presents an analysis of consolidation settlement and consolidation time due to the construction of a road embankment on the Kratovska Stena–Lučani section. The study was performed for three representative sections between bridge structures, considering different embankment heights and subsoil improvement options. The analysed cases included no soil replacement, full-width replacement of the soft layer with thicknesses ranging from 1.5 to 2.5 m, and bench-shaped replacement. The results indicate that the applied subsoil improvement measures significantly reduce total settlement and reduce consolidation time. The findings provide a sound basis for selecting a technically and economically optimal engineering solution in practice.

Keywords: road embankment, soil replacement, settlement, consolidation time

UTICAJ ZAMENE TLA NA SLEGANJE PUTNOG NASIPA

Rezime: U radu je prikazana analiza konsolidacionog sleganja i trajanja konsolidacije usled izgradnje putnog nasipa na deonici Kratovska stena–Lučani. Analiza je urađena za tri karakteristične deonice između mostovskih konstrukcija, pri različitim visinama nasipa i varijantama poboljšanja podtla. Razmatrani su slučajevi bez zamene, pune zamene sloja u debljini 1.5–2.5 m i zamene promenljive geometrije. Rezultati pokazuju da primena mera poboljšanja podtla značajno utiče na smanjenje ukupnih sleganja i skraćenje vremena konsolidacije. Dobijeni rezultati mogu poslužiti kao osnova za izbor tehnički i ekonomski optimalnog rešenja.

Ključne reči: putni nasip, zamena tla, sleganje, vreme konsolidacije

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1. INTRODUCTION

Road embankments constructed on soft subsoil may be associated with large total and differential settlements, while consolidation may continue long after embankment construction. Post-construction settlements can affect road serviceability and maintenance requirements [1, 2]. The analysis should therefore include settlement magnitude, consolidation time and the efficiency of possible ground improvement measures. In engineering practice, several ground improvement techniques can be used to reduce settlements and accelerate consolidation. These include preloading, staged construction, vertical drains, stone columns, deep soil mixing, rigid inclusions, geosynthetic reinforcement, lightweight fill, and partial or full replacement of weak soil. The selection of the most suitable method depends on the soil profile, thickness of the compressible layer, groundwater conditions, embankment height, allowable settlement, construction time, availability of materials, and economic constraints.

This paper analyses the Kratovska Stena–Lučani section of the new state road IIA-181, where embankments are planned between bridge structures. The analysis includes three representative embankment sections. The embankment height is approximately 6–7 m in Sections 1 and 2, while in Section 3 it ranges from about 3 to 6 m. Available geotechnical data indicate weak foundation soils to a depth of approximately 5–6 m, requiring an assessment of settlement magnitude and consolidation time.

PLAXIS 2D finite element models were developed for representative embankment cross-sections. The models included the adopted soil stratigraphy, embankment geometry and geotechnical parameters derived from the available investigation data. The calculations were performed for the embankment without replacement of the soft layer and for several replacement solutions, including full-width replacement and bench-shaped replacement. The results were compared in terms of total settlement and consolidation duration.

2. GROUND IMPROVEMENT METHODS

Ground improvement methods include a wide range of techniques used to modify the engineering behaviour of natural soils. These techniques may be classified into four main groups: mechanical modification, hydraulic modification, physical and chemical modification, and methods based on inclusions, reinforcement or confinement [3].

Mechanical methods include compaction, densification and replacement of unsuitable soil with material of better mechanical properties. Hydraulic methods act through drainage control and pore pressure dissipation, including dewatering, preloading and vertical drains. Physical and chemical methods, such as lime and cement stabilisation, deep soil mixing and grouting, modify the soil structure or composition. Methods based on inclusions and reinforcement, such as stone columns, rigid inclusions and geosynthetics, change the load transfer mechanism within the ground.

For embankments on soft foundation soils, mechanical replacement is a direct improvement measure. It removes the weakest material from the upper foundation zone and replaces it with compacted granular fill, producing a stiffer and more uniform support for the embankment. The efficiency of this method depends on the depth, width and geometry of the replacement zone, as well as on the compressibility of the remaining subsoil. Hydraulic methods could also be considered when consolidation rate has a significant influence on the deformation response. Measures such as preloading or vertical drains primarily accelerate pore pressure dissipation, but they require additional construction time and monitoring. In comparison, replacement provides an immediate modification of the foundation zone and is therefore suitable when the improvement has to be achieved during embankment construction.

3. CASE STUDY

The Kratovska Stena–Lučani road section was divided into three embankment sections, extending over 143 m, 218 m and 550 m, respectively. The division follows the position of embankments between bridge structures, the variation in embankment height and the interpreted ground conditions along the route. Sections 1 and 2 represent the higher embankment zones, with adopted embankment heights of 6 m and 7 m, while Section 3 represents the part of the route with a somewhat different subsoil profile and embankment heights in the range of 3–6 m.

The geotechnical investigation programme included in-situ and laboratory testing along the analysed road section. In-situ data were obtained from CPT tests, boreholes and trial pits within the embankment and bridge zones [4]. Laboratory testing provided the physical, strength, compressibility and permeability parameters of the foundation soils. These data were used to interpret the ground profile and define the parameters adopted in the numerical model.

The embankment is founded on fine-grained and granular deposits, underlain by sericite–chlorite schists and phyllites with a weathered zone. The upper part of the subsoil consists of clayey–sandy silt of low stiffness, with thicknesses of 3.0 m in Sections 1 and 2 and 4.0 m in Section 3. This layer is followed by sandy silt and sand, with a thickness of 2.0 m in all sections, and by a 6.0 m thick gravel layer. The underlying schists and phyllites were treated as the base of the model. The adopted profile is shown in Figure 1, and the material parameters used in the analyses are given in Table 1.

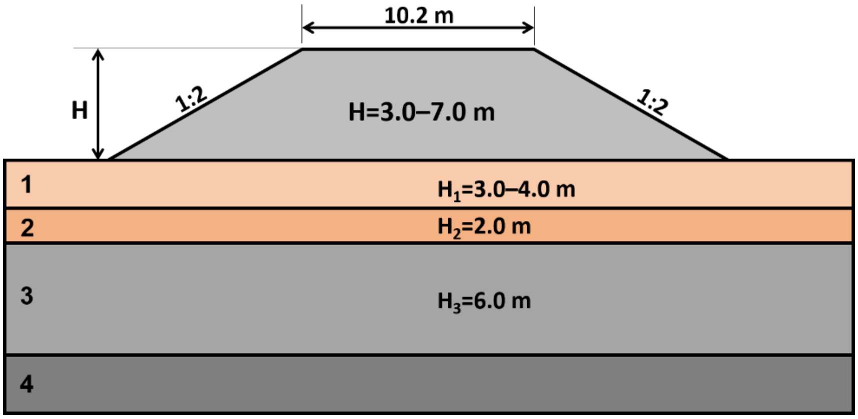

Figure 1: Adopted embankment geometry and subsoil profile for the analysed sections

Table 1: Material parameters used in the analyses

Layer	Material	Thickness (m)	γ (kN/m³)	Mv (MPa)	ν	φ′ (°)	c′ (kPa)	k (m/s)
1	Clayey-sandy silt, CI	3–4	17.5	2.0	0.40	21	10	10^{-8}, 10^{-9}
2	Sandy silt CI, sand SP	2	20.0	4.5	0.35	25	8	10^{-7}
3	Gravel, GP / GC	6	21.0	20, 33	0.20	36	0	10^{-5}
4	Schists and phyllites	model base	/	/	/	/	/	/
5	Embankment fill	3–7	22.0	30.0	0.20	38	1	10^{-5}

The stiffness of the gravel layer was taken as 33 MPa in Sections 1 and 2 and 20 MPa in Section 3. For the upper soft layer, two permeability values, 10^{-8} m/s and 10^{-9} m/s, were considered.

Subsoil replacement was adopted because the soft deformable layer is relatively shallow. Replacing part of the fine-grained soil with compacted granular material increases the stiffness of the foundation zone and shortens the drainage path, which can reduce both settlement and consolidation time.

4. NUMERICAL ANALYSIS

The numerical analyses were performed for several embankment heights within each representative section. The results presented in this paper correspond to the maximum embankment heights of 7.0 m in Sections 1 and 2 and 6.0 m in Section 3.

Several variants of soft-layer replacement were considered. The reference case was the embankment constructed on the existing subsoil, with only a shallow mandatory replacement layer 0.3 m thick. This case was used as the basis for comparison with the replacement variants. Full-width replacement was analysed for depths of 1.5 m, 2.0 m and 2.5 m. In these cases, the replacement zone extended beneath the embankment base over the adopted design width. The replacement width was 22.0 m in Sections 1 and 2 and 18.0 m in Section 3.

Bench-shaped replacement was also considered, with maximum replacement depths of 2.0 m and 1.5 m in the central part of the embankment foundation. The replacement depth was reduced towards the embankment edges, resulting in a narrower improved zone compared with the full-width layout. The adopted widths were 18.0 m in Sections 1 and 2 and 14.0 m in Section 3.

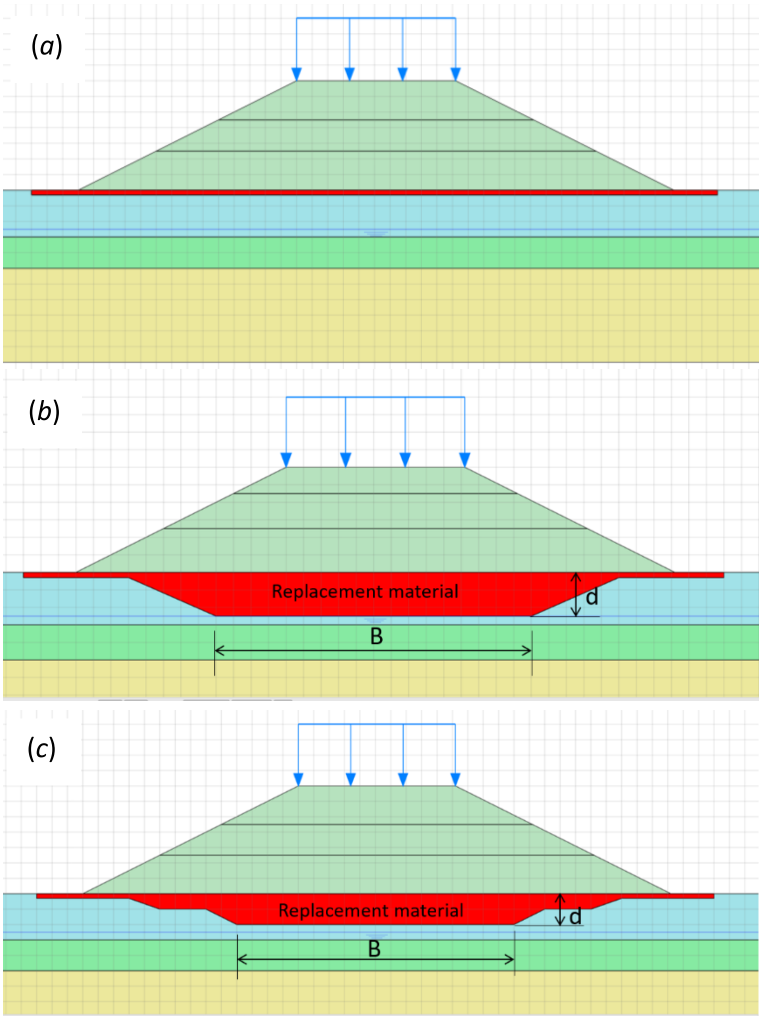

Figure 2: Analysed subsoil replacement variants: (a) reference case with 0.3 m shallow replacement, (b) full-width replacement, and (c) bench-shaped replacement

Settlement analyses were performed in PLAXIS 2D under plane strain conditions. A fully coupled flow–deformation consolidation analysis was used, allowing simultaneous calculation of deformations and pore pressure dissipation during and after embankment construction [5]. The soil layers, embankment fill and replacement material were modelled using the Mohr–Coulomb constitutive model. The material parameters of the soil layers and embankment fill are given in Table 1, while the parameters adopted for the replacement material are presented in Table 2.

Table 2: Material parameters for replacement material

Material	**Thickness (m)**	**γ (kN/m³)**	**Mv (MPa)**	**ν**	**φ′ (°)**	**c′ (kPa)**	**k (m/s)**
Replacement fill	1.5–2.5	22.0	30.0	0.20	38	0	10^{-5}

The calculation procedure consisted of two stages. In the first stage, embankment construction was simulated over a period of 45 days. In the second stage, consolidation was continued after construction until the calculated excess pore pressures had sufficiently dissipated and the development of settlements became negligible.

Standard displacement boundary conditions were applied to the finite element model. Horizontal displacements were fixed along the vertical model boundaries, while both horizontal and vertical displacements were fixed at the bottom boundary. Hydraulic boundary conditions were defined in accordance with the adopted drainage conditions of the ground profile.

5. RESULTS AND DISCUSSION

The results are presented through the crest settlement and consolidation time for the analysed replacement variants. The comparison was made for two values of the permeability coefficient of the upper soft clayey-sandy silt layer, $k=10^{-8}$ m/s and $k=10^{-9}$ m/s. Sections 1 and 2 were analysed with a 3 m thick upper soft layer, while Section 3 was analysed with a 4 m thick upper soft layer and lower stiffness of the underlying gravel layer.

For Sections 1 and 2, the calculated crest settlements for the 7 m high embankment are shown in Figure 3. The reference case without replacement gives the largest settlement, about 45 cm. Full-width replacement reduces the settlement considerably. The most effective case is full-width replacement with a thickness of 2.5 m, where the crest settlement is reduced to about 23 cm. Bench-shaped replacement gives results close to the corresponding full-width replacement of similar depth.

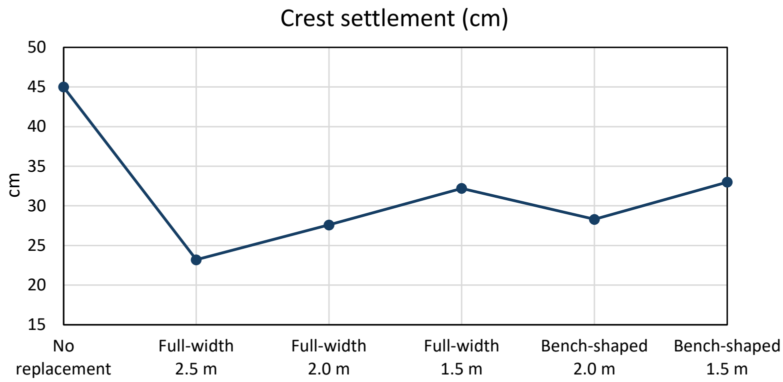

Figure 3: Crest settlement for Sections 1 and 2, $k=10^{-8}$ m/s

The influence of permeability on the calculated final settlement is relatively small. For the same replacement geometry, the settlements obtained for $k=10^{-8}$ m/s and $k=10^{-9}$ m/s are very similar. This indicates that the final settlement is mainly controlled by the stiffness and thickness of the compressible layers and by the replacement geometry.

In contrast, the consolidation time is strongly affected by the adopted permeability of the upper soft layer. As shown in Figure 4, in the reference case without replacement the consolidation time increases from about 150 days for $k=10^{-8}$ m/s to about 200 days for $k=10^{-9}$ m/s. Similar differences are also observed for the replacement variants. This confirms that reliable estimation of the permeability coefficient is essential for predicting the time development of settlements. However, defining a representative value of permeability is not straightforward, since laboratory and in-situ results may differ and the coefficient can vary significantly within fine-grained soils. The replacement variants reduce the consolidation time for both adopted permeability values. This is mainly due to partial removal of the fine-grained layer and its replacement with granular material, which shortens the drainage path during consolidation. For full-width replacement, the calculated consolidation time is generally reduced to about 60–100 days, depending on replacement depth and permeability. Bench-shaped replacement also reduces the consolidation time, although the reduction is less pronounced for the smaller replacement depth.

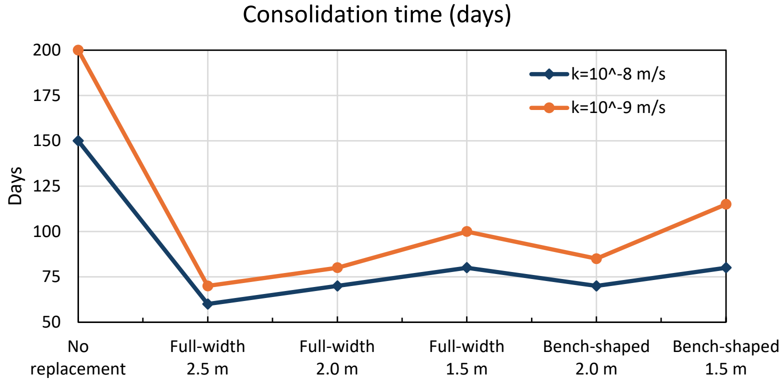

Figure 4: Consolidation time for Sections 1 and 2 for different values of permeability

For Section 3, the same comparison was made for the 6 m high embankment, as shown in Figures 5 and 6. Although the embankment height is lower, the calculated settlements remain higher. This is mainly a consequence of the thicker upper soft layer and the lower stiffness adopted for the gravel layer. The reference case gives a crest settlement of about 50 cm, while full-width replacement of 2.5 m reduces it to about 32 cm. Bench-shaped replacement also reduces settlement, although the effect is less pronounced for the smaller replacement depth.

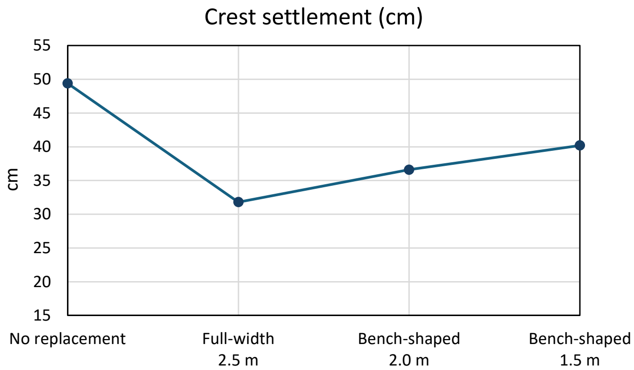

Figure 5: Crest settlement for Section 3

The difference between the two adopted permeability values is again more evident in the consolidation time than in the final settlement. For the reference case, reducing the permeability from 10^{-8} m/s to 10^{-9} m/s increases the consolidation time from about 90 days to more than 200 days. This confirms the importance of the adopted permeability for time-dependent settlement analysis. Replacement reduces the consolidation time for both permeability values, with the shortest times obtained for full-width replacement.

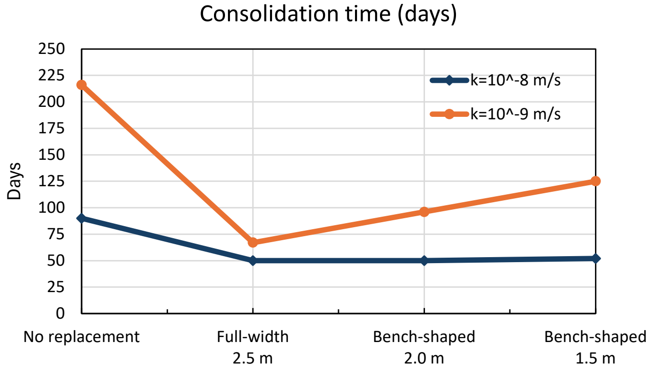

Figure 6: Consolidation time for Section 3 for different values of permeability

6. CONCLUSIONS

The analyses confirm that subsoil replacement reduces both crest settlement and consolidation time. Full-width replacement at the largest analysed depth gives the largest reduction. Bench-shaped replacement also provides considerable settlement reduction, while requiring a smaller excavation volume.

The results also show that the reliability of settlement and consolidation predictions depends directly on the quality of the adopted soil parameters. For this reason, appropriate in-situ investigations and laboratory testing are essential for defining the stiffness, strength and permeability of the foundation soils. This is particularly important during phased construction, where decisions on further embankment construction should be based on the observed and predicted soil response under the actual loading and drainage conditions.

REFERENCES

[1] Schaefer V. R., Berg R. R., Christopher B. R., Elias V., DiMaggio J. A. Ground Modification Methods – Reference Manual, Volume I, Federal Highway Administration, U.S. Department of Transportation, FHWA-NHI-16-027, USA, 2016.

[2] Schaefer V. R., Berg R. R., Christopher B. R., Elias V., DiMaggio J. A. Ground Modification Methods – Reference Manual, Volume II, Federal Highway Administration, U.S. Department of Transportation, FHWA-NHI-16-028, USA, 2016.

[3] Nicholson P. G. Soil Improvement and Ground Modification Methods, Butterworth-Heinemann, Oxford, 2015.

[4] Institut za ispitivanje materijala IMS. Izveštaj o ispitivanju br. G-0073/24: Laboratorijska geomehanička ispitivanja uzoraka tla za potrebe izgradnje nove trase državnog puta IIA-181, deonica Kratovska Stena–Lučani, Beograd, 2024.

[5] Obradović N., Jocković S. Numerical evaluation of road embankment settlements, Journal of Road and Traffic Engineering, 2026, 84-91.