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Settlement evaluation of reinforced embankment over a soft subgrade: Numerical modelling with different soil models based on a full-scale study

Évaluation des tassements d'un remblai renforcé sur une couche de fondation meuble: Modélisation numérique avec différents modèles de sol basés sur une étude à l'échelle réelle

B. Janevski*
Civil Engineering Institute "Macedonia", Skopje, RN Macedonia

J. Br. Papić
Faculty of Civil Engineering, Skopje, RN Macedonia

A. Skejić
Faculty of Civil Engineering, Sarajevo, Bosnia and Herzegovina

A. Turalić
Design & QC, Sarajevo, Bosnia and Herzegovina

**bojan.janevski@gim.mk*

ABSTRACT: This paper presents results from comparative numerical analyses for an experimental study performed to investigate the soil behaviour for airfield pavement design in Bihać, Bosnia and Herzegovina. A 300 m long and 45 m wide multilayer reinforced embankment is constructed and surcharged in three zones by static loads over thick soft deposits. The monitoring comprises the observation of the settlements with a geodetic survey, horizontal inclinometers, and magnetic extensometers. Different constitutive models are used to model the terrain and estimate the settlements, and the results are compared to the monitoring. Although the results of the analyses generally confirm the terrain response, regardless of how precisely the terrain is modelled, it is difficult to accurately model all loading phases with constant values of the input parameters. The findings obtained through the numerical modelling are presented in the paper.

RÉSUMÉ: Cet article présente les résultats d'analyses numériques comparatives pour une étude expérimentale réalisée pour étudier le comportement du sol pour la conception de la chaussée d'un aérodrome à Bihać, en Bosnie-Herzégovine. Un remblai renforcé multicouche de 300 m de long et 45 m de large est construit et surchargé en trois zones par des charges statiques sur d'épais dépôts d'argiles molles et de limons. La surveillance sur le terrain comprend l'observation des agglomérations avec un levé géodésique, des inclinomètres horizontaux et des extensomètres magnétiques. Différents modèles constitutifs sont utilisés pour caractériser le terrain et estimer les tassements, et les résultats sont comparés au suivi. Bien que les résultats des analyses confirment généralement la réponse du terrain, quelle que soit la précision avec laquelle le terrain est modélisé, il est difficile de modéliser avec précision toutes les phases de chargement avec des valeurs constantes des paramètres d'entrée. Les résultats obtenues grâce à la modélisation numérique sont présentés dans l'article.

Keywords: Embankment; monitoring; numerical modelling; settlements; soft soil.

1 INTRODUCTION

The evaluation of the consolidation settlements in soft soils represents an everyday challenge, and it is a subject of research by many authors, starting from the constitution of the theory of consolidation (Terzaghi, 1925) until today. The engineer should precisely assess the uncertainties about the geological and hydrogeological conditions, correctly interpret the field investigations and the laboratory test results, and evaluate the influence of the construction phases and the structure on the terrain, the variation of the stresses, the total stresses, etc. The construction activities on soft soils commonly include placing layers of geosynthetic reinforcement and controlled fill material beneath the loading area to enhance performance, especially in embankments, unpaved roads, and large stabilized areas like car parks or platforms (Giroud et al., 1984; Rowe and Soderman, 1986; Love et al., 1987; Rowe and Li, 2005).

The benefits of geosynthetic as a reinforcing layer between the fill and the subsoil offers benefits such as a potential for reduction in fill thickness for specified compaction values and bearing capacities and a decrease in rut formation, thereby extending the serviceable life of the track (Hufenus et al., 2006). The large and small-scale experiments generally illustrate that the geogrid aids in spreading the applied load over a broader area on the subgrade layer, leading to reduced permanent deformation accumulation in the subgrade (Abu-Farsakh and Chen, 2011; Demir et al., 2013; Kapor et al., 2023a, 2023b). However, the case studies supported by back-numerical analyses using relatively complex soil models are somewhat limited.

This paper briefly presents an experimental study investigating soil behaviour for airfield pavement design in Bihać, Bosnia and Herzegovina. Unlike Skejić and Turalić (2022), the numerical analyses included a complex soil model with stress and time-dependent parameters. Good agreement was achieved between the model and in-situ records. Finally, some conclusions and recommendations are emphasized for future similar projects.

2 DEFINING THE PROBLEM

2.1 Geotechnical characteristics

Up to a depth of about 1,5 m, the terrain for the airfield is composed of sandy clays and silts (CL/ML) with low plasticity and soft to very soft consistency. There are silts and clays with organic content (OL) in a liquid-consistent state under it, with a thickness of around 17 m. Under these quaternary deposits, there are practically impermeable Miocene sediments with very low compressibility. The average groundwater level is 0.5 m below the terrain. Table 1 shows the parameters of the represented soil layers.

Table 1. Geotechnical parameters of the soil materials.

Parameter	CL/ML	OL
γ [kN/m^3]	16,5 – 19,0	16,5 – 18,5
φ [°]	18 – 22	16 – 18
c [kPa]	10 – 15	10 – 15
q_c [MPa]	0,5 – 4,0	0.2 – 1.0
N_{spt} [/]	2 – 4	1 – 2
E [MPa]	1,5 – 7,0	0,7 – 2,3
k_f [m/s]	$5\times10^{-6} – 5\times10^{-8}$	$5\times10^{-8} – 1\times10^{-9}$

2.2 Brief overview of the experimental study

An experimental study was conducted to investigate the soil behaviour for an airfield pavement design (Nuhić et al., 2021).

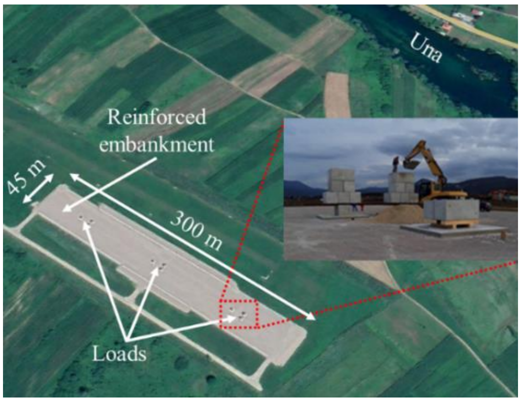

Figure 1. Aerial view of the subject location.

The embankment was constructed in three reinforced and compacted layers with a total height of 1,1 m over a very soft subgrade, where static loads are applied on top (Figure 1). All three layers are reinforced with geogrids 60/60 kN/m. The compressive modules of the embankment layers are 25/60/90 MPa, with construction time of 30/33/42 days, respectively. The static loads were applied in 1 day, in three zones, 40 days after the completion of the embankment. They simulate a load of 20 kN on an area of 16 m^2. The characteristic cross-section of the reinforced embankment is shown in Figure 2.

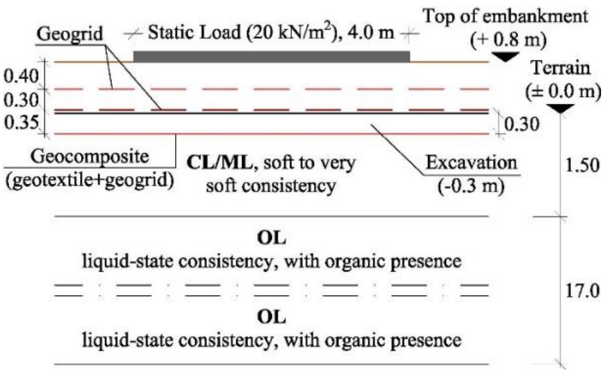

Figure 2. Characteristic cross-section of the study.

2.3 Results from the monitoring

The settlements were monitored continuously with geodetic measurements, horizontal inclinometers, and magnetic extensometers. The inclinometers were placed along the entire embankment width, 35 cm under the loads. The initial measurement was done immediately after loading. The average cumulative settlement 170 days after the loading was 8,4 cm and 8,2 cm as measured by geodetic monitoring and the horizontal inclinometer readings, respectively. The settlement distribution presented in Figure 3 shows the impact of the loads on the embankment.

The magnetic extensometers were placed on the contact between the first two embankment layers when the initial measurement was performed.

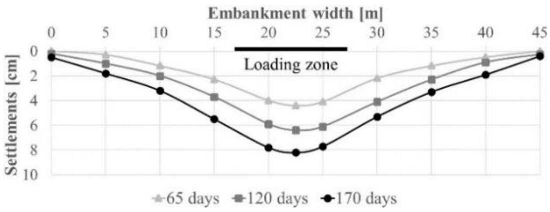

Figure 3. Embankment settlement distribution along its width (readings from horizontal inclinometers).

Figure 4 shows characteristic settlement curves for different depths. The primary consolidation has a significant part in the cumulative settlements since most of the deformations occur after the construction of the embankment. The secondary consolidation is not completed as there is no flattening of the settlement curve. A relatively short monitoring period represents a drawback of the experimental study, where the monitoring was unfortunately stopped due to unclear reasons.

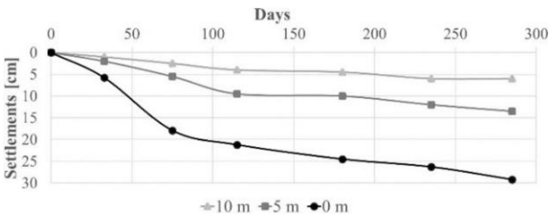

Figure 4. Magnetic extensometer measurements.

3 NUMERICAL CALCULATIONS

The three-dimensional numerical simulation was performed in Plaxis 3D software (Bringreve and Manoj, 2019). The half-space is discretized with 10-noded tetrahedral finite elements. The soil is characterized according to the Mohr-Coulomb (MC) criterion and Soft-Soil (SS) model. The simulation is conducted in several successive phases, according to the stages of the experimental study, that is:

- Phase 1: initial state (before construction);
- Phase 2: topsoil excavation (30 cm);
- Phase 3: construction of 1st layer, t=30 days;
- Phase 4: construction of 2nd layer, t=33 days;
- Phase 5: construction of 3rd layer, t=42 days;
- Phase 6: consolidation, t=40 days;
- Phase 7: static loading p=20 kN/m^2, t=1 day;
- Phase 8: consolidation, t=170 days.

The input parameters, depending on the model, are shown in Table 2, based on the in-situ and laboratory test results. For the Soft-Soil model, correlations from contemporary literature were used (see Van Baars, 2003, and Long et al., 2020).

Table 2. Input parameters in the software Plaxis 3D.

	CL/ML		**OL**		
	MC-p	MC-c	MC-p	MC-c	SS-c
γ [kN/m^3]	17,0	17,0	16,5	16,5	16,5
φ [º]	20,0	20,0	17,0	17,0	29,0
c [kPa]	10,0	10,0	10,0	10,0	0,0
E [MPa]	4,5	7,0	1,2	2,2	/
k_f[m/s]	/	5*10^{-6}	/	5*10^{-7}	2*10^{-8}
C_c [/]	/	/	/	/	1,0
C_s [/]	/	/	/	/	0,22
λ* [/]	/	/	/	/	0,145
k* [/]	/	/	/	/	0,064

* MC = Mohr-Coulomb; SS = Soft-Soil; p = plastic; c = consolidation

The geogrids are defined with elastoplastic behaviour and isotropic characteristics, with axial stiffness EA_1=EA_2=1200 kN/m and maximum tensile force $N_{p,1}$=$N_{p,2}$=60 kN. Due to small deviations in the results compared to the monitoring, a calibration of the permeability (k_f) and the deformation modulus (E) was conducted. These parameters are not constant in reality but are directly dependent on the degree of the stresses and the time, that is from the analysed phase. Namely, the deformation modulus tends to increase with the stresses while the permeability decreases and vice versa. Therefore, the analyses are repeated using a variable set of parameters: for the sandy clays and silts (CL/ML), E_{oed}=1,5-7,0 MPa, and for the silts with organic content (OL), E_{oed}=0,7-2,25 MPa and k_f=1*10^{-7}-1*10^{-8} m/s.

Figure 5 shows an overview of the settlement evaluation in Plaxis 3D, depending on the analyzed phase, the model used, and the calculation method, compared to the average values of the settlement obtained during the monitoring. The highest value of settlements (30,38 cm) is obtained using a variable set of parameters and the Soft-Soil model, where the settlement curve is the closest to the monitoring curve. The deformed mesh in the vertical direction for this analysis is shown in Figure 6.

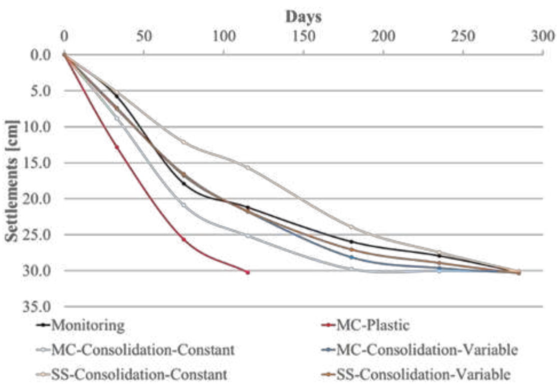

Figure 5. Settlement curves obtained in Plaxis 3D.

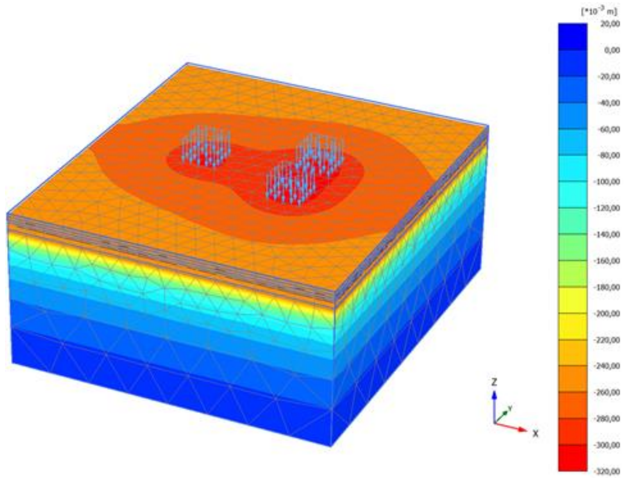

Figure 6. Deformed mesh in Plaxis 3D, using variable parameters in the Soft-Soil model.

4 CONCLUSIONS

3D numerical analyses with different constitutive models were performed to study the soil behaviour for airfield pavement design in Bihać, Bosnia and Herzegovina. The results are compared to findings from field monitoring at 300 m long and 45 m wide surcharged multilayered reinforced embankment over thick deposits of soft clays and silts.

According to the numerical analyses, it can be concluded that although there is a certain deviation between the settlement curves, the cumulative value of the settlements is very similar to the measured settlements. It should also be emphasized that when using variable parameters directly dependent on the degree of stresses and time, the settlement curves are much more realistic when compared to the analyses where only one set of parameters is applied.

The next step of this research will be to investigate the dependence between the degree of the stresses on one side and the values of the compressibility modulus and permeability on the other.

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