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Numerical analysis of embankment construction founded on subsoil improved by different types of stone columns

Analyse numérique du remblai basé sur des pieux de gravier et constitué de différents types des agrégats

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ABSTRACT: A new highway in Slovakia was constructed under adverse geological conditions. Construction of road embankments required the use of a soil improvement. The article deals with numerical analysis of an embankment section which was founded on the subsoil improved by stone columns. The original subsoil consisted of soft clay sandy and clay with medium plasticity. Stone columns of a diameter of 600 mm and a length of a 5 m were made of pebble gravels. They were installed using the vibro–replacement technique. The settlement of the road embankment was measured during all the time of construction using a horizontal inclinometer. Aim of the study presented is to analyse consolidation of the road embankment founded on the subsoil improved by stone columns made of pebble gravel as well as quarry stone. The shear strength and index properties of these materials were determined using field and laboratory tests. The results showed that the improvement of the subsoil using stone columns made of quarry stone reduced settlement and time required for consolidation more than stone columns made of pebble gravels.

RÉSUMÉ: La nouvelle autoroute a été proposée dans des conditions d'ingénierie géologiques complexes. Il était nécessaire de construire les remblais routiers sur le sol amélioré. L'article traite d'une analyse numérique de l'amélioration du sol peu porteur sous un remblai routier avec la technologie des pieux de gravier. L'environnement géologique original était constitué d'argiles sableuses et d'argiles de plasticité moyenne. Les pieux de gravier de 600 mm de diamètre et de 5 m de longueur ont été construits des graviers du fleuve par technologie des colonnes ballastées. Le tassement du remblais routier a été mesuré pendant la période entière de la construction par un inclinomètre horizontal. Le but de la étude présentée est de comparer l'influence du type des agrégats, de gravier du fleuve et de pierre de carrière, sur le tassement final et la période de la consolidation du remblai. Les propriétés de chaque type d'agrégat ont été déterminées par des essais en laboratoire et sur le terrain. Les résultats de l'analyse ont montré que si les pieux de gravier sont constitués des pierres de carrière, le tassement sera plus petit et le temps nécessaire pour la consolidation sera plus court que dans le cas des pieux de gravier constitués du gravier de fleuve.

Keywords: Stone columns; Soil improvement; Numerical analysis

1 INTRODUCTION

A soil improvement using stone columns is well known and one of the most used technology of the soil improvement in the world. The stone columns improve properties of original subsoil and they increase drainage of the subsoil. In the past, the stone columns were designed using analytical methods or empirical methods based on previous experiences in given region. Greenwood (1970) was the first who stated empirical and analytical equations determining the stone column resistance. The analytical method was based on exceeding of passive lateral earth pressure for bulged stone column. The main equation determining the stone column resistance taking into account the friction failure was presented by Wong (1975). A simple analytical method determining the ultimate bearing capacity of the stone column using the Coulomb lateral earth pressure theory was published by Afshar and Ghazavi (2014). They stated that stone column bearing capacity increases with increasing the angle of shear strength of the coarse-grained material used and the diameter of the stone column. The simple analytical method usually used in our practise considering homogenisation of the improved subsoil according to Barksdale and Bachus (1983), and Abusharar and Han (2011). At present, numerical modelling of the soil improvement using the stone columns is commonly used also in practise. The stone columns are mostly modelled using the plane strain model. Transformation of the stone columns to continuous walls was presented by Van Impe and De Beer (1983). Reduction of the coefficient of filtration in the zone of compaction was presented by, e.g., Tran and Mitachi (2008). An impact of the improvement depends on the properties of original subsoil as well as the properties of coarse - grained material used for stone columns. The properties of coarse-grained material used for stone columns are not usually sufficiently taken into account. The article presents results of the study focused to change of coarse-grained material for stone column and its impact to the final settlement of the road embankment.

2 INPUT SOIL PROPERTIES FOR NUMERICAL MODELLING

The original subsoil was layered, consists of clay sandy of a thickness of 2.5 m; clay with medium plasticity of a thickness of 3.5 m; gravel clayey of a thickness of 5 m and clay with medium plasticity of stiff consistency (Mušec, et al. 2018). Properties of these soils were determined using standard laboratory tests, e.g., the oedometer test and the direct shear test. The soils were modelled using the Hardening soil material model. The properties which were not measured using laboratory tests, e.g., E_{ur}, E_{50} and m were determined according to previous experiences (Stacho, 2018). The properties of materials of stone columns were determined using field and laboratory tests. The unit weights were determined using the pit tests. The deformation modules were determined using the light dynamic penetration tests. The shear strength properties were determined using a large dimensional direct shear test apparatus. These tests were presented in detail by Stacho and Sulovska (2017). All required input soil properties for calculations are shown in Table 1.

3 MODELLING OF EMBANKMENT ON IMPROVED SUBSOIL

The numerical model using the FEM was created using the Plaxis software. The task was solved as a plane strain model. The basic geometry and the boundary conditions of the model are shown in Figure 1. The ground water level (GWL) was constantly 1.7 m below the surface. The water was modelled as a free phreatic level. The stone columns were created as continuous walls. The continuous walls have the same volume as individual stone columns.

Table 1. Basic input soil properties used in calculation

Parameter / Unit		Material						
		Embankment	Clay Sandy	Clay with medium plasticity	Gravel clayey	Clay with medium plasticity	Stone column - Quarry stone	Stone column - Crushed pebble gravel
γ	kN.m^{-3}	19.00	19.80	19.80	19.50	19.80	16.84	17.40
γ_{sat}	kN.m^{-3}	20.45	20.20	20.10	20.72	20.10	19.57	19.57
E_{50}	MN.m^{-2}	48.00	12.26	19.14	67.57	40.88	65.80	82.50
E_{oed}	MN.m^{-2}	48.00	12.26	19.14	67.57	40.88	65.80	82.50
E_{ur}	MN.m^{-2}	192.00	61.30	95.70	202.71	204.40	197.40	247.50
m	-	0.7	0.8	0.8	0.7	0.7	0.5	0.5
φ'	°	21	21.7	16.7	30.0	18.8	52	48
ψ'	°	0	0	0	0	0	22	18
c'	kN.m^{-2}	30	14	18	4	21	1	57

A width of the wall was 0.14 m. The stone columns are usually modelled as a "wished-in-place" which corresponding to a replacement technology. The stone columns installing vibro-replacement technique are typical member of a displacement technology. The installation process is described by the Keller company (2017). A radial displacement causes compaction of surrounding soils (soils between stone columns). It has significant impact onto final settlement and consolidation time of the subsoil. The impact of the technology was determined using separate axisymmetric model of a single stone column. It allows determining the change of the horizontal stress (the coefficient of lateral earth pressure) and deformation modulus around the stone column. The changed properties were activated for the soil between stone columns in the phase of stone columns installation. The averaged value of the coefficient of lateral earth pressure was equal to 1.75 for the first layer and 2.22 for the second layer. The deformation modules were increased 1.36-times for the first layer and 1.39-times for the second one. The process of single stone column modelling which allows determining changed properties was published by Stacho (2018).

The first step of the analysis was verification and comparison of calculated settlements with measured ones. The calculation was divided to 13 construction phases with corresponding time according to the real construction process. The calculation was divided into following construction phases: the initial phase (initial stress state); removing of upper part of the original subsoil; the installation of stone columns (including activation of improving between stone columns), the geotextile; the bearing gravel layer; the geomad; the bearing gravel layer; construction of the first part of the embankment (6 m), the consolidation phase; construction of the second part of the embankment (to full height), the consolidation phase, the consolidation until excessed pore pressures decrease below 1 kN.m^{-2}.

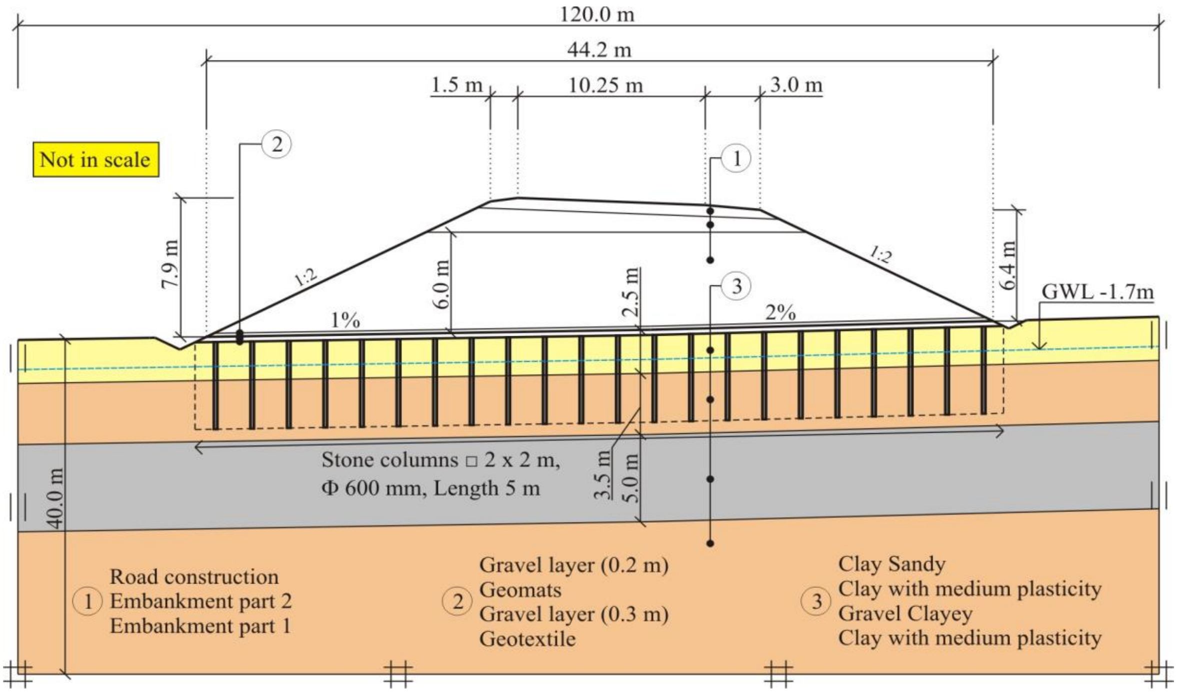

Figure 1. Scheme of numerical model (according to Stacho, et al., 2018)

The stone columns were originally made of crushed pebble gravel - it was taken into account in this model. The comparison of the calculated and measured time-settlement curves is shown in Figure 2. The results show that calculated curve is in good agreement with the measured one. The time required for consolidation is almost the same.

The difference between settlements can be caused by small inaccuracies in the properties of the original subsoil, especially deformation properties. These results were already published by the author (Stacho et al., 2018) and they showing accuracy of the numerical model used for the following study.

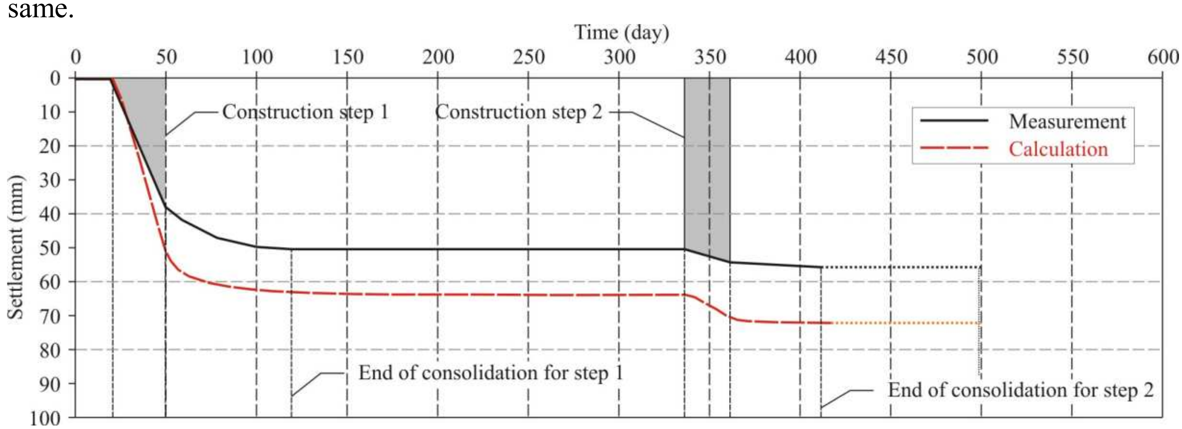

Figure 2. Scheme of numerical model (according to Stacho, et al., 2018)

4 RESULTS OF THE STUDY

The main aim of the study was comparison of the settlement of the embankment based on the subsoil improved by the stone column made of different types of coarse-grained materials. In the second part of the study, the same model with the same construction phases was used. The soil improvement was modelled using the stone columns made of quarry stone. The settlement of the embankment base decreased from 69 mm (stone column made of crushed pebble gravel) to 60 mm (stone column made of quarry stone) at the end of consolidation phase.

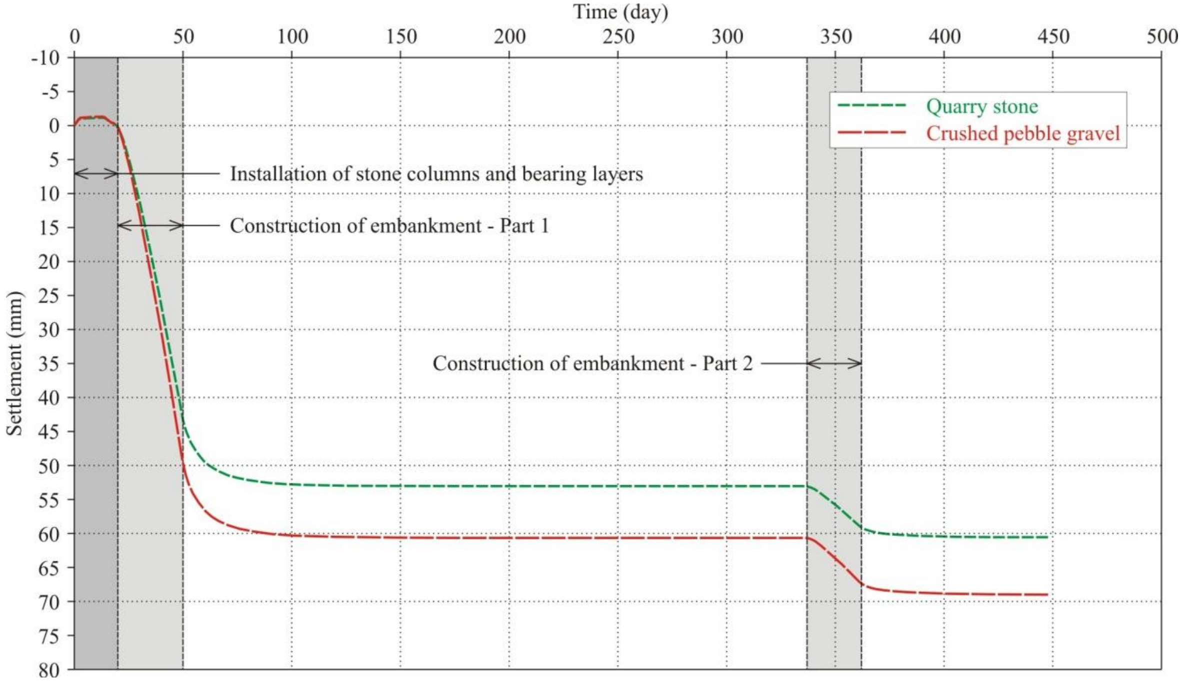

Figure 3. Time – settlement curves determined using numerical model 1

The second model estimated continual construction of road embankment (sum of construction times of both embankment parts from model 1). First phases (installation of stone columns, geotextile, geomad and bearing layers) were modelled the same way. The analysis include again two variants: stone column made of crushed pebble gravel and stone column made of quarry stone. The calculated time-settlement curves of the second model are shown in Figure 3. The settlement of the embankment base was about 70.7 mm in case of stone column made of crushed pebble gravel and 61.6 mm in case of stone column made of quarry stone. Final settlements computed using model 2 were very similar to results of settlements computed using model 1.

The numerical model 3 did not take into account time of construction. Construction phases were defined as plastic phases. Only the last one phase was modelled as consolidation phase. The end of consolidation phase was defined by requirement of decreasing of excess pore pressure under 1 kN.m^{-2}. The results of this model are shown if Figure 4.

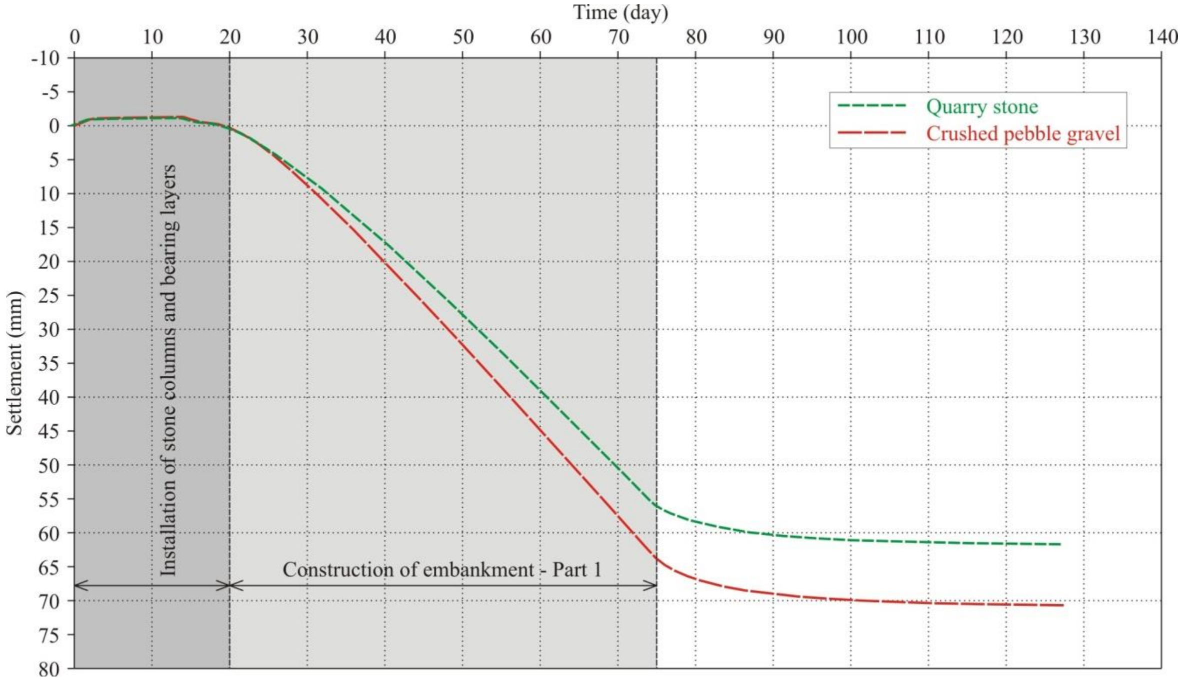

Figure 4. Time – settlement curves determined using numerical model 2

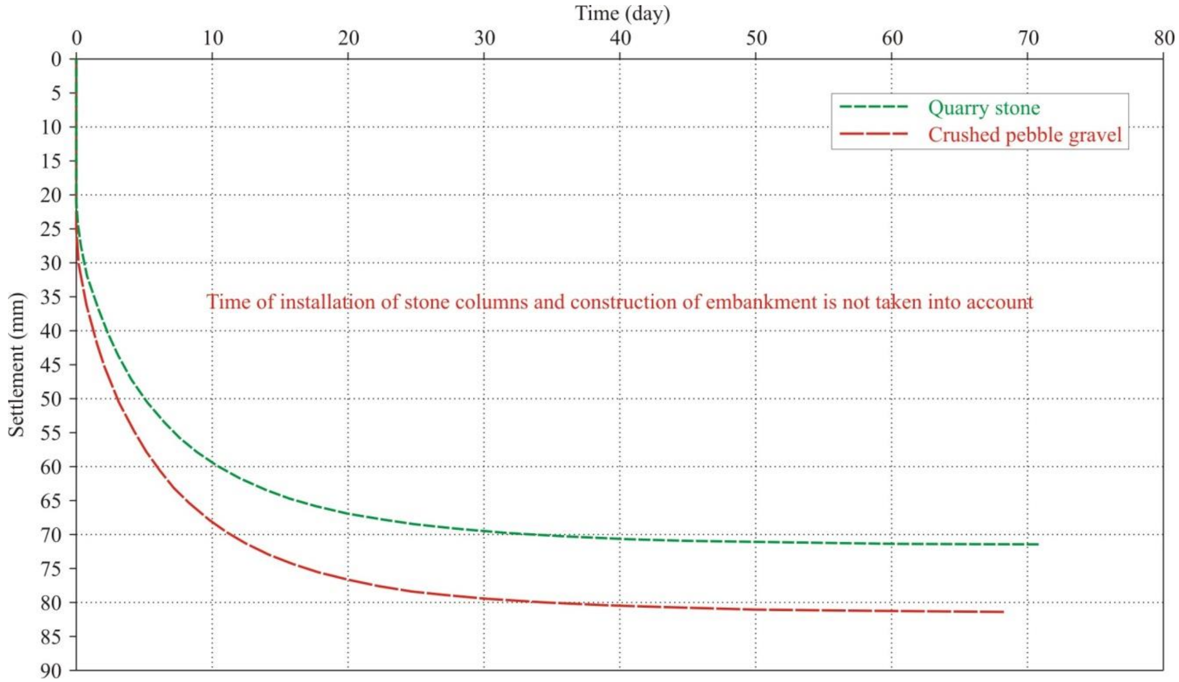

Figure 5. Time – settlement curves determined using numerical model 3

The settlement of the road embankment base was about 81 mm in case of stone column made of crushed pebble gravel and about 72 mm in case of stone column made of quarry stone. These settlements were about 16 % bigger than settlements computed in model 1 and model 2. Times required for consolidation were about 70 days. The results of study confirmed that part of settlement is obtained continuously during construction of the embankment. The results of all three models are summarized and compared in Table 2.

Table 2. Results of calculations – summary and comparison

Model	Material	Settlement (mm)	Time (day)	Differences Settlement (%)	Differences to Numerical Model 1 Settlement (%)
Numerical Model 1	Quarry stone	60.41	447	12.4	-
	Crushed pebble gravel	68.99	447		-
Numerical Model 2	Quarry stone	61.60	127	12.9	1.9
	Crushed pebble gravel	70.70	127		2.4
Numerical Model 3	Quarry stone	71.69	71	11.9	15.7
	Crushed pebble gravel	81.37	68		15.2

The differences between the settlements of the embankment based on the stone column made of crushed pebble gravel and quarry stone were about 12 % in all three models. The differences are not negligible, but not very significant in this case because of relatively small settlements of the embankment. The "small" settlements of the embankment were caused by the improved subsoil as well as the gravel layer immediately below the improved subsoil. More permeable original soils caused also relatively short consolidation times, which were confirmed also by the results of the horizontal inclinometer measurements.

5 CONCLUSION

The road embankment was founded on soft soils which required the soil improvement using the stone columns. The impact of the improvement depends on the properties of the original fine-grained soils as well as the properties of the coarse-grained materials used for stone columns. Especially properties of the coarse-grained materials are often not taken into account correctly in numerical modelling. The article presents results of the settlement analysis of the road embankment based on the subsoil improved by stone columns made of crushed pebble gravel and quarry stone. The results showed that the settlement of the road embankment was about 12 % smaller in the case of the stone columns made of quarry stone in comparison to the case of the stone columns made of crushed pebble gravel. The second common mistake made by our practical engineers is that the numerical models do not take into account the times of the each construction phases correctly. The results presented showed that neglecting the times of the construction (model 3) lead to determining the bigger settlement of the embankment for about 16 % (in this case) in comparison to the models which take into account construction times correctly (model 1 and model 2). The different type of stone column material has impact only to the settlement. The time required for consolidation is similar in both presented cases.

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