Trenchmix technology as the answer in the railway's modernization problems.

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ABSTRACT: There is the immense development of the infrastructure network of railways in Poland in recent years. The railway's embankments are often just modernized and customized. The aged embankments were often built without keeping the proper technology regime. The material used, according to present geotechnical tests are highly nonhomogeneous, and the geotechnical parameters are really challenging to predict. The soils below the embankment can be problematic. There is also the aspect of the regulations which are significantly improved, are stricter in the manner of settlement and slope stability. This means that the existing embankments need additional treatment before railways reopen, even without increasing the maximum velocity of trains on the particular line. For that purpose, Trenchmix technology can be used. The current paper describes how to guaranty fulfilling requirements for railway's embankments, using the Trenchmix method and also includes FEM analyzes for that problem.

Keywords: Trenchmix, soil improvement, soil mixing techniques, railways, embankments.

1. The railway's modernization program in Poland.

The railway's system in Poland is one of the biggest in Europe with 19275 km of railways, but at the same time, it is one of the most backward. In its basic shape, it comes from before 1918. The density of the railway's system is one of the smallest in central Europe counties as well. In 2011 the PKP PLK S.A. (Polish State Railways) published the report [1] about the railway infrastructure development. 29% of the railways was in unsatisfactory condition. In 2017, due to the finished investments, only 15.6% remained in unsuitable condition [2]. The report from 2017 [2] was showed also the maximum speed of the trains in the train schedule (Fig. 1). Only 11.4% of trains exceeded the velocity of 160 km/h.

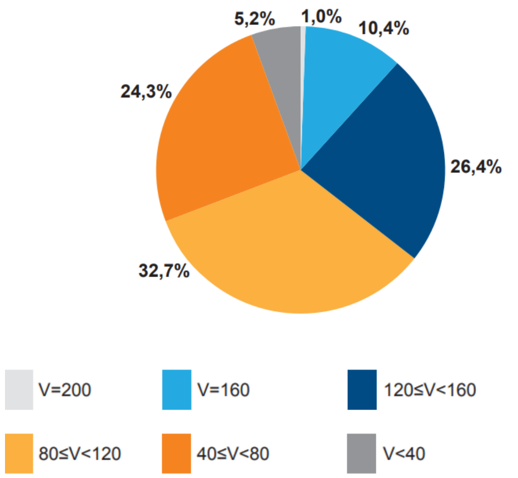

Figure 1. Percentage structure of top timetable speeds as at the day when the Train Timetable 2017/2018 [2]

The European trend in railway's development is increasing the number of high-speed train lines. In accordance with Regulation (EU), No 1315/2013 of the European Parliament and of the Council of 11 December 2013 on EU regulation concerning the development of the Transeuropean Network - Transport (TEN-T) [3] Poland is obligated to implement this development program, due to cross-border connections improvement. This means building new railways for example the high-speed line Warszawa – Łódź – Poznań with the connection to the Berlin, and Warszawa – Łódź – Wrocław with the connection to Prague, and as well modernizing existing ones.

Figure 2. Current investment in the railways in Poland. Red color means the planned investment. Green means the already begun investment [4]

The main investment goals of Polish State Railways are the improvement of railways transport efficiency by upgrading the technical condition of the rail lines, increasing the maximum velocity on the rail lines and as well as fulfilling European union regulations about the Transeuropean Network - Transport (TEN-T) [3]. Current investment in the railways in Poland are presented in Fig. 2.

2. The current requirements for the railway’s embankment in Poland.

The actual requirements are in the Id-3 instruction released by Polish State Railways [5].

2.1. Settlement.

The requirements for the embankment settlement are 4 mm per year on length 30 meters and 10 mm per year on length 200 meters. There is no information about the total allowed settlement.

2.2. Slope stability.

The instruction gives the safety factor for slope stability, but not points out how the slope stability should be calculated (Table 1).

Table 1. Safety factors value given in Id-3 Instruction [5].

Conditions	Required safety factor value
new build and rebuild railway embankment	F ≥ 2.0
railway embankment in exploitation	F ≥ 1.5
railway embankment immediately after repair	F ≥ 1.3

According to Eurocode PN-EN 1997-1 [6] for slope stability safety factors, the DA3 design approach should be used. For that approach, partial safety factors are:

- γ_Q = 1.3 for the a variable action;
- $\gamma_{\varphi'}$ =1.25 for the angle of shearing resistance (tan φ’);
- $\gamma_{c'}$ =1.25 for the effective cohesive;
- γ_{cu} =1.4 for the undrained shear strength;
- γ_{qu} =1.4 for unconfined strength;
- γ_{γ} =1.0 for the weight density;
- $\gamma_{R,e}$ =1.0 for passive earth resistance.

Thus the sufficient value of the stability safety factor $\gamma_{R,e} \geq 1$.

Seeing what’s above, the accepted practice is to consider safety factor values from the Id-3 instruction as the global safety factor, which should be combined with the characteristic values for action and as well soil parameters.

3. The impact of the cyclic load.

The repeated application of train loading causes progressive shear failure (Fig. 3) and cumulative plastic settlement (Fig. 4). The influence of the cyclic and dynamic load are significant especially in weak soils like organic soils or soft clays.

In each cycle of loading, the pore pressure rises, but the excess pore pressure does not return to zero before the next cycle, which leads to the reduction of the shear resistance of the soil [7]. Progressive shear failure causes the formation of the cess heave in the subgrade.

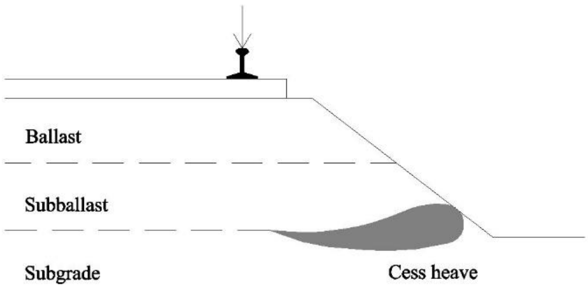

Figure 3. Progressive shear deformation due to subgrade shear failure.

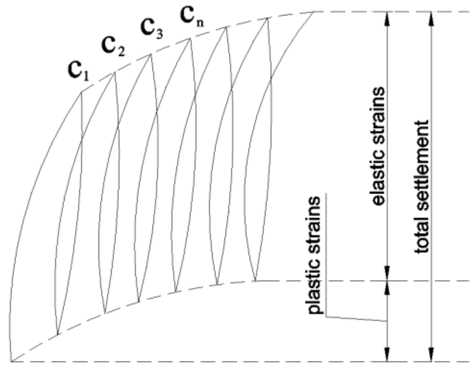

Figure 4. Cumulative plastic deformation scheme.

At the same time, cyclic train loading generates settlement of soil. This settlement consists of elastic displacement but as well plastic one. The biggest part of the settlement is elastic displacement. Nevertheless, permanent plastic displacement accumulates and induces displacement of the subballast and even tracks as well.

4. The Trenchmix technology.

Trenchmix is one of deep soil mixing methods. The general rule is the same as for the widely known DSM technology. The soil is mixed with the binding agent.

The machine called trencher is used as the mixing tool. The continuous chain is cutting and destroying the natural structure of the soil and at the same time mixing it together with the binding agent. As a binder, one can use cement, lime, specially designed mix to fulfill special situations or particular objectives. Pulverulent or pre-mixed grout can be introduced respectively for the dry and wet method. The first stage of the execution is preparing pre-trench excavation on the top of the working platform. In the dry method, the cement is put in that excavations. In the wet method, cement grout is prepared aside in batching plant. Then the panels are done. All the above mentioned stages are present in Fig. 5.

As the final result, one get panels of treated soil with far much better parameters comparing to the untreated soil.

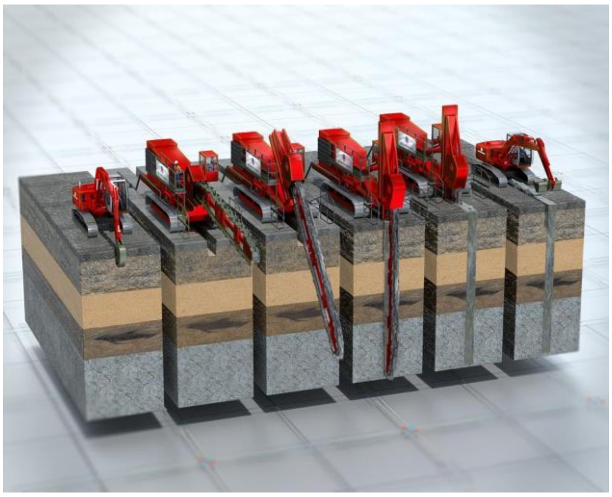

Figure 5. The mechanism of soil stabilization.

5. The mechanism of soil stabilization.

The general mechanism of soil stabilization with the cement binder could be divided into 4 main parts: hydration of cement binder, cation exchange, hardening due to the hydration of the cement binder and pozzolanic reaction (Fig. 6). The process of the water absorption decreasing the initial moisture of the stabilized soil. The cation exchanges lead to the change of the physical parameters of the soil and decreasing the plasticity of the soil.

Hardening due to the hydration of the cement is a fast reaction, in contrast to the hardening which relies on the pozzolanic reaction which is a long process. That is why the strength of the Trenchmix panels should be tested not after the 28 days, but at least 56 or even 90 days.

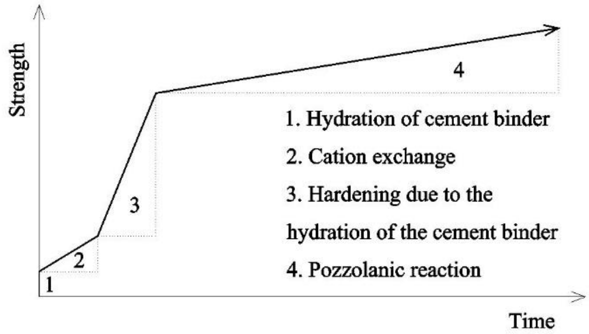

Figure 6. The general mechanism of soil stabilization with the cement binder [9].

6. Factors affecting strength of deep mixed soil.

To design soil mixing technologies is necessary to predict the physical and mechanical parameters of the soil-mix material. The leading parameter is the unconfined compressive strength (UCS). Many factors affecting the strength of the deep mixed soil, such as characteristics of binder, characteristic of soil, mixing condition, curing condition and loadings condition (Table 2). Not every factor affects the UCS to the same extent. Most of the panel material is natural soil, so in fact, the soil has the biggest influence on the Trenchmix panels material parameters (Fig. 7). Investigation of the soil properties is thus a very important part of the design process.

Table 2. Factors affecting strength of deep mixed soil [10].

Category	Factors
Characteristics of binder	Type of binder(s) Quality Mixing water and additives
Characteristics of soil	Physical, chemical and mineralogical properties of soil Organic content pH of pore water Water content
Mixing conditions	Amount of binder Mixing efficiency Timing of mixing/remixing
Curing conditions	Temperature Curing time Humidity Wetting and drying, freezing and thawing
Loading conditions	Loading rate Confining pressure Stress path (compression, tension, and simple shear)

As it can be seen from the table above, the prediction of the UCS could be a very complex task and need experience. The UCS values could be taken from the previous practise in a similar soil condition, but the best option is to design the program of the pilot samples testing. Samples prepared in the laboratory (for example with different amount of the cement, and other components of mix material) are examined for the UCS. Because the laboratory samples are mixed way better than on the building site, the reduction coefficient should be used. The reduction coefficient for the UCS values is usually between 0.5 to 1.0 [9]. Base on the data obtained from the laboratory the optimal composition of mix or amount of the cement can be found. Type of cement does not have such a huge impact on the UCS. The cement CEM I - III are widely used. It is also worth to mention that the aggressive environment is not the method limitation. Trenchmix panels can be used freely in case of XA1 aggression, and for sulfate attack even for XA2 [9].

Another very important parameter which affects the UCS is mixing factor (Fig. 8). The classics BRN (Blade rotation number) formula for the mixing factor cannot be applied for this method. In spite of that below formula can be used:

$$I_m = \frac{N \cdot V\ chain}{V_a} \tag{1}$$

where:

N - nb blades / ml chain [1/m]

V_{chain} - linear speed of the chain [m/s]

V_a - advance speed of the trencher [m/s]

Table 3. Mixing factors values according to Soletanche experience.

Minimum mixing ratios	Granular Soils	Cohesive soils
Wet method	100 to 150	200 to 250
Dry method	150 to 230	250 to 350

The trencher tool allows mixing the soil trough all layers from the surface to the lowest part of the panel, because of that, all layers are mixed together not only in the horizontal direction but as well in a vertical one, which leads to the more homogenous material, than in case of the DSM columns. Mixing ratio is displayed in the cabin to monitor whether the minimum degree of mixing is reached. Mixing factors values according to Soletanche experinece are prestened in Table 3.

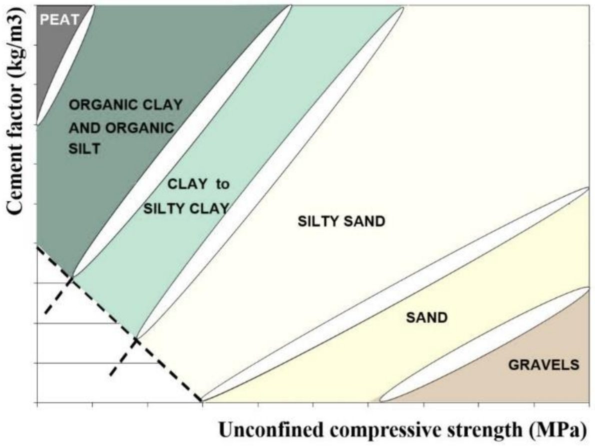

Figure 7. Cement dosage (kg cement/m^3 soil).

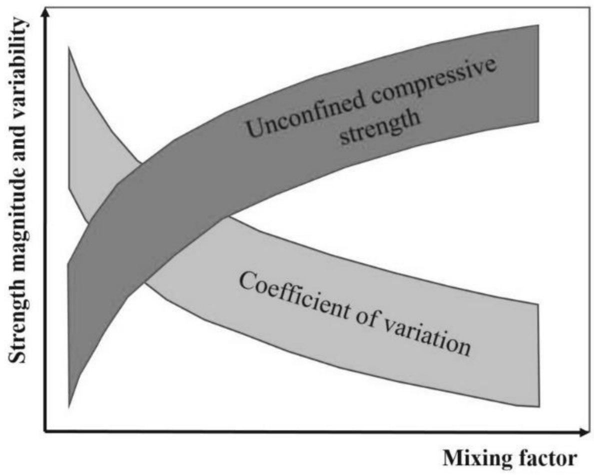

Figure 8. Mixing factor (number/meter).

7. Deep soil mixed material properties.

7.1. The characteristic and design values of the UCS.

The strength of stabilized soil has relatively high variability. The characteristic values of the UCS could be evaluated on the basis of the statistical method. It is shown in [9,11] that the lognormal distribution approximates better the UCS values than the normal distribution. In [9,11] the following procedure for determining the characteristic value of the UCS is given:

$$f_{ck} = \min \begin{cases} \exp\,[\,f_{cm}(lnf_c) - ms_d(lnf_c)] \\ 12\;MPa \end{cases} \quad (2)$$

$$f_{cm}(lnf_c) = \frac{1}{n}\sum_{i=1}^{n} ln(f_{ci}) \quad (3)$$

$$s_d\,(lnf_c) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(ln(f_{ci}) - f_{cm}(lnf_c))^2} \quad (4)$$

where:
f_{ck} − the characteristics value of UCS for the whole population
f_c − the UCS
f_{ci} − the UCS for i sample
f_{cm} − the mean value of ln(f_{ci})
12 MPa − the maximum values fo the f_{ck} given in [12]
n − number of samples in the population
m − the probabilistic parameters which correspond to the confidence that any measured f_{ci} would be higher than f_k, for the 90% confidence $m = 1.28$
s_d − standard deviation of ln(f_{ci})

Topolnicki [9] suggests also to use this method for the number of samples greater than 10.

Once the characteristics UCS is found, the design values should be calculated as well. According to [12] the design UCS is:

$$f_{cd} = 0.85\;\cdot \frac{f_{ck}}{y_m} \quad (5)$$

where:
0.85 − reduction factor for long-term effects which can reduce the strength of the deep mixed soil,
y_m − partial factor, $y_m = 1.5$ for permanent and transient loads, $y_m = 1.3$ for accidental loads.

At the first step, the designer should assume the UCS value from the previous realization or the pilot sample tests. Then the maximum stress in panels should be found and compared to the assumed UCS.

Lesniewska [11] gives another way to evaluat values of the UCS. According to [11] the arithmetic mean value of the whole population of the UCS cannot be smaller than the maximum stress in single Trenchmix panel multiplied by the safety factor. In the case of the foundation directly on the Trenchmix panels, the minimum measured value of the UCS cannot be smaller than the maximum characteristic stress in single Trenchmix panel.

$$\bar{f_c} \geq y_F \cdot \sigma_k = \sigma_d \quad (6)$$

but, the value of every measured UCS should be limited to:

$$f_{c,i} \geq 2 \cdot \sigma_d = 2 \cdot y_F \cdot \sigma_k \quad (7)$$

$$\min f_{c,i} \geq \sigma_k \quad (8)$$

where:
y_F − safety factor
$\bar{f_c}$ − the arithmetic mean value of the whole population of the UCS
$\min f_{c,i}$ – the minimum measured value of the UCS, for the for i sample
σ_k − the maximum characteristic value of stress in the panel
σ_d – the design value of stresses in panels

7.2. The elasticity modulus.

In the design practice, E_{50} - secant Young's modulus of the elasticity at 50 percent of the unconfined compressive strength is used. To determine the E_{50} value one can use the result of the UCS test with the measurement of the strain (Fig. 9).

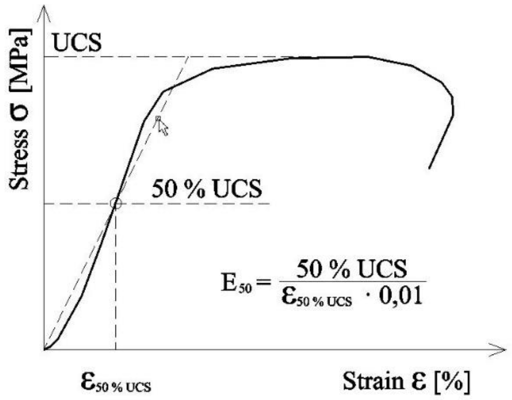

Figure 9. E_{50} modulus estimation from the UCS test with deformation measurement.

To estimate modulus one can use also correlation between E_{50} and UCS. Different researches show various values of this correlation. It is stated in [11,13] that good estimation for the design purpose is E_{50} as 380 times the f_{cm}. In [9] the relations are given:

$$300\ f_{cm} \leq\ E_{50} \leq 400\ f_{cm} \tag{9}$$

$$500\ f_{ck} \leq\ E_{50} \leq 800\ f_{ck} \tag{10}$$

where:

f_{ck} − the characteristics value of UCS

f_{cm} − the mean value of UCS

7.3. Other parameters.

The design shear strength could be assumed from the relation to the UCS. The safe estimation of shear strength is 20% of the f_{cd} [9,13]. However, it is shown in [9,13] that relation between the shear strength and the UCS changes depending on the UCS values:

$$0.4\ to\ 0.5 \times\ f_{cd}, for\ f_{ck} < 1\ \text{Mpa} \tag{11}$$

$$0.3\ to\ 0.35 \times\ f_{cd}, for\ 1 <\ f_{ck} < 4\ \text{Mpa} \tag{12}$$

$$0.2\ \times\ f_{cd}, for\ f_{ck} > 4\ \text{Mpa} \tag{13}$$

where:

f_{ck} − the characteristics value of UCS

f_{cd} − the design value of UCS

The tensile strength is usually between 10% to 20% of the f_{cd} [9,11,13].

The Poisson ratio taken to the calculation should be between 0.3 and 0.4 [9] and it does not depend on the UCS.

8. Trenchmix technology implementation options.

Trenchmix technology can be used in most case when the requirements for rail embankment cannot be fulfilled without any soil improvement. This means that the Trenchmix can solve problems connected with:

- Fulfilling the requirement for the stability safety factor for the high embankment. Fig. 10 shows the example of extension of the railway line by the second track. On the right side of the embankment, because of worse unconsolidated weak soil, the safety factor of the embankment global stability is lower than 2.0, thus the soil improvement is necessary.
- Fulfilling the settlement requirements. When the soil condition vary really much with the length of the tracks. The requirements for the differential settlement cannot be fulfilled without soil improvement. Also close to the railway's bridge and other structures like culverts, settlement of the rail embankment should be limited to small value.
- The low embankment on the weak soil, the possible negative impact of the cyclic loading for the embankment settlement, as it is shown in Fig. 11.
- Increasing the velocity of trains to high-speed trains. It causes a bigger influence of the dynamic loading (especially for velocity which exceeds the 160 km/h [8]) thus can lead to an excessive settlement on the railway line.

Lots of the execution aspects need to be considered during the implementation of the method. Especially water flow condition should be checked, as Trenchmix panels are impervious. In the case of the blockade of the flow of the groundwater, the special technology breaks in the panel should be designed. There are some limitations with the organic soil mixing. Organic matter content and pH should not exceed some safe value for using this technology.

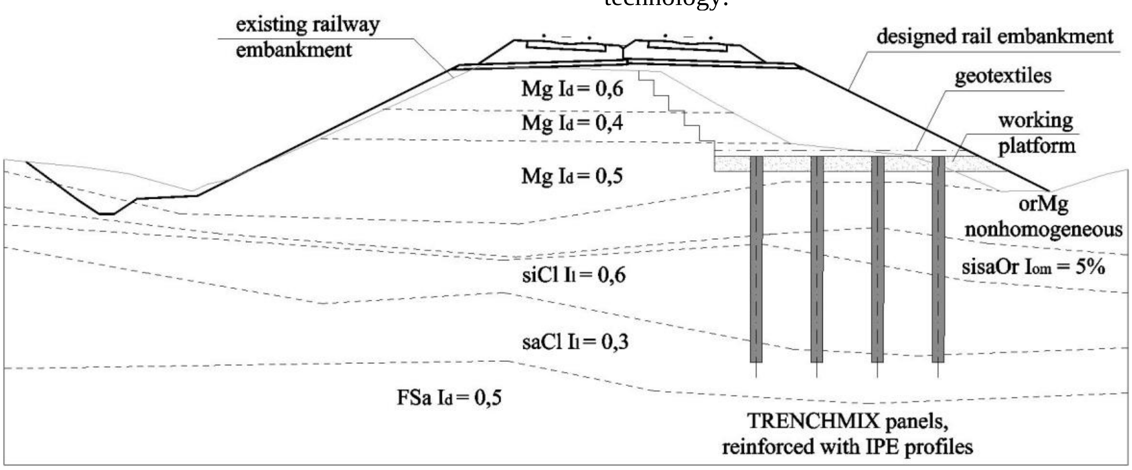

Figure 10. Improvement of the global stability safety factor for the embankment through used Trenchmix panels.

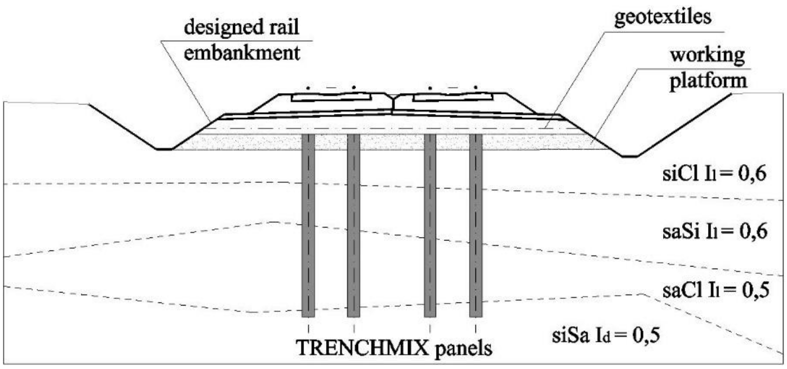

Figure 11. The embankment settlement reduction through used Trenchmix panels.

9. The FEM calculation.

As the example, reopened and rebuilt line with additional construction of the second track is shown. The live load is 63 kPa in every case.

9.1. Geotechnical profiles.

The geotechnical profiles show a significant difference in layers (Fig. 12). Section A consists of sands (IVa, IVb) and clays (IIIc) with compression index C_c = 0.1. About 50 metres further the conditions changes to the very soft clays (IIIa) with compression index C_c = 0.3.

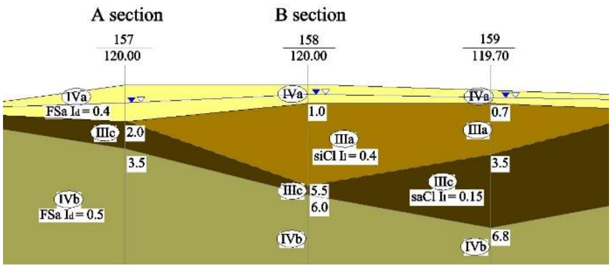

Figure 12. Geotechnical profiles.

9.2. Trenchmix panel parameters.

The Trenchmix panels are represented by the linearly elastic perfectly plastic Mohr – Coulomb model with parameters:

$f_{ck} = 1.8\ [MPa]$ - the characteristics value of UCS
$f_{cd} = 1.0\ [MPa]$ - the designed value of UCS
$s_u = 0.3 \cdot f_{cd} = 300\ [kPa]$ - shear strenght
$E_{50} = 500 \cdot f_{ck} = 900\ [MPa]$ - the elasticity modulus
$\gamma = 24\ [\frac{kN}{m^3}]$ - weight of panels
$\nu = 0.3\ [-]$ - the Poisson coefficient

9.3. Soil parameters.

Hardening soil model is employed. For the non-cohesive soils (sands IVa, IVb) $E_{50}^{ref}, E_{oed}^{ref}, E_{ur}^{ref}$ are used and for the cohesive soils (clays IIIa, IIIb) the compression and swell indexes C_c, C_s from the oedometer test are used (Table 4).

Table 4. Soils parameters used in calculation.

		IIIa	IIIc	IVa	IVb
φ'	[°]	25	30	33	35
c'	[kPa]	5	5	1	1
γ	[kN/m3]	20	21,5	19	19
E_{50}^{ref}	[MPa]	-	-	50	60
E_{oed}^{ref}	[MPa]	-	-	50	60
E_{ur}^{ref}	[MPa]	-	-	100	120
m	[-]	-	-	0,5	0,5
C_c	[-]	0,1	0,03	-	-
C_s	[-]	0,03	0,01	-	-
e_{init}	[-]	0,52	0,42	0,5	0,5
$k_x = k_y$	[m/day]	0,0002	0,0002	1	1

9.4. Calculation phases.

The calculation phases are the same as the work sequence:

- demolition of the old-track;
- working platform execution;
- panels execution;
- transmission layer execution;
- rest of the line's structure.

9.5. Numerical results.

The calculation is done for the A and B section. The level of the embankment and live loading (63 [kPa]) are more or less the same for both cases, but the soil condition changes a lot, which means that one can expect too large difference in the settlement in these two sections. As the requirements for settlements are time related, the consolidation analysis needs to be done.

On the first step, the settlement without soil improvement is determined. Details about models used are presented in the below figures. FEM model for A section without soil improvement is presented in Fig. 13 (the first phase, existed rail embankment) and in Fig. 14 (the last phase, new-build rail embankment with live loads). FEM model for B section without soil improvement is presented in Fig. 16 (the first phase, existed rail embankment) and in Fig. 17 (the last phase, new-build rail embankment with live loads).

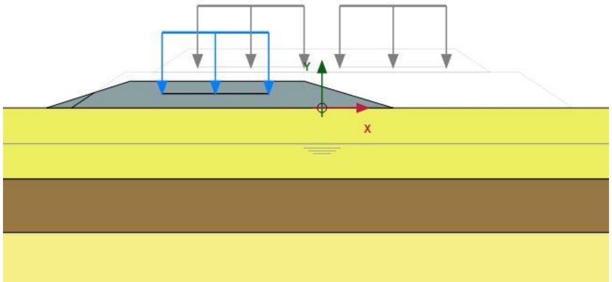

Figure 13. FEM model for A section without soil improvement: the first phase, existed rail embankment.

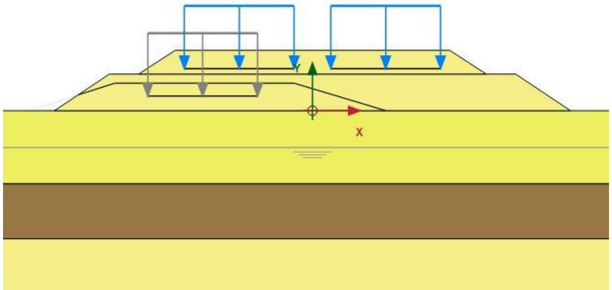

Figure 14. FEM model for A section without soil improvement: the last phase, new-build rail embankment with live loads.

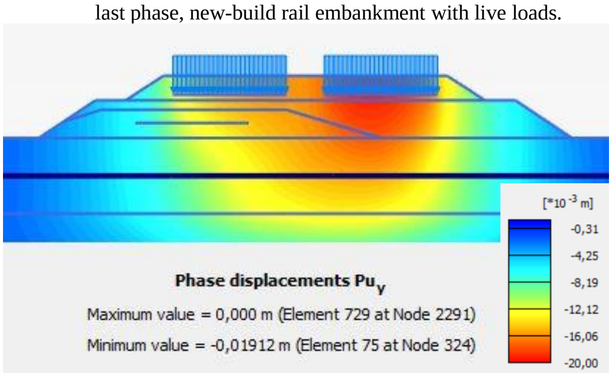

Figure 15. The settlements for the A section without soil improvement, the first year of the line operation.

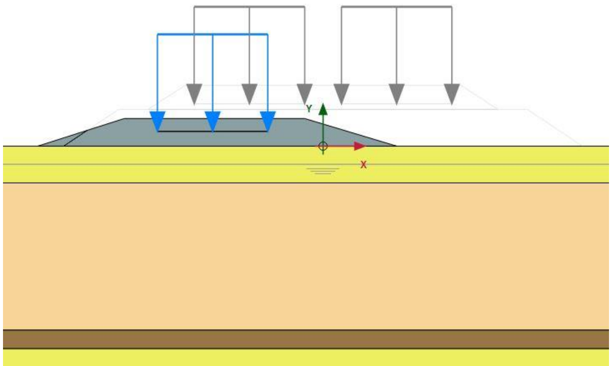

Figure 16. FEM model for B section without soil improvement: the first phase, existed rail embankment.

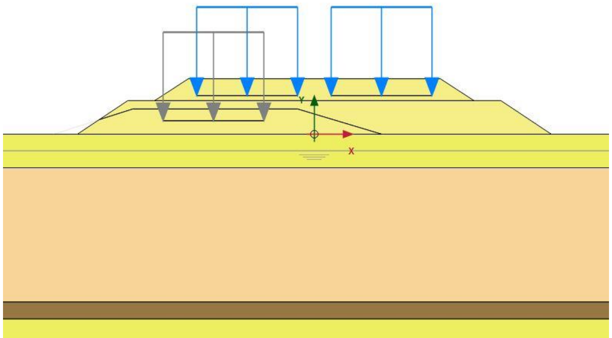

Figure 17. FEM model for B section without soil improvement: the last phase, new-build rail embankment with live loads.

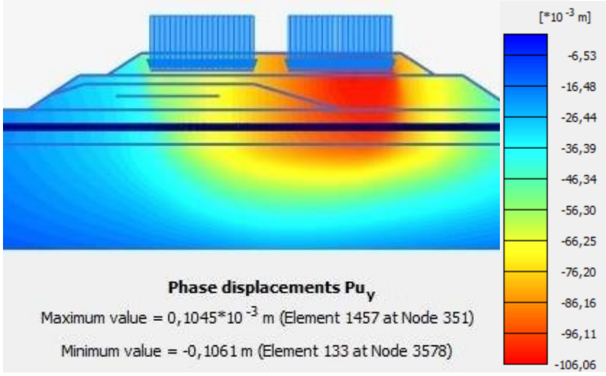

Figure 18. The settlements for the B section without soil improvement, first year of the line operation.

The settlement for the A section (good soil conditions) is 19.1 [mm] for the first year of the rail line operation (Fig. 15). For section B (worse soil condition) for the same period of time, the settlement is 106.1 [mm] (Fig. 18), thus the soil improvement is necessary.

Section B is recalculated with Trenchmix panels. FEM model for B section with Trenchmix panels is presented in Fig. 19.

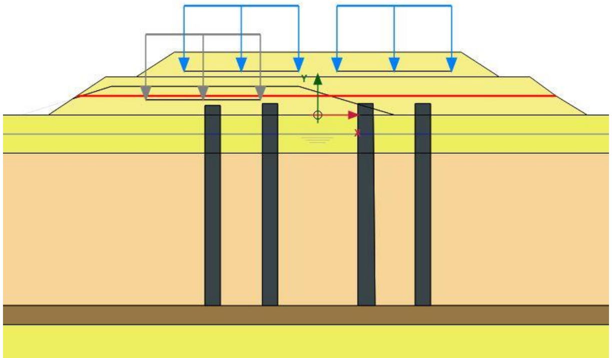

Figure 19. FEM model for B section with Trenchmix panels: the last phase, new-build rail embankment with live loads.

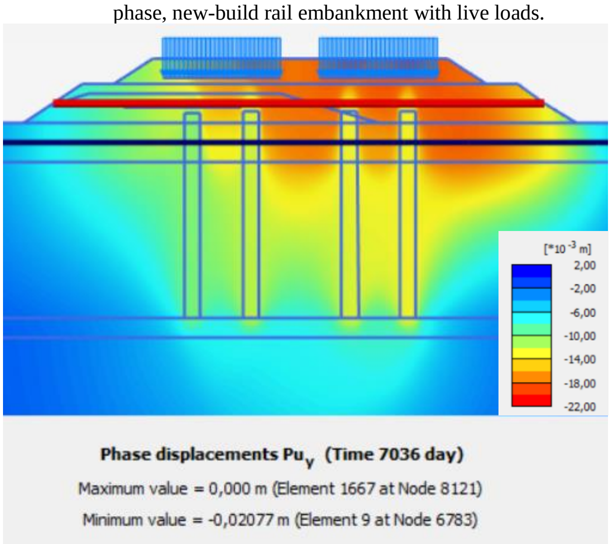

Figure 20. The settlements for the B section with Trenchmix panels, the first year of the line operation.

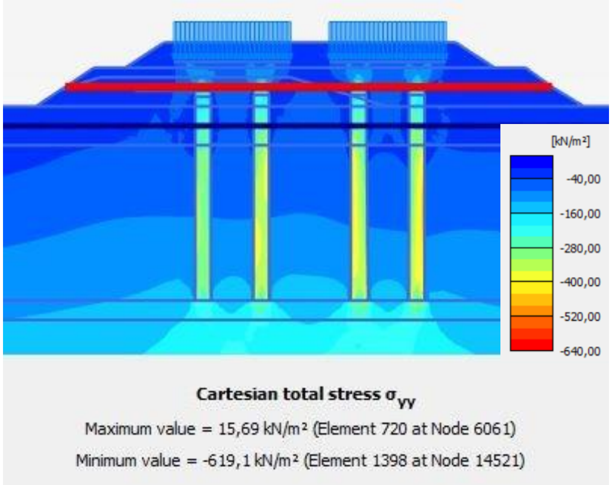

Figure 21. The stresses in Trenchmix panels.

The settlement for the first year of line operation with panels is 20.8 [mm] (Fig. 20). The difference between improved section B , and unimproved section A is 20.8 – 19.1 = 1.7 [mm], which is lower than the required 4 [mm].

The maximum stress in the panels is 0.62 MPa (Fig. 21), which with the proper dosage of the mix material, can be easily achieved. The maximum stress in panels is smaller than assumed UCS. The maximum tension in the panels in much less than 10% of the UCS, so the reinforcement is not necessary.

The above calculation showed that the requirements about the settlement, can be fulfilled by using just 4 continuous panels.

10. Conclusions.

Trenchmix panels, widely used as the slurry wall in the levees, can be adjusted to the soil improvement method. Trenchmix panels can easily help to meet the basic requirements for the railways' embankments (especially on the weak soil) such as maximum settlements, maximum differential settlement, assurance of the embankments slope stability. Trenchmix can also be considered to solve more complex problems like reducing the impact of the cyclic or the dynamic load (the increase of the velocity of the trains). The properties of the Trenchmix are ideal to block the propagation of the dynamic load in the soils.

The Trenchmix allows execution of these works in huge efficiency which is the additional value of the method.

To the limitation in method application, the pH lower than 5 (acidic environment) or high content of the organic matter in the soil, can be listed.

With good soil investigation, pilot sample testing, design experience, as well as technology regime and quality control Trenchmix is a very useful and efficient technology for the railways' embankments improvement.

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