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PREDICTIVE RISK MAPPING RELATED TO THE SHRINK-SWELL OF CLAYS UNDER THE RAILWAY TRACK IN THE SETTAT PLATEAU (MOROCCO)

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ABSTRACT

Clay soils are generally linked to the shrink-swell phenomenon. This phenomenon causes many disorders in the infrastructure and in particular railway infrastructures, which are extremely sensitive to soil deformations. This is mainly reflected through the deterioration of the geometry and performance of the railway, and it has a notable impact on maintenance and servicing costs. This paper presents the analysis of the settlement of clay soils, on the one hand on the basis of the results of geotechnical tests carried out in-situ and in the laboratory and on the other hand by using numerical modelling using the finite element method. This analysis shows that the results are very close and allows a preventive mapping of the risk distribution along the section of the studied railway track. To mitigate these risks, the feasibility of the substitution technique was studied through removing 4 m from the soil and replacing it with selected materials. This technique has shown a significant improvement in the performance and behavior of the clay formation.

Keywords: geotechnical test, railway track, settlement, soil improvement, swelling clay.

1. INTRODUCTION

The railway line linking Casablanca and Marrakech crosses an area known for expansive soils between the Settat and Mechraa Ben Abbou railway stations. They are essentially composed of marl-limestone topped with clay and tufa silt, and the whole is covered with vegetal soil or heterogeneous fill [1].

Swelling clay soils are present all over the world and cause significant damage and disruption to structures and infrastructures. The shrinkage-swelling of clays is a costly natural risk that can cause serious economic consequences and losses [2-5]. This predictable risk is due to the differential movement of land by volume change according to the variation of climatic conditions and the mechanical and physicochemical properties of the materials [6-8]. In fact, in a humid environment clay soil becomes malleable and flexible. Which leads to an increase in the water content, this leads to an increase in the volume of the soil. However, in a dry period this soil retracts and becomes hard and brittle because of the lack of water. These variations in the state of soil hydration have an influence on its mechanical and physicochemical properties. Moreover, this is reflected in the failure of the subsoil [9] bearing capacity and induces differential settling causing damage to constructions and infrastructures.

The abundance of expansive soils worldwide and their impact is the subject of several studies to better understand their geotechnical properties [10], in order to avoid and control any risks that may arise. Thus, the prior soil survey is essential to determine its nature and characteristics, it makes it possible to limit the geotechnical risks and constraints that can have a direct or indirect impact on the conditions under which infrastructure projects are carried out It is an inescapable step in the design of civil engineering structures [11], [12]. Poor quality expansive soils are frequently encountered; therefore, it is necessary to improve these geotechnical properties in order to eliminate their expansive ability and make them suitable for designing projects [2], [3]. Different methods can be used to strengthen and improve compressible soils [13]. These techniques include: embankment on rigid inclusions, light embankment, ballasted columns, slab on piles and substitution or by the use of additives such as lime, fly ash, polymers and cement.

Railways infrastructures are particularly sensitive to geotechnical hazards. With the increase in train speed and the transport of heavier goods merchandise imposing more stringent safety standards. To establish a predictive mapping of the natural risks associated with the shrinkage and swelling of clay formations, we calculated the settlement of clay soils along the railway line using in-situ and laboratory geotechnical identification parameters. Similarly, we use the simulation by the finite element method, then we compared the results obtained. Finally, we studied the feasibility of the substitution technique, which consists in removing part of the clay formation and replacing it with selected materials to improve soil properties.

2. GEOTECHNICAL INVESTIGATIONS

In order to identify the geotechnical characteristics of the subsoil in the study area, some 20 core drilling 15 meters deep were achieved on either side of the railway track (Figure-1). These boreholes were accompanied by pressureometric tests to identify the intrinsic parameters of the soil and its behavior according to the applied stress. Soil samples were then analyzed in the laboratory to obtain more information on the properties of the formations encountered.

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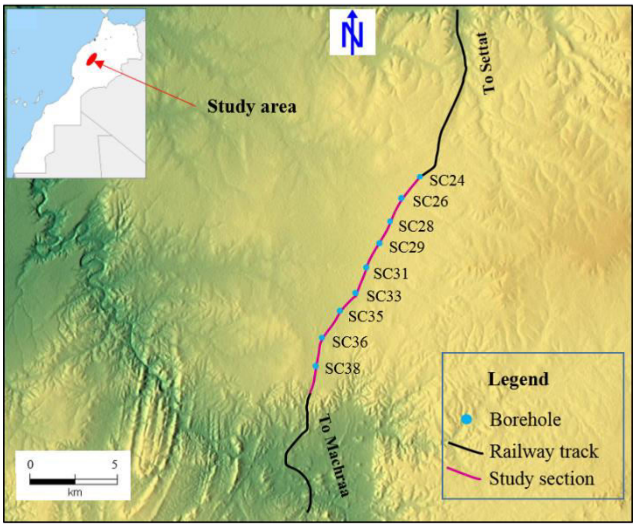

Figure-1. Geographical location of the boreholes.

The analysis of the results of geotechnical and geological investigations shows that the subsoil is essentially composed of a marl-limestone layer topped by clay and then the silts. The whole is covered with topsoil or heterogeneous backfill. Figure-2 represents the lithological cross section of the soundings.

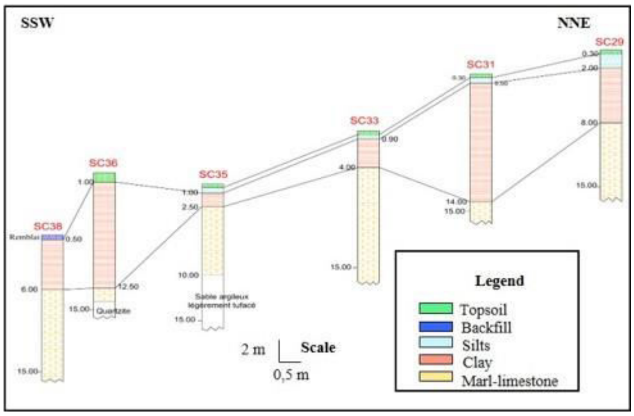

Figure-2. Lateral variation of formations from the boreholes.

Correlations between the various holes allow us to establish a local geological section of the study area (Figure-3). It can be seen that the clay formation has a variable thickness, it is framed by the marl-limestone layer at the base and the silts upwards. It is relatively thick between holes SC28 and SC31 and at hole level SC36 with a thickness of 10 m to 12 m, while its thickness is about 2 m between holes SC33 and SC35.

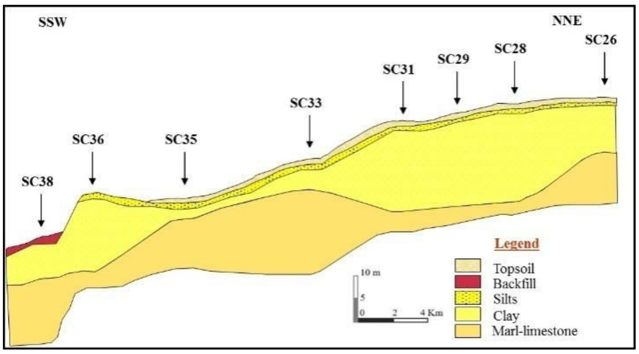

Figure-3. Geological section of the study area.

2.1 In situ tests: Pressuremeter tests

Pressuremeter tests have been widely used to identify the geomechanical characteristics of the soil [14]. About 20 of 15-meter deep boreholes were drilled on either side of the railway track, combined with pressuremeter tests. The principle of this test is to descend at different depth intervals between 1.50 m and 13.5 m, an inflatable electric probe and measure the volume variations according to the horizontal stress applied by the probe on the walls of the sounding. Also, this test allowed the measurement of soil behavior at a given depth by providing the following three parameters: soil deformation modulus (EM), creep pressure (Pf) and limit pressure (Pl). Moreover, it provided information on the state of consolidation of the soil in place and also allows us to obtain the rheological coefficient.

The limit pressure follows a geometric distribution in the field, and the pressuremeter modulus is in direct correlation with harmonic distribution values. The geometric mean of the values for the limit pressure and the harmonic mean for the pressuremeter modulus are retained. Table-2 shows the pressuremeter modulus (EM) averages and the effective limiting pressure (Pl* (MPa)) for the clay and marl-limestone layers for each borehole. Using these results, the rheological coefficient (α) and non-drained cohesion (Cu) for the clay and marl-limestone layers were calculated (Table-2).

Table-1. Pressuremeter modulus and limit pressure of the clay and marl-limestone per borehole.

		Borehole					
	Formation	**SC26**	**SC28**	**SC31**	**SC33**	**SC35**	**SC36**
E_M (MPa)	Clay	67,50	28,10	27,41	17,13	13,30	20,80
	Marl-limestone	141,18	121,50	150,82	121,56	150,82	-
P_l*(MPa)	Clay	3,46	1,70	1,77	1,60	0,97	1,77
	Marl-limestone	5,14	4,10	5,52	4,11	5,52	-

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Table-2. Rheological coefficient and undrained cohesion.

Formation	E_M	Pl*	α	Cu
Clay	24,2	1,84	2/3	52.65
Marl-limestone	143,4	4,84	2/3	138.37

2.2 Laboratory tests

In order to understand the mechanical behavior of the soils, particularly clay formations that cause the degradation of the geometric quality of the railway track in the study area [1], a series of laboratory tests are conducted on soil samples.

2.2.1 Water content

The water content by weight (W %) is a physical parameter that makes it possible to determine the mass percentage of water in the soil and deduce its density (ρ (kg/m3)). Table 3 depicts the results of the water content tests of the clay formation at depths determined along the railway according to NF P94-050. It shows that it varies from one borehole to another and increases with depth.

Table-3. The water content depending on the depth.

Borehole	Depth (m)	W %	ρ (Kg/m3)
SC26	2,50	14,00	1965
	5,50	35,00	2173
SC28	4,00	17.80	2084
	8,00	18,70	2093
SC29	2,50	12,80	2106
	4,50	27,80	1804
SC31	3,50	8,00	2133
	5,00	11,00	1886
SC36	2,50	14,00	2058
	5,00	22,00	2000
	8,00	33,40	1857

2.2.2 Atterberg limits

The Atterberg limits are tests that consist of identifying the consistency limits given by the water content located at the boundary between the different states of a soil. These limits are conventional physical constants [15], they define the transitions between the liquid and plastic behaviour of a soil [16], namely the plasticity limit (WP) which separates the plastic state from the solid state and the liquidity limit (WL) which is a boundary between the plastic and liquid state. These limits make it possible to provide essential data on soil mechanics and to predict its behaviour in advance.

From these Atterberg limits, we can determine the plasticity index (IP) which corresponds to the extent of the plastic state zone, it is calculated by the difference between the liquidity limit and the plasticity limit: IP = WL - WP. Table-4 illustrates the Atterberg limits of the clay formation between depths of 2 m and 11.50 m.

Table-4. Atterberg limits per borehole.

Borehole	Depth (m)	WL (%)	WP (%)	IP (%)
SC28	5,00	71	38	33
	8,00	58	21	37
	11,00	42	17	25
SC29	3,00	34	18	16
	4 ,60	42	19	23
SC31	3,50	56	34	22
SC33	4,00	43	23	20
	5,50	32	17	15
SC36	2,50	41	16	25
	5,00	40	18	22
	8,00	41	17	24

2.2.3 Methylene blue value

The methylene blue test (MBS) quantifies the water absorption capacity of soil particles [17] from the amount of dye necessary to cover the external and internal surfaces of all clay particles. It generally expresses the quantity and activity of the clay fraction contained in the soil [18]. Spreadsheet 5 shows the results of these tests performed, according to standard NF P94-068, on samples collected in the geotechnical boreholes conducted at different depths. The analysis of the test results makes it possible to distinguish two main classes of soils: clay to very clayey soils with a VBS value higher than 6 and silty-clay soils with VBS values between 2 and 3.

Table-5. Methylene blue values per borehole.

Borehole	Depth (m)	% fraction 0/5 mm	VBS
SC26	2,50	99	2,89
SC28	5,50	90	7,70
SC28	8,00	93	7,91
SC28	11,00	87	7,98
SC33	2,50	52	1,20
SC33	5,50	93	1,82
SC35	11,00	99	1,90
SC36	4,00	99	7,30
SC36	5,00	98	8,47
SC36	8,50	100	7,50

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2.2.4 Granulometric analysis

Particle size analysis by dry sieving after washing according to Standard NM 13.1.008 is to break up the adherent clay grains and determine the proportion of fines and the distribution of soil grains by size classes. The particle size analysis carried out show a predominantly clay granulometry with a proportion of the elements passing to 80µ varies between 53% and 98%. Figures 4 and 5 show the grain size curves of the soil from boreholes SC29 (depth 2.50 m) and SC36 (depth: 5.5 m).

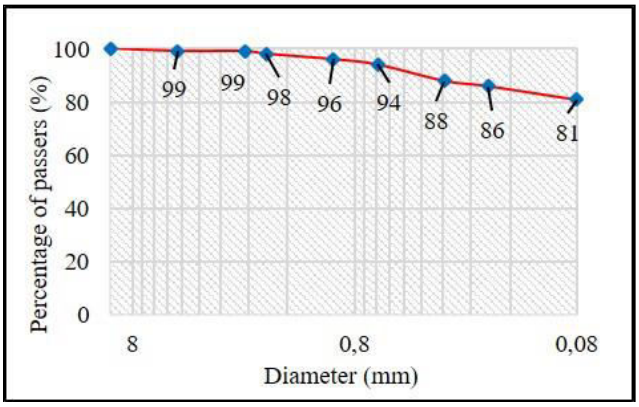

Figure-4. Particle size analysis in SC29 borehole at 2.50 m deep.

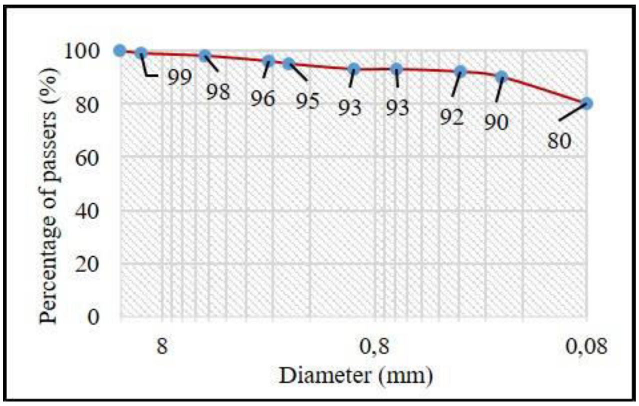

Figure-5. Particle size analysis in SC36 borehole at 5.50 m deep.

2.2.5 Oedometric test

The purpose of the odometer test is to determine the parameters used to characterize the behavior of clay soils, particularly in the design phases of civil engineering projects. These parameters include: compressibility index (Ic), swelling index (Ig), pre-consolidation pressure (Pc (KPa)) and swelling pressure (Pg (KPa)). Table-6 shows an example of the stepwise odometer compressibility test according to XP P94-090-01 performed in borehole SC36 and the Figures 6 and 7 illustrate the oedometric compressibility curves of the tests performed on samples from the boreholes SC31 (depth 5 m) and SC36 (depth 8 m). With reference on the classification based on the compressibility index, it can be concluded that the clay formation in this study generally has moderate to high compressibility and that the swelling index is above the threshold for swelling materials (Table-7).

Table-6. Stepwise compressibility test: borehole SC36 survey (8.00 m).

P (Kpa)	Mp (cm)	H-Mp-hp (cm)	e
8	0,0000	1,044	1,093
19	0,0000	1,044	1,093
38	0,0000	1,044	1,093
76	0,0000	1,044	1,093
114	0,0000	1,044	1,093
152	0,0000	1,044	1,093
305	0,0335	1,011	1,058
610	0,0940	0,95	0,995
1200	0,2150	0,829	0,868
610	0,1880	0,856	0,896
305	0,1510	0,893	0,935
152	0,1015	0,943	0,987
8	-0,0500	1,094	1,145

P: Pressure - Mp: Settlement - H: Initial sample height - hp: Height of solids - e: Void indices

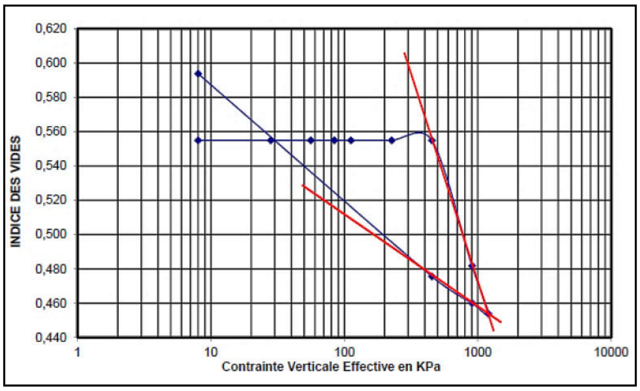

Figure-6. Graphical representation of the compressibility test in borehole SC31 (5.00 m).

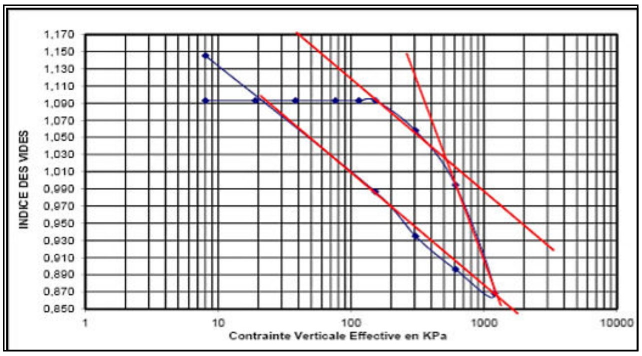

Figure-7. Graphical representation of the compressibility test in borehole SC36 (8.00 m).

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Table-7. Results of the oedometric test by borehole.

Borehole	Depth (m)	Ic	Ig	Pc (KPa)	Pg (KPa)
SC28	8,00	0,32	0,06	700	681
SC31	5,50	0,24	0,05	460	452
SC36	5,00	0,18	0,07	230	221
SC36	8,00	0,43	0,13	510	152

Ic: compressibility index - Ig: swelling index - Pc: pre-consolidation pressure - Pg: swelling pressure

2.2.6 Shear test

The last laboratory test performed is the shear test, the purpose of which is to identify the shear strength parameters of the soil subjected to direct shear [19]. It is used to measure the characteristics of a soil to solve stability problems. Using this test, we can deduce the values of the effective friction angle φ´ and the effective cohesion C' (Table-8).

Table-8. Shear test results from boreholes SC28 and SC36.

Borehole	Depth (m)	C´(Kpa)	φ´
SC28	8.00	34	20°
SC36	6.00	34	22°

3. CALCULATION OF SETTLEMENT FROM GEOTECHNICAL TESTS

The soil compression properties are the result of the relationships between the applied stress and parameters related to the soil settlement condition [20]. The settlement is calculated from the stress versus strain relationship using mechanical parameters measured by in situ and laboratory tests [21].

Based on the results of all the geotechnical tests performed in situ and in the laboratory on samples from boreholes along the railway track including pressuremeter tests, the settlement at each borehole was calculated depending on the depth using the formula, known as Louis Ménard's global formula below:

$$\Delta h = \frac{\alpha . \Delta\sigma . e}{Em}$$

- **e**: thickness of the compressible layer
- **α**: Rheological coefficient
- **Δσ**: Applied stress
- **Em**: Pressuremeter modulus

Taking into account the influence of the soil volumetric weight on the value of the total stress applied at a given depth, we calculated the total settlement (total S) as a function of the thickness of the clay formation (e Clay) in the two extreme cases, when the soil is dry (γ = γunsat) and when the soil is saturated (γ = γsat). The results obtained show that the settlement is proportional to the thickness of the clay formation and is greater when the soil is saturated (Figure-8). The same calculation has been reproduced on all the boreholes to determine the settlement distribution along the railway (Figure-9).

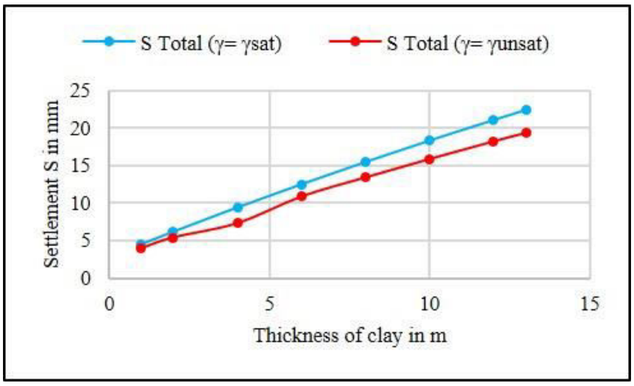

Figure-8. Variation of the settlement depending on the thickness and the state of the clay saturation.

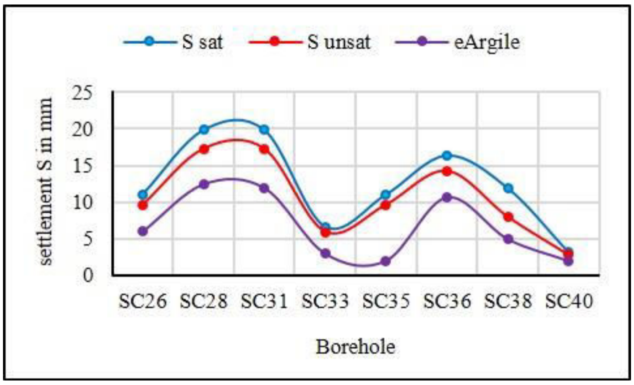

Figure-9. Distribution of the settlement along the studied section.

4. MODELING OF SOIL SETTLEMENT OF UNDER THE RAILWAY TRACK

The finite element method is an effective and powerful tool for analyzing the problems of complex soil mechanics and engineering. Its use in geotechnics dates back to the early 1960 [22, 23]. The Plaxis software is a finite element program commonly used in geotechnical engineering for deformation and stability analysis of projects [24]. Moreover, it provides realistic predictions of volume change behavior of expansive soils when they undergo seasonal changes [25, 26].

To analyze the problem of soil settlements, it is important to create a model of geometry. This model should include a representative division of the subsoil into distinct layers, structural objects, construction stages and loads. The subsoil below the railway platform of the studied section is composed essentially of 3 elements. These elements are the marl-limestones, clay and silts, to which are added the components of railway track: subgrade, underlayment, ballast, sleepers and rails (Figure-10). In order to form the model, each of these elements must be well defined by assigning to it its own

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characteristics. Table-9 summarizes the characteristics retained for the different components of this model.

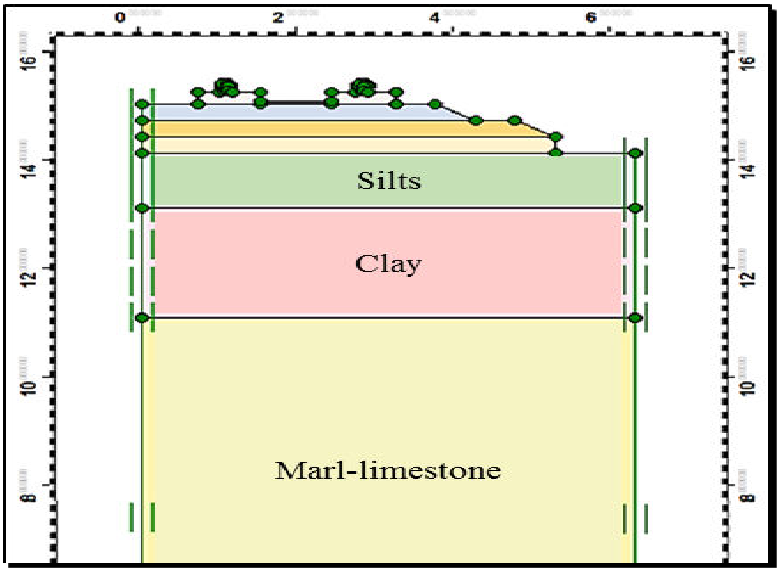

Figure-10. Geometric model.

To better understand the problem of soil settlement in our study area, we chose to study the two extreme cases concerning the state of soil saturation as a function of the thickness of the clay layer under the railway platform. The model of the rail section is symmetrical with respect to the track centre distance, therefore we will model the settlement of track 1 and the results will be reproduced in the other track. In this case, the only condition imposed on the limits is the maximum permissible rail load, which is in the order of 25 tons per axle. Figure-11 illustrates the mesh size and the first simulation with a 2 m thickness of the clay layer taking into account the rail load.

Table- 9. Characteristics of the model parameters.

Formation	K (m/day)	E (kN/m^2)	ν	C (kN/m^2)	Φ (°)	γ_{sat} (kN/m^3)	γ_{unsat} (kN/m^3)
Ballast	**150**	**2.8. 10^5**	**0.30**	**0**	**40**	**18**	**16**
Underlayment	6	3. 10^4	0.37	0.2	35	23	21
Subgrade	4	4. 10^4	0.35	0.1	42	23	21
Silts	0.3	3. 10^3	0.19	0.2	25	18	16
Clay	0.015	2. 10^3	0.33	24	21	20	18
Marl-limestone	1.16	5. 10^3	0.30	40	29	22	20

K: Permeability coefficient - E: Young's modulus - ν: Poisson's ratio - C: Cohesion - Φ: Angle of friction - γsat: Saturated volume weight - γunsat: Unsaturated volume weight

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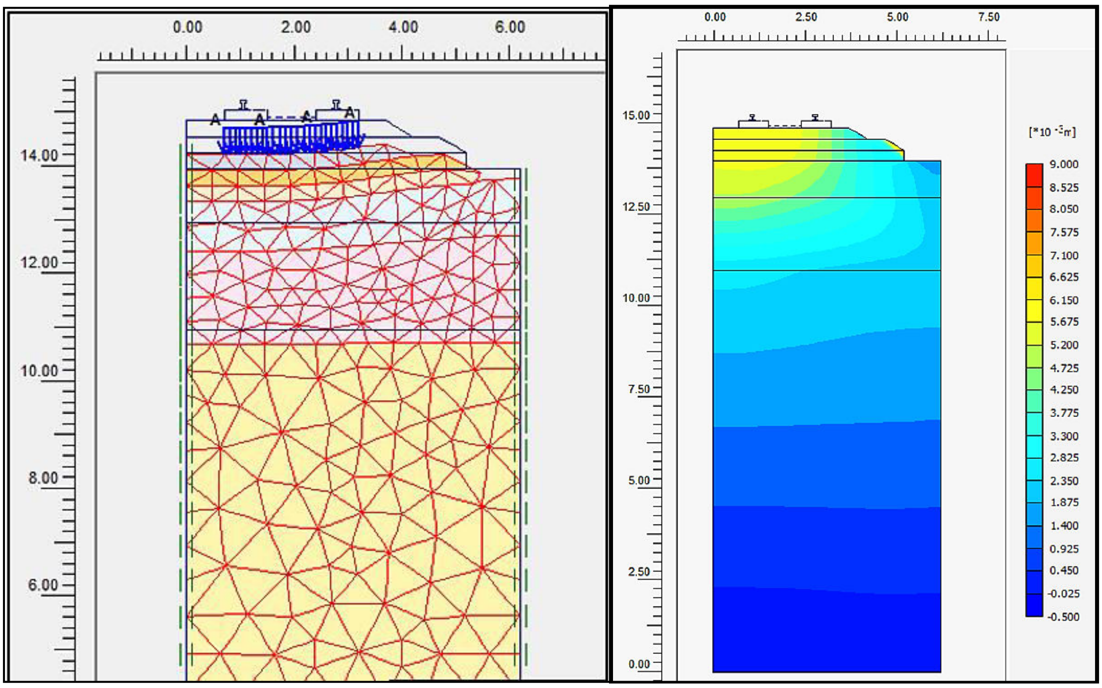

Figure-11. Meshing and settlement modeling for 2 m clay.

Figure-12 illustrates the results of the modeling of the soil settlement depending on the thickness of the clay layer and the saturation state of the clay formation. It is found that the rate of settlement is proportional with the thickness of clay.

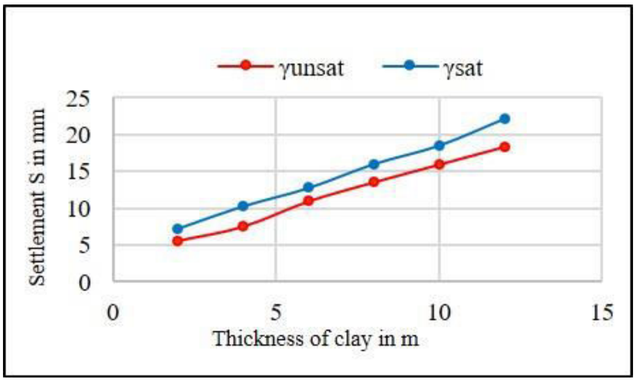

Figure-12. Variation of the settlement depending on the thickness and saturation of the clay.

A comparative study between the settlement results obtained from geotechnical investigations and those of finite element modelling by the Plaxis software, leads to very close results which confirms the calibration and validation of the model. Figure-13 shows the settlement rates calculated using pressuremeter tests for saturated (SPsat) and unsaturated (SPunsat) soils and settlements obtained using Plaxis modelling in the same saturation cases (SMsat and SMunsat).

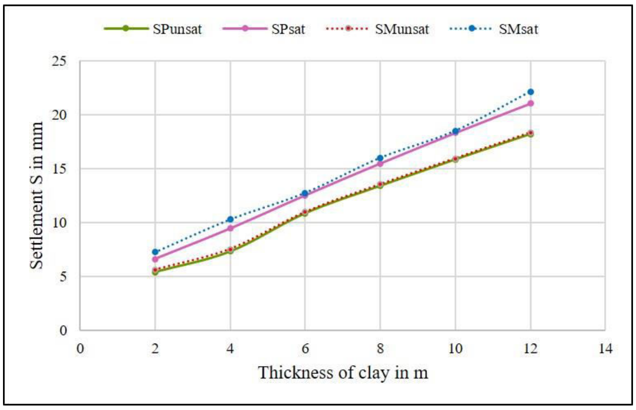

Figure-13. Comparison of settlements by pressuremeter and modeling methods.

The analysis of the results allows the establishment of a predictive mapping of the natural risk distribution associated with the shrinkage and swelling of clay formations along the railway line in the study area. Two areas were identified where settlement exceeds the intervention limits (IL) for the length profile. These limits are in the order of ±13 mm for train speed between 80 Km/h and 120 Km/h and ±10 mm for speed between 120 Km/h and 160 Km/h [27] (Figure-14). The first zone is located between kilometer points (PK) 58 and 96 and the second zone between PK 102 and 106. To conclude, these zones require adequate treatment to improve soil performance to avoid the risks of settlement.

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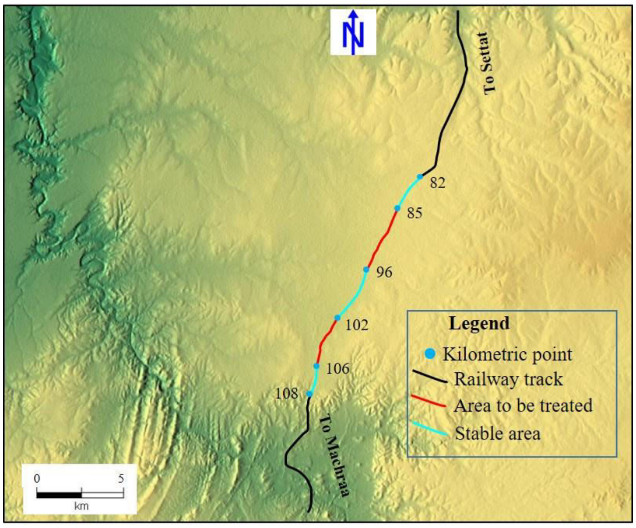


Figure-14. Location of risk areas.

5. TREATMENT OF COMPRESSIBLE AREAS

The development of soil mechanics and geotechnical engineering has made it possible to highlight a variety of techniques for improving and reinforcing poor quality basement performance [28]. These techniques are appropriate solutions both in terms of reducing settlement and increasing bearing capacity [29], by modifying the properties and behavior of expansive soils [30]. The choice of reinforcement method varies according to its feasibility, the geotechnical properties of the location and its economic impact [31]. Substitution is a technique whereby the wrong soil is excavated and replaced with good materials, it is a technique implemented during the preparatory work in order to make the soil suitable for the project. This method must be evaluated in advance financially, technically and in terms of its impact on the environment.

The analysis of the geotechnical boreholes carried out makes it possible to determine the thickness of the clay layer along the track. We therefore propose to substitute 4 m of soil by selected materials whose characteristics are as follows: Angle of friction (Φ) = 35 °, volumetric weight (γ) = 20 KN/m2 and Cohesion (C) = zero (Figure-15).

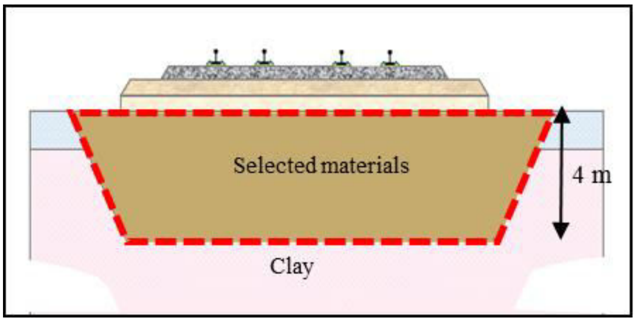
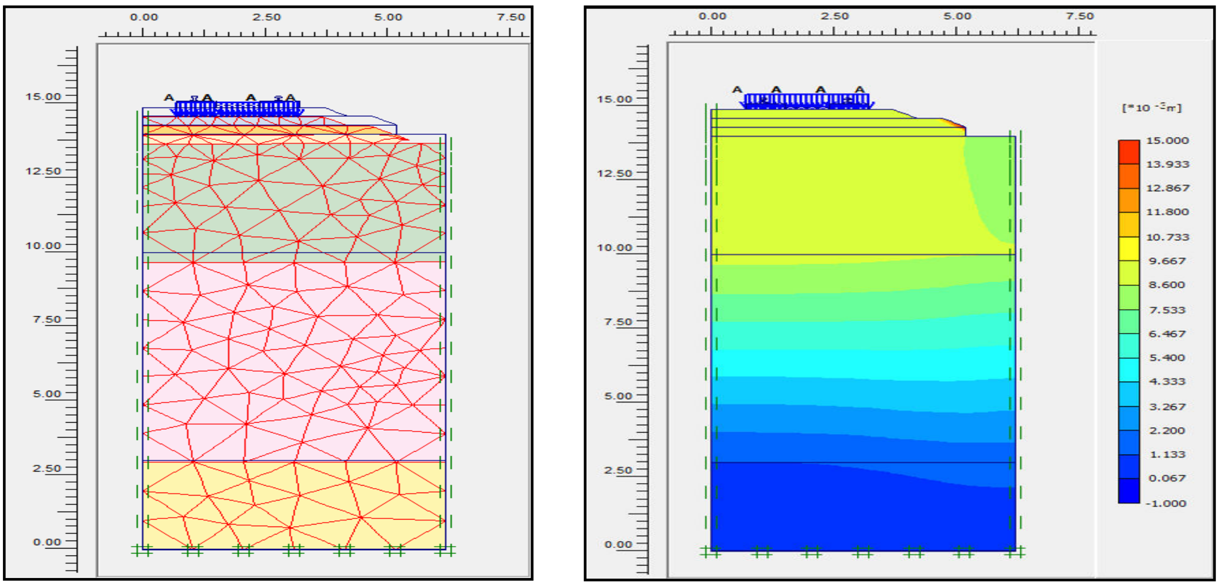


Figure-15. The technique of substitution

The technique of improvement by substitution first requires a verification of its feasibility and the quantification of the performance of the improved soil. To do this, the soil behavior was modeled after a 4 m purge of the clay layer and substituted with selected materials, using the finite element method (Figure-16). This allowed the comparison of the properties of the soil before and after the substitution operation.

In order to study the impact of soil reinforcement by a 4 m purge, we calculated the safety factor to evaluate the punching safety for the clay layer whose thickness varies from 6.5 m to 12 m and taking into account the rail load. It was found that the safety factor varies between 2.02 and 5.11 depending on the thickness of the clays (Table-10). From these results it can be concluded that punching stability is largely ensured as long as the safety factor is above the stability threshold of 1.5.



Modeling the substitution technique

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Table-10. Parameters for Calculating the Factor of Safety.

H (m)	C_u (KPa)	B_m	B_m/H	Nc	q_{max} (KPa)	q (KPa)	F
12	52.60	12	1.00	5.14	270.30	133.30	2.02
10			1.20	5.14	321.90		2.41
8			1.50	5.14	405.50		3.03
6			2.00	5.40	681.69		5.11

H: Thickness of the clay layer - Cu: Cohesion - Bm: Average width of the backfill - Nc: lift factor - qmax: Maximum permissible pressure - q: Constraint provided by the railway infrastructure - F: The factor of safety

The analysis of these results revealed of the relevance of the substitution technique as a soil improvement method in the studied location. Indeed, the excavation of 4 m of soil in areas where the thickness of the clay layer exceeds 6 m and replacing it with selected materials significantly reduces vertical and horizontal soil displacement. This procedure will contribute to improving the stability and performance of the railroad. Then, the substitution operation reduced the settlement of the clay formation from 61% to 54% depending on the thickness of the formation. The choice of this technique is justified not only by the considerable reduction in settlement, but also by taking into account its ease and speed of execution and its economic feasibility.

6. CONCLUSIONS

The railway infrastructure is very sensitive to the phenomenon of settlement of compressible soils, a phenomenon that is manifested by the degradation of the geometry and the performance of the track. In order to better understand the distribution and to prevent risks related to the settlement and the shrink-swelling phenomenon the clay soils in the study area, we first calculated the settlement using the pressuremeter method from the analysis of the results of the various geotechnical tests carried out in situ and in the laboratory. Secondly, we modelled the settlement via the finite element method. The results obtained are approximately similar and showed that the settlement follows the variations of the amplitude of the clay layer with a much more marked increase in wet periods. This made it possible to establish a predictive mapping of the distribution of the risk of settlement along the subject section of this study.

Furthermore, the modeling by finite element method of the settlement after improvement of soil behavior using the substitution technique, replacing 4 m of soil in areas where the clay thickness exceeds 6 m by selected materials, makes it possible to modify soil performance and properties. The results show the feasibility and efficacy of this technique, where the factor varies between 54% and 61% depending on the thickness of the clay layer. This treatment helps in reducing the deformations caused by the expansive soils under the railway track, which cause the degradation of the geometric quality and performance of the track.

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