Proceedings of the 20th ICSMGE – Post-conference Volume – Rahman and Jaksa (Eds)

Lessons learned from the Moroccan high-speed railway embankment constructed on soft soils

Leçons Tirées du Remblai de la Ligne à Grande Vitesse Marocain Construit sur Des Sols Mous

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ABSTRACT: Challenges associated with excessive settlement are typically encountered in limited areas under the Moroccan high-speed railway embankment. A variety of mechanisms are controlling these soft soils depending on their deposition environments and their inherent characteristics. Therefore, each compressible area presents a unique behavior that requires a unique approach to be fixed during the deformation analysis. This paper presents a comparative study between two compressible areas, by highlighting the priorities to be followed during the settlement prediction process when using numerical simulations. The numerical modeling prediction results for both cases, for soft alluvial and lacustrine deposits, are compared with in-situ settlement measurements during and after the embankment construction. Based on the back-analysis, the time-dependent behavior in both cases was found necessary for capturing the in-situ behavior. However, soft lacustrine deposits are particularly complex in this case. For that, a systematic combination which consist of constructing dipped layers in the numerical model, selecting a constitutive model that include creep and adding artesian pressure effect can lead to accurate predictions during the numerical analysis of lacustrine soft soils.

RÉSUMÉ : Les défis associés au tassement excessif sont généralement rencontrés dans des zones limitées sous le remblai de la ligne à grande vitesse Marocain. Divers mécanismes contrôlent les sols mous en fonction de leurs environnements de dépôt et de leurs caractéristiques inhérentes. Par conséquent, chaque zone compressible présente un comportement unique qui nécessite une approche unique à fixer lors de l'analyse de la déformation. Cet article présente une étude comparative entre deux zones compressibles, en mettant en évidence les priorités à suivre lors du processus de prédiction du tassement par simulations numériques. Les résultats des prédictions de modélisation numérique pour les deux cas, pour les dépôts alluviaux et lacustres mous, sont comparés aux mesures de tassement in-situ pendant et après la construction du remblai. D'après la rétro analyse, le comportement dépendant du temps dans les deux cas s'est avéré nécessaire pour capturer le comportement in situ. Cependant, les dépôts lacustres mous sont particulièrement complexes dans ce cas. Pour cela, une combinaison systématique qui consiste à construire des couches inclinée dans le modèle numérique, sélectionner un modèle constitutif incluant le fluage et ajouter l'effet de la pression artésienne peut conduire à des prédictions précises lors de l'analyse numérique des sols mous lacustres.

KEYWORDS: Soft soil behavior, vertical drains, embankment, settlement, numerical modelling

1 INTRODUCTION

The high speed railway project involves the construction of rail lines linking between Tanger and Kenitra north of Morocco (Phase 1, section 1 &2), then to Marrakech and Agadir (Phase 2) in the south. Phase 1 of the current project has been completed during the year 2018 which covered a 200 km segment; this was divided into 2 sections. The first section is the one linking between Tanger and larache. The second section, which makes the object of this work, is the one linking between Larache and Kenitra. Phase 2 however, is currently under the early planning stages.

At numerous locations along the high-speed railway line, soft soil deposits are encountered mainly near river beds, lakes and small streams. For that, many solutions were chosen during the railway line construction. The later, depends on the type of the problematic behavior, its boundaries, depths and costs of the construction process.

In general, locations where soft soils are predominantly present near the major rivers in the northern section "section 1" (e.g. Loukkos river, El hachef river and el Mharhar river). Those sites were improved by deep piles under the concrete bridges Foundations. This improvement method is chosen for its efficiency to encounter the imminent challenges of bearing capacity failures and excessive settlements. The soft soils studied in this work are located in section 2 of the high-speed railway line. In this section soft soil deposits are improved by a combined effect of prefabricated vertical drains (PVDs) and preloading. For cost effective outcomes, this method is applied in both Sebou and Drader study areas selected for this work. This method main objective is to reduce the drainage length for rapid consolidation time (Walker et al. 2012, Indraratna et al. 2012). PVDs are used under surcharge "or preloading" to accelerate the dissipation of excess pore water pressure that accumulates during the embankment construction phases (Barron 1948), to ensure its safety and increase the subsoils shear strength by the end of the embankment construction.

To accurately capture the soft soils in both study areas 2D finite element analysis is used to predict the excessive settlements during the embankment construction for the PVD improved subsoils. Similar studies are routinely accomplished for PVD improved soft soil by many researchers (Rezania et al. 2017, Tschuchnigg and Schuweiger 2018), to examine some relevant approaches or advanced constitutive models in alluvial or marine deposits (Kim and Do 2010, Da Silva et al. 2017). However, very few publications have discussed the geological mechanism such as the deposition environment (Mridakh et al 2019), the artesian pressure (Kim et al. 2018), shallow tectonic structures effects on soft soil behavior and its influence on predicting the subsoil deformation, precisely excessive settlement.

Therefore, this paper aims at presenting a comparison between field measured settlement and predicted settlements of a well monitored embankment sections constructed on PVD-improved Sebou soft alluvial deposits and Drader lacustrine deposits.

2 GEOLOGY AND SOIL PROPERTIES

2.1 *Geological setting*

Both study areas are located in the Rharb basin, where Drader study area is at the northern basin limit and Sebou area is at the southern one (Figure 1). Drader area can be described as a subsiding sedimentary min-basin, that is controlled by neo-tectonic activities (Combe 1963, Le Coz 1964, Cirac 1985). The mini-basin filling process is marked by marine and continental sedimentary units. Those units are mainly plio-quaternary deposits (Combe 1963), where its continental origins are the cumulated sediments carried out from rif domain and Middle Atlas domain (Benmouhammadi 2007). In the Centrale part of drader mini-basin, the plio-quaternary deposits are mainly soft soils that are formed in lacustrine environment, where artesian pressures are documented in deep captive aquifers (Combe 1963).

Sebou area is located in the southern limit of the Rharb basin (Figure 1). Its geological configuration is marked by Neotectonic activity mainly due to the south-rifaine front structure. However, the deposition mechanism is controlled by both onshore and offshore environments (Le Roy et al 2014). Sedimentary systems geometries are mainly formed by the Plio-quaternary filling, which are controlled by sea level fluctuation and tectonic activities (Le Coz 1964, Cirac 1985, Flinch 1993). The sedimentary regime is mostly dominated by clays and sand Brought by the Sebou and Loukous rivers (Jaaidi 1993).

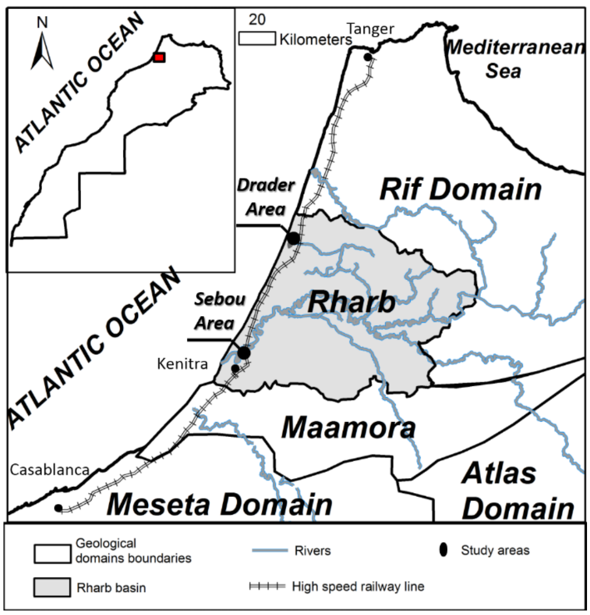

Figure 1. Localization of the study areas.

2.2 *Background information and data-base*

The selected high-speed railway line embankments were constructed both constructed in the right bank sides of Sebou and Drader rivers. Subsoils were characterized during the early geotechnical investigations that were followed by complementary fields tests (such as boreholes, cone penetration tests (CPTs), pressuremeters (PRs), vanes shear tests (VS)) and laboratory tests. Based on the analyzed database, stratigraphy models demonstrated rather undulated subsoil layers in the N-S orientation, and a rather uniform soil layers in the E-W orientation in Sebou area (Mridakh et al 2019). however, Drader area stratigraphy presented inclined layers in the W-E orientation following the deep syncline formation in Drader mini-basin (Combe 1975). The N-S orientation presents a depression shaped stratigraphy model that resulted from the flexure fault (Combe 1975).

The depositional history is described in case of Sebou compressible area as lightly over-consolidated for the shallower layers, and normally consolidated in deeper layers (Mridakh et al 2019). In Drader compressible deposits, subsoils are described as normally consolidated based on the interpreted odometers tests according to Casagrande method.

Ground water varies between –1 m during the humid period to -2m during the dry period in Sebou area. However, in Drader area ground water fluctuates between –0.5 m during the humid period and -1m during the dry period. In addition, Drader area is affected by a mean value artesian pressure of about 40 kPa that acts from a shallow aquifer underlying the compressible lacustrine soft soil deposits.

3 NUMERICAL MODELING

3.1 *Finite element models and approaches*

The numerical modeling is carried out based on the finite element (FE) software Plaxis 2D. For both cases, Class B prediction (predictions during the embankment construction) is applied at first by following the simplest modeling procedure possible. Then the modeling process develops by adding additional advanced soft soil behavior components during the back-analysis, by setting the priorities that should be added for each case study. This process is presented in a form of a chart as below:

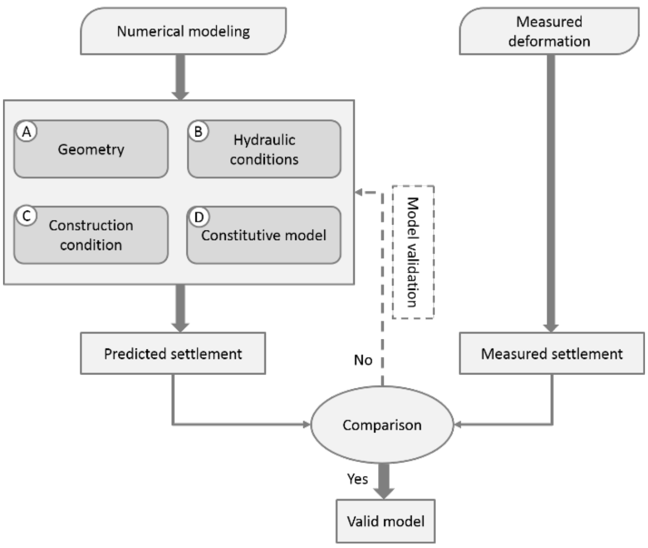

Figure 2. Simplified numerical modeling framework.

Only half of Sebou site embankment was modeled (20 m width) due to the subsoil layers symmetry, on 47 meters of different types of soft soils which are included in the FE model see Figure 3. Groundwater was assumed as hydrostatic at the ground water level (–1m). A 15-node triangular element were used following plane strain condition with very fine mesh option. The resulting elements number after meshing is 1682 and 13,681 nodes.

Mohr-Coulomb was used for both embankments (Sebou and Drader) granular and fill materials and the working platform layer.

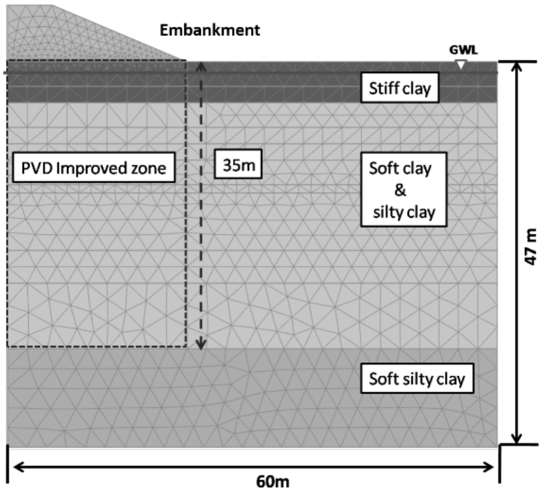

Figure 3. Sebou subsoil finite element mesh.

The full width of Drader site embankment was modeled (45 m width) due to the dipped subsoil layers. In this case 38 meters of multiple soft soil layers were modeled see Figure 4. Groundwater was assumed as hydrostatic at the ground water level (–0.5m). A 15-node triangular element were used following plane strain condition with very fine mesh option which resulted to 2319 elements and 18,807 nodes.

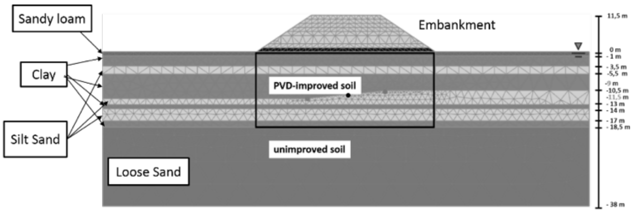

Figure 4. Drader subsoil finite element mesh.

3.2 *Matching method*

Including PVDs in the numerical modeling process is usually done as 3D problem under axisymmetric conditions. However, many researcher have resolve this problem to a 2D plain strain format to reduce time of computation (Hird et al. 1992, Kim and Lee 1997, Indraratna and Redana 2000, Chai and Miura 2001). In this study, Chai et al 2001 is used for both case studies. The later matching method proposed is based on calculating an equivalent vertical hydraulic conductivity k_{ve} as expressed in Eq. 1:

$$k_{ve} = \left(1 + \frac{2.5l^2 k_h}{\mu.D_e^2.k_v}\right).k_v \quad (1)$$

Where l= drainage of unit cell, D_e: diameter of unit cell. The value of μ can be expressed as:

$$\mu = \ln\left(\frac{n}{s}\right) + \frac{k_h}{k_s} ln(s) - \frac{3}{4} + \frac{2\pi.l^2.k_h}{3.q_w} \quad (2)$$

Where $n = D_e/d_w$(d_w diameter of a PVD); $s = d_s/d_w$(d_s is equivalent diameter of smear zone).

3.3 *Input parameters*

The models input parameters based on laboratory tests were directly used for the Class B analysis. However, a complementary study during the back-analysis is accomplished for the soft soil creep model parameters to match the field measured settlement for short- and long-term predictions.

For the drainage layer and the fill materials of the embankment the same parameters were fixed for both case studies as presented in Table 1.

Table 1. Embankment parameters values (For Sebou and Drader Embankments).

Material	$E'(MPa)$	ν'	ϕ'	ψ'	$c'(kPa)$	$\gamma\ (kN/m^3)$
Fill	40	0,2	35	0	0.1	20
granular	100	0,2	40	0	0.1	20

Where E' is the young modulus,ν' is the poison's ratio, ϕ' is the friction angle, ψ' is the dilatancy angle, c' is the cohesion and γ is the unit weight of the embankment materials.

The soil properties values for constitutive models (SSM and SSCM) used in Sebou and Drader soft subsoils are listed in Tables 2 and 3.

Table 2. Soil constant values for SSM and SSCM for Sebou subsoils.

Layer	Depth (m)	K^*	λ^*	μ^*	k_h (m/day)	k_{ve} (m/day)
L1	0-3	0.02	0.05 (0.052)	4.0E-4 (5.0E-4)	9.0E-5	9.0E-5
L2	3-5	0.02	0.05	9.0E-4	3.4E-4	9.0E-5
L3	5-8	0.03	0.09	14E-4	4.0E-5	1.1E-5
L4	8-10	0.02	0.05	12E-4	5,0E-8	1.4E-8
L5	10-12	0.06	0.08	14E-4	1.4E-4	4.0E-5
L6	12-15	0.04	0.07	13E-4	1.6E-4	4.4E-5
L7	15-16	0.01	0.04	7.0E-4	2.4E-4	6.4E-5
L8	16-23	0.04	0.09	11E-4	1.3E-4	3.5E-5
L9	23-27	0.02	0.06	11E-4	4.0E-8	1.0E-8
L10	27-35	0.01	0.04	7.0E-4	2.4E-4	6.4E-5
L11	35-47	0.05	0.09	16E-4	1.0E-4	2.6E-5

(-) Back calculated parameters

Table 3. Soil constant values for SSM and SSCM for Drader subsoils.

Layer	Depth (m)	K^*	λ^*	μ^*	k_h (m/day)	k_{ve} (m/day)
L1	0-1	-	-	-	2.5E-2	1.0E-1
L2	1-3.5	0.020	0.08	1.80E-3	2.6E-4	1.0E-2
L3	3.5-5.5	0.006	0.03	-	2.0E-3	6.4E-2
L4	5.5-10.5	0.016	0.07	1.9E-3	3,0E-4	3.5E-4
L5	10.5-13	0.04	0.02	-	5.5E-4	2.1E-2
L6	13-14	0.020	0.07	1.6E-3	1.2E-5	1.0E-5
L7	14-17	0.006	0.02	-	8.3E-3	1.5E-1
L8	17-18.5	0.04	0.09	1.2E-3	1.3E-4	1.1E-2
L9	18.5-38	-	-	-	2.5E-2	1.0E-1

Where λ^* is the modified compression index, K^* is the modified swelling index used by the soft soil model (SSM). The additional parameter used by the soft soil creep model μ^* is the creep index, more details can be found in Neher et al (2001) describing the use of both constitutive models in soft soils.

4 RESULTS AND DISCUSSIONS

4.1 *Sebou site*

Class B prediction is based on using the soft soil model and the minoring data from the settlement cells for comparison. The SSM soil parameters are presented in Table 2. The settlement results included for the Sebou site used only half of the embankment, subsoil geometry as a result of the will stratified soil layers in the W-E direction.

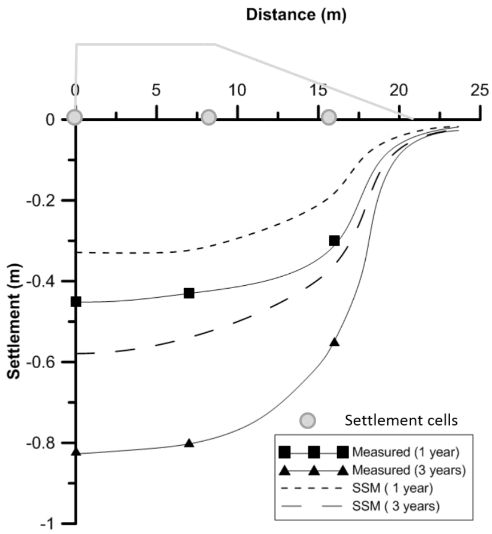

Figure 5. Predicted Settlements using the SSM compared with the measured settlements at the Sebou site.

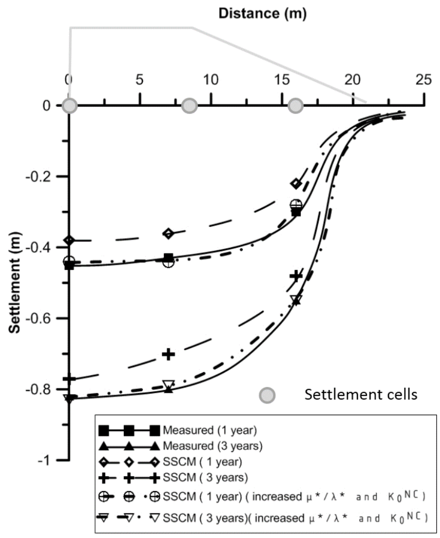

Figure 6. Predicted Settlements using the SSCM compared with the measured settlements at the Sebou site.

The comparison between the predicted settlements and the monitoring data in Sebou site after 1 year and 3 years is presented in Figure 5. The measured maximum settlement at the center of the embankment is at 0.43 m after 1 year and 0.82 m after 3 years. The SS model predicted a maximum settlement of about 0.32 m after 1 year and 0.58 after 3 years. This represents an under estimation close to 25% at 1-year mark and 30 % at 3-year mark.

Therefore, the predictions based on soft soil model is getting less accurate with time, which indicate the necessity of including the creep effect into the analysis for Sebou soft soils.

When using the soft soil creep model (which include the creep effect based on the μ^* parameter), the maximum settlement at the center is about 0.36 m after 1 year and 0.76 after 3 years. Thus the underestimation settles at 17% after 1 year and 7% after 3 years. The results show that the prediction is at a good agreement especially in long term.

The remaining underestimation was analyzed in detail after a sensitivity analysis where it was found that layer L1 (see Table 2) parameters λ^* and μ^* were not following the general interval value variation of Sebou subsoils. In addition, the SSC model is not suitable for modeling the lightly over-consolidated state of L1 and L2 as discussed in (Mridakh et al. 2019). For that, we proceeded to increase the creep effect contribution in the discussed layers to obtain the near perfect results presented in Figure 6.

For that, prioritizing the use of constitutive models in Sebou area for prediction settlements is sufficient (Figure 2, D). more accuracy can be reach during the back-analysis (or the parameter sensitivity analysis) phase.

4.2 *Drader site*

Contrary to Sebou area, Drader site presented some high compressibility values for lacustrine Clay deposits and very low compressibility value for silty sand and sandy silt deposits. Thus, a different approach is fixed in this case by using both soft soil and soft soil creep models during the Class B prediction. The back-analysis phase is mainly reserved for the artesian pressure effect on settlement. In addition, the minoring data from the settlement cells is used for comparison.

The soil parameters for the SSM and SSCM are presented in Table 3. All values from the presented settlement cells measurement under the fall embankment is used in this case. This is due the complex subsoil geometry in the Drader subsoil which presented some dipped layers under the embankment in the W-E direction. In the analysis it was found that including the inclination in layer 4 is sufficient.

During Class B prediction (without including the artesian pressure (AP) effect), The maximum measured settlement at the center of the embankment is at 0.62 m after 1 year and 0.85 m after 2.5 years. The maximum predicted settlement without the AP at the center of the embankment at 0.51 after 1 year and 0.78 after 3 years. This represents an underestimation of the settlement of about 18% after 1 year and 8% after 2.5 years. Thus, is seems that the constitutive models used in combined manner produced acceptable predictions when compared to the measured settlement in short term, and in a good agreement in long term.

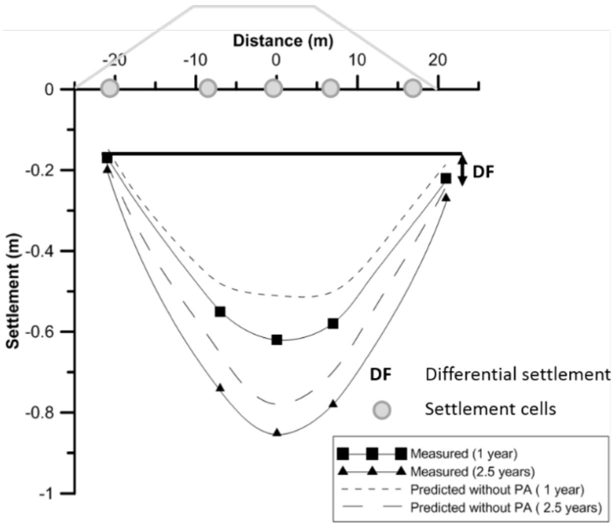

Figure 7. Predicted and measured deformation profiles without the artesian pressure effect at the Drader Site.

Based on some excess pore pressure measurement and field work, artesian pressure (AP) was estimated at a mean value of 40 kPa during the 2.5 years. Therefore, during the back analysis the authors included the AP effect in the numerical modeling to assess its effect on settlement. Figure 8 presents the results of adding the AP in the numerical modeling process, which results in a precise prediction in both short- and long-term settlements.

It can be added that the inclination used in layer 4 led to producing the exact differential settlement measured under the embankment. Therefore, multiple priorities are fixed to obtain such a good match between the predicted and the measured settlements. Those can be resumed as: having inclined layer or layers during the numerical model construction, including the

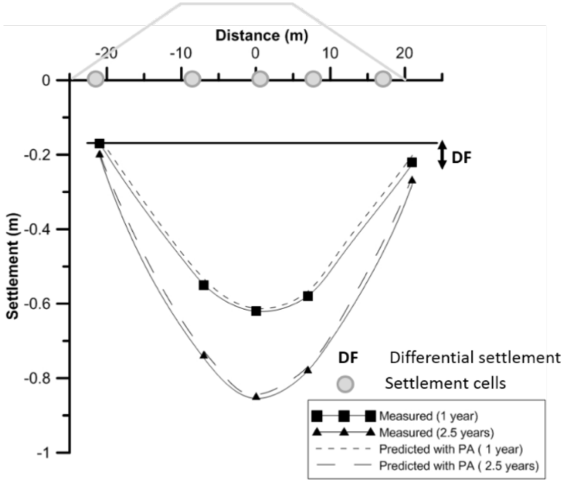

Figure 8. Predicted and measured deformation profiles with the artesian pressure effect at the Drader site.

artesian pressure effect and using two types of constitutive models is the approach that can lead to accurate predictions (Figure 2, A, B, D).

5 CONCLUSIONS

This study analyzed the issue of excessive settlement under two sections of the Moroccan high-speed railway embankment constructed on compressible subsoil improved with PVDs and preloading. Each compressible area (Sebou and Drader) had some specific priorities that should be fixed to accurately predict settlements for short and long term. For that, the following conclusions can be drawn:

- Each compressible area is unique by its geology, deposition environment and hydraulic conduction. Thus, each site should have its own numerical modeling approach for soil behavior prediction.
- Many aspects of soil behavior can affect the overall soft soil behavior in both sites. For that, priorities should be fixed for each site, to simplify the modeling process.
- The back-analysis showed that in Sebou compressible area, time-dependent behavior (i.e. creep) has an important effect on soil behavior prediction. Thus, choosing the constitutive model that includes creep effect such as soft soil creep is a priority in the Sebou compressible area.
- Drader site presented multiple priorities that should be fixed for accurate subsoil behavior prediction, due to its complex geology and hydraulic condition.
- Modeling the full embankment in the Drader area is a must, due to the dipped subsoil layers, however it was found that inclining the Clay layer between 5.5 m and 10.5 m depth, is sufficient to capture the differential settlement under the embankment in short and long term.
- Combining between the soft soil creep model for soft clays and soft soil model for low compressibility silty sands and sandy silts, can produce some good agreement with the measured settlements at the Drader site.
- During the back-analysis it was found that including an artesian pressure of about 40 kPa during the numerical modeling at the Drader site, can produce some near perfect results for settlement prediction in short and long term.

6 ACKNOWLEDGEMENTS

The work presented was supported by the LPEE (Laboratoire Public d'Essais et d'Etudes). The author would like to thank all personnel in the LPEE for providing all data necessary for the completion of this work.

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