International Journal on Advanced Science Engineering Information Technology

Vol.12 (2022) No. 4
ISSN: 2088-5334

Application of the Nailing Technique to Stabilize a Slope in a Section of the Twinning of Road and Rail Infrastructure

Mohamed Ben Ouakkass [a,*], Latifa Ouadif [a], Ahmed Akhssas [a]

[a] *3GIE Laboratory, Mohammadia Engineering School, Mohammed V University in Rabat, Morocco*
*Corresponding author: *ben.ouakkass@gmail.com*

***Abstract*— Nailing is one of the most widely used stabilization techniques because of its technical and economic advantages. It is a practical and effective solution for the reinforcement of in-place slopes. It consists of placing in the soil high resistance nails to increase the cohesion of the soil and its resistance to traction and shear, which allows having a new material of great capacity. In this paper, we present the slope stability study in a section twinning of the road and railroad infrastructures between the kilometer points (KP) 105+938 and 106+263 of the line connecting Casablanca to Marrakech. The railroad track's topographic constraints and geometric requirements made the nailing method appeal to the realization of the new railroad in this area. The objective of this work is, on the one hand, to present the stability analysis of the slope before the earthwork and the implementation of the new railroad and, on the other hand, to evaluate the performance and stability of the nailed walls. The stability analysis of the soils in this section was verified in terms of safety coefficient using the calculation software TALREN. In the end, it can be concluded that the stability calculation results are conclusive and allow for highlighting the effectiveness of the innovative solution of nailing. This technique can be considered a good alternative to improve the safety and performance of excavation walls.**

***Keywords*— Reinforcement; nailing; stability; twinning; slope; retaining.**

Manuscript received 16 Jul. 2021; revised 18 Nov. 2021; accepted 12 Apr. 2022. Date of publication 31 Aug. 2022.

I. Introduction

Soil reinforcement by nailing is one of the practical techniques for improving the mechanical characteristics of in-place soils. This stabilization method is currently undergoing a very significant and widely employed development [1]–[5] due to its many advantages, namely its ease and speed of implementation [6]–[10], but also it preserves the geometry of the treated site. Soil nailing is a versatile and cost-effective technique for stabilizing slopes and retaining structures [11]–[13]. It involves placing metal inclusions or other high-strength materials in the ground. These inclusions increase the cohesion of the soil as well as its tensile and shear strength by producing a new compound material with a high capacity [6], [11], [14], [15].

The nailing technique is a geotechnical solution used mainly to reinforce slopes and vertical excavations. It is a stabilization technology allowing the reinforcement and maintenance of slopes. It began in France with the first nailed soil wall constructed in 1972 [3], [16], [17]. Nailing reinforcement can be used both to construct cuttings retaining walls and reinforce existing slopes. It can also be realized temporarily to support and stabilize the ground during the realization of the works in a building site, or on the contrary, can have a definitive function.

In the context of the doubling of the railroad track between Settat and Marrakech, on the railroad line connecting the two major cities of Morocco: Casablanca and Marrakech [18], we proposed to proceed with the nailed wall solution for the stabilization of the embankment in a section of the twinning of the railroad track and the national road N9. This paper presents a case study of embankment reinforcement using the nailed wall method to allow for the placement of the second railroad track. Our objective is to analyze the stability and evaluate the performance of the nailed slope to undertake the widening of the railway rights-of-way and the construction of the new railroad track. The ease of implementation, the economic efficiency, and the performances brought to the nailed soil [19], [20] have made the nailed retaining technique widely solicited universally in temporary and permanent applications.

II. MATERIALS AND METHODS

A. The geographical Location of the Study Area

Our study area concerns the section of the railroad track twinned with the N9 national road over 325 m. It is located between the kilometers points (KP) 105+938 and 106+263, on the Railway line connecting Casablanca to Marrakech. In the context of doubling the track between Settat and Marrakech, it was decided to find an adequate solution allowing the realization of the new track between the national road N9 and the existing track. During the study of the implementation of the second track in this section of the twinning, we encountered several constraints, notably land and technical issues. Figure 1 represents an extract of the road map of the province of Settat showing the situation of the section of the tight twinning, the object of the present study.

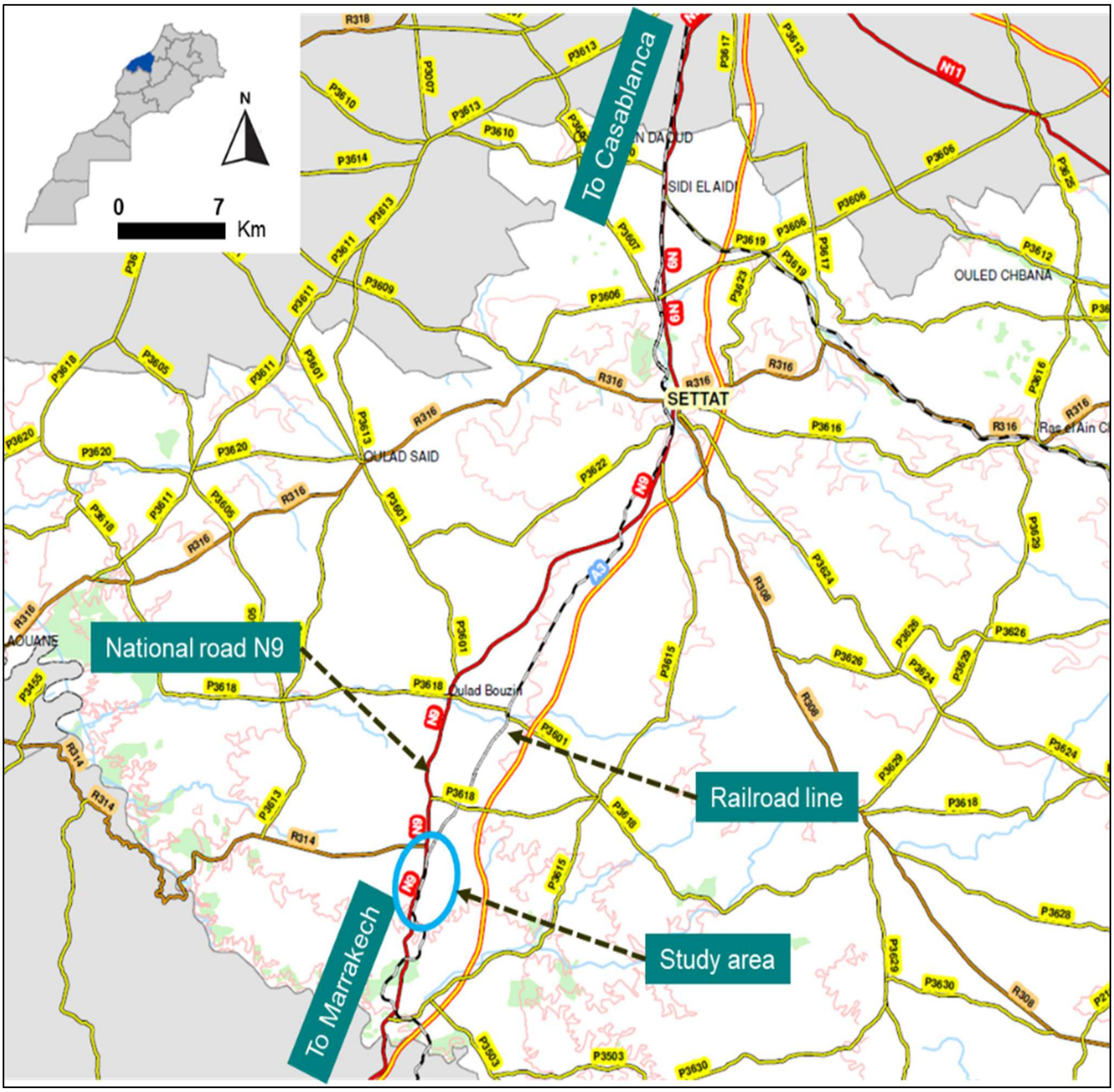

Fig. 1 Extract of the road map of the province of Settat

B. Analysis of the Stability of the Existing Slope

Considering the topographical constraints of the site and the geometric requirements of the railroad, we have undertaken a study of the possibility of building the new railroad. It is between the N9 national road and the existing track at the level of the section of the twinning between KP 105+938 and KP 106+263. This variant allow us to reduce the land impacts on the N9 right-of-way and avoid the temporary detour of traffic from this overly trafficked road. Considering the big difference in level, that is about 5,40 m, between the existing railroad track and the national road N9 in this zone of the twinning, we thought of the solution of nailed walls for the reinforcement and the stabilization of the slope between the road and railway infrastructures. The satellite image in figure 2 illustrates the situation of the existing railway line concerning the national road N9.

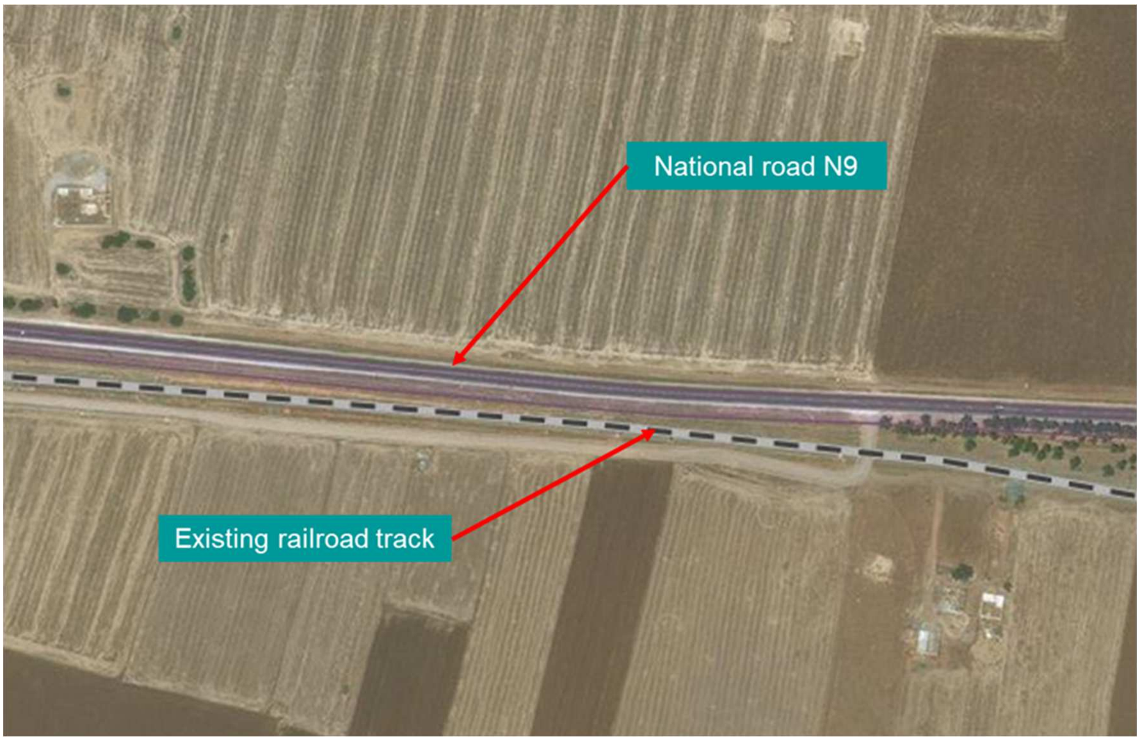

Fig. 2 Situation of the existing railway line and the N9 national road

Before starting the earthworks and the widening of the railway rights-of-way for installing the second track, it was necessary to study the stability of the existing slope. This examination allows us to justify the current stability of the slope in the study area. The parameters, thus, deduced is used for the feasibility analysis of the reinforcement and stabilization of the slope, by the nailed wall technique, after the earthworks and the realization of the new railroad. The stability of the nailed walls is generally evaluated based on a global safety factor (SF) under a predefined failure mechanism [21], [22].

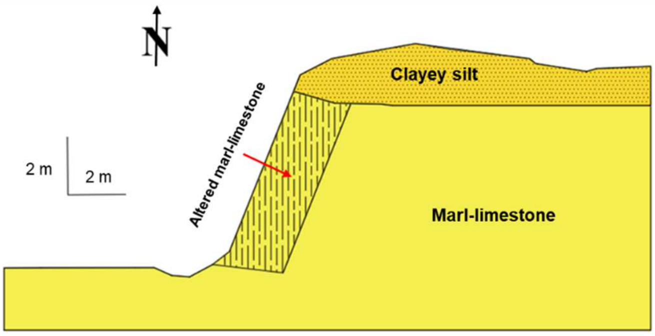

Fig. 3 Terrain configuration at the twinning section

During our site visits, we noted that the slope has held up fairly well for several decades, which is to say as soon as the first railway line was put in place. This observation testifies to the excellent resistance of the land in place. In addition, we also occasionally observed clusters of altered friable marl limestone at the foot of the current slope. In the geometric model of the calculation, we took into account a fringe of about 2 m of the skin of the current slope which consists of altered marl-limestone. Figure 3 illustrates the configuration of the land at the twinning section.

The geotechnical reconnaissance companions carried out in the study area, particularly in the vicinity of the calculation profile, show that the lithological section of the land is mainly composed of silty to gravelly clays on the 2.50 m overlying a marl-limestone formation that extends in depth [23]. The mechanical and geotechnical characteristics of the natural materials on the site were first defined from the preliminary investigations' conclusions. Subsequently, they are completed by analyzing the results of the geotechnical tests carried out in-situ and in the laboratory. For the dimensioning of a nailing reinforcement, the determining geotechnical parameters are essentially the weight by volume (γ), the cohesion (c), and the angle of internal friction (φ). The weight by volume is the weight per unit volume of a material. The tests carried out in the laboratory make it possible to determine each geological formation in the study area. In addition, cohesion expresses the shear strength of the soil under null normal stress. It is the structure's resistance due to Physico-chemical bonds. It allows to limit soil exposure to the danger of landslides. As for the angle of friction of the soil is a parameter of resistance to soil shear and normal effective stress. In order to identify the friction angle and the cohesion of different geological formations (silty clay and marl-limestone), we carried out rectilinear shear tests in the box on samples of these formations. The characteristics retained are summarized in Table I. We assumed that the weathered marl-limestone layer had lost half of its cohesion to justify the signs of weathering observed on the slope.

Our approach is indeed to perform a backward calculation with a minimum SF of 1,10. This overall factor is defined as the ratio of the maximum shear stress (Tmax) to the mobilized shear stress (Tm) along the failure surface [24]. Generally, Tmax is related to destabilizing actions such as water and surcharges. In comparison, Tm depends on the intrinsic characteristics of the material (cohesion c and the internal friction angle φ). Theoretically, the slope is said to be stable if SF > 1. The limit state of equilibrium (rupture) is obtained when SF = 1.

TABLE I
GEOTECHNICAL CHARACTERISTICS OF GEOLOGICAL FORMATIONS

Geological formations	Geotechnical characteristics retained		
	Volume weight γ (kN/m3)	Friction angle φ (°)	Cohesion c(kPa)
Silty clay	18,00	25,00	5,00
Altered marl-limestone	20,00	35,00	13,00
Healthy marl-limestone	20,00	35,00	26,00

The stability assessment was carried out on the slope with the greatest height (about 8.10 m) located at KP 105+738 and which is part of the same lithological context of the site with marl-limestone formations at the base topped by silty clays. Using the Bishop calculation method, these calculations was be carried out using the TALREN version 5 rupture calculation software. Figure 4 shows the geometrical model taking into account a 2-m fringe that was cleared during the widening works allowing direct contact of the nailed wall with the healthier marlstone.

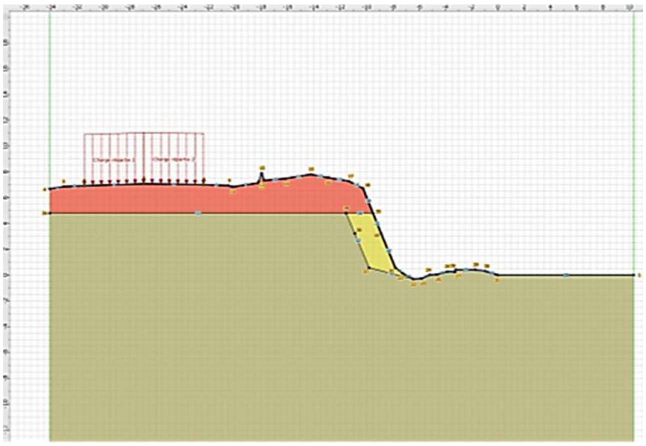

Fig. 4 Geometric model

The fracture stability calculation performed in our study section led to a safety coefficient SF = 1,114. The calculation shows that we can obtain at least the desired safety coefficient (SF ≥ 1,10) by assigning the shear parameters and the mechanical characteristics of the formations in place. Figure 5 shows the result of the calculation.

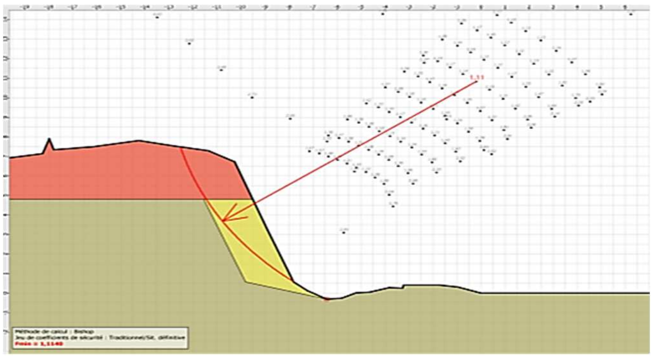

Fig. 5 Result of the stability calculation

C. Study of the Stability of the Nailed Slope

The topographical constraints of the twinning section and the geometrical conditions of the track and the need to limit the right-of-way led to ensuring the stability of the embankments. It is during the earthworks and after the construction of the new track. After verifying the stability of the existing slope, we propose to examine the stability of a nailed slope along this section of the twinning, between KP 105+938 and KP 106+263. This cuttings reinforcement solution replaces the reinforced concrete retaining wall alternative. The nailed wall method can dig almost vertically and minimize the impact on traffic on the RN9 during the construction phase. The nailed walls have become technically and economically more efficient than traditional walls.

The nailing technique is an artificial reinforcement method that is increasingly used for in-situ soil reinforcement [25]. It allows the improvement of these soils' mechanical properties by installing resistant inclusions. The stability analysis of a nailed soil wall has been approached by several methods [26], namely the finite element method using the deformation calculation and the rupture calculation, which allows a continuous passage from the internal stability to the external one and then to the general stability.

The nailed wall solution reinforces the soil by placing passive bars inclined concerning the horizontal plane. These nails are usually placed parallel to each other. The length and inclination must be adapted to the shape of the nailing and the properties of the soil [27]–[29]. Habitually, the nails utilized have a similar length and equal inclination. The reinforcement of trains by nailing is generally done in successive phases as the soil is excavated [30]. The operation must be carried out from top to bottom to prevent any disturbance. A protective facing is placed at the end of the nailing work, generally consisting of a welded wire mesh and shotcrete.

III. RESULTS AND DISCUSSION

A. Stability Check by Execution Phases

Taking into account the geological and geotechnical investigations carried out at the level of the twinning section, we next proceed to the analysis of the stability of the nailed slope. The study focused on the profile located at KP 105+938, which has a maximum slope height of approximately 5.40 m. Using the TALREN version 5 fracture calculation software, stability calculations allow the minimum safety coefficient to be evaluated at various stages. This verification of the safety coefficient SF was carried out as the nailing operation progresses according to a phasing described as follows:

1) Phase 1: This is a provisional phase that consists of terracing 1.00 m from the crest of the slope. The earthworks are carried out in order to obtain the most regular slope possible. Subsequently, the first bed of nailing is carried out according to a horizontal mesh of 2.00 m (Figure 6).

2) Phase 2: After the earthwork and excavation of 1.50 m of the slope in relation to the level of the ground of the first phase, we move on to the activation of the second bed of nailing according to a horizontal mesh of 2.00 m and vertical of 1.50 m (Figure 7). The nails 32 mm in diameter and 4.00 m in length are placed inside the sub-horizontal holes (angle of inclination is 10 °) and 110 mm in diameter. This choice of the angle of inclination is optimal given the nature of the geological formations on site. Wei Han and al (2020) investigated the impact of nail tilt angle on horizontal soil displacement. The angle was set at 5°, 10°, 15°, 20°, 25°, 30°, and 35°, respectively, and they found a positive correlation between nail tilt and horizontal displacement at the top of the slope. Then, the displacement increases with the increase of the tilt angle, and when the tilt exceeds 30° to 35°, there is an obvious break. When applying the soil nailing technique, it is necessary to consider the impact of the nail inclination angle. Horizontal arrangements should be avoided as much as possible, and the inclination should be kept below 30° [17].

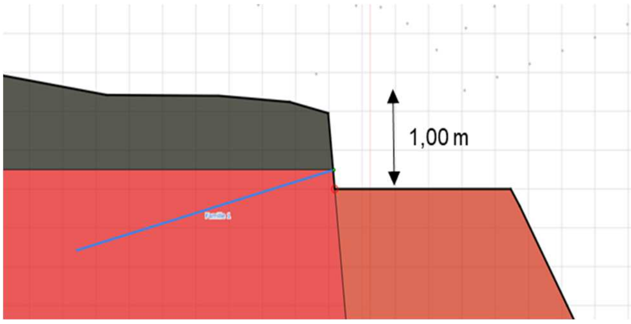

Fig. 6 Earthmoving and activation of the first nailing bed (Phase 1)

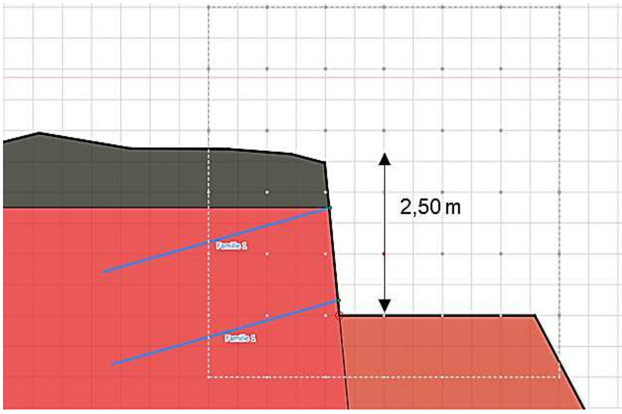

Fig. 7 Earthwork and activation of the 2nd bed of nailing (Phase 2)

3) Phase 3: In this phase, the earthwork is continued by excavating 1.50 m from the previous level, i.e., the earthwork up to 4.00 m from the crest of the slope. At this level, the third and last bed of the nailing is placed (Figure 8).

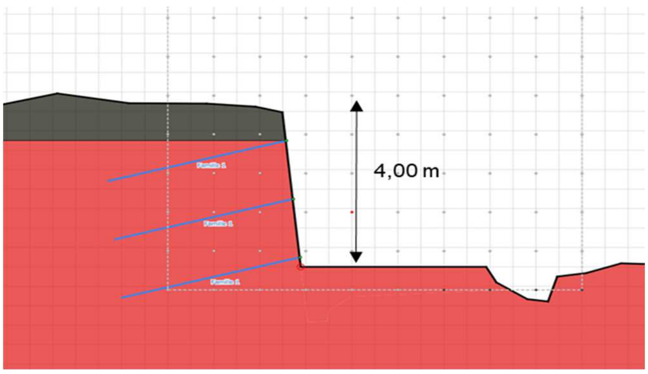

Fig. 8 Earthwork and activation of the 3rd bed of nailing (Phase 3)

4) Phase 4: Figure 9 shows the final phase of the nailing operation. It consists of the final earthworks and the application of the drainage parameters at the ridge level in the silty clay formation and the realization of the gutter at the level of the platform. At this stage, we arrive at the definitive situation of the nailing.

Fig. 9 Final earthworks and drainage system (Phase 4)

The simulations carried out in the framework of the slope stability study in the section of the twinning, between KP 105+938 and KP 106+263, validate a reinforcement by nailing and show a good stabilization of the slope during the construction period and in the long term. Moreover, we also proceeded to the nailed slope's stability calculation, taking into account the seismic action (ascending and descending earthquake). Table II presents a summary of the safety coefficient sought for the stability of the slope at each phase and the minimum coefficient calculated at each stage of the nailing operation. These results have been verified by a technical engineering Office and validated by a Control Office. In addition to the reinforcement and stability of the slope, the nailed wall also has the advantage of protecting the marl-limestone slope from external effects. It thus allows this formation to keep its intrinsic shear parameters for as long as possible.

TABLE II
SUMMARY RESULTS OF THE CALCULATION OF THE SAFETY FACTOR

Phase	SF sought	SF minimal	Maximum traction in nails (kN/m)
1	1,3	2,28	20,80
2	1,3	3,14	16,44
3	1,3	2,23	25,75
4	1,3	1,77	33,70
Long term	1,3	1,80	29,75
Ascending earthquake	1,0	1,51	49,20
Descending earthquake	1,0	1,69	74,00

B. Implementation of the nailing technique

The technique of nailed walls is a process of stabilization of natural grounds in situ. It consists in reinforcing a ground in excavation by the installation of passive bars slightly inclined compared to the horizontal. The survey carried out on nailed retaining structures allows, from the examination of the main characteristics of these structures, to deduce some general rules of design and pre-sizing. It proves that the length of the bars is determined according to the height of the structure. For a vertical facing structure, the average length of the nails is about 0.8 to 1.4 H (H total height of the structure) for nails made by drilling [31]. In our study, the average height of the structure is 5.32 m, which allows us to ensure strength by using rows of nails 4.00 m long and 32 mm in diameter. These nails are arranged in a rectangular mesh, with a vertical spacing of 1.5 m and a horizontal spacing of 2 m. The installation of these nails is carried out by sealing a reinforcement in a 110 mm diameter borehole by means of a cement grout. The nailing is generally done in successive phases as the earth is excavated. This operation of the support is executed generally with the advance of the earthworks by descending and this to ensure the stability and to avoid any disturbance during work. At the end, a protective facing inclined at 1H/5V is placed, generally consisting of a welded mesh and shotcrete 20 cm thick. Figure 10 shows the properties and characteristics of the elements of the nailing solution carried out in the section of the road and rail infrastructure twinning between PK 105 + 938 and PK 106 + 263. Table III shows some significant figures regarding the nailing operation in this section.

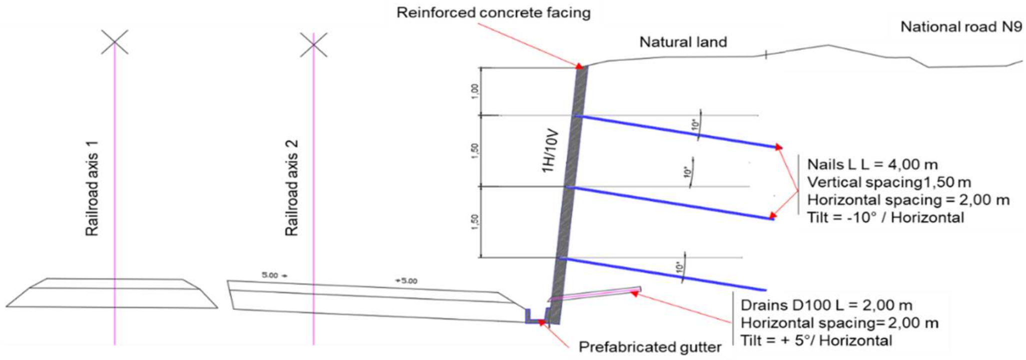

Fig. 10 Characteristics of the nailing technique

TABLE III
SOME SIGNIFICANT FIGURES OF THE NAILING OPERATION

Designations	Properties
Length of nailed section	340, 00 m
Average height of the slope	3,52 m
Surface of the nailed facing	1198 m2
Number of nails	400 unit
Length of nails	4,00 m

After the analysis and verification of the stability and reinforcement of the nailed slope in our study section, we found that the nailing and the establishment of the new track were carried out safely and in the right conditions. The work was completed within all the parameters and requirements of the study. Figure 11 illustrates the twinning area after the nailing and track realization. During the execution of the project, it was necessary to apply an effective internal drainage complex of the soil-face interface made by means of sub horizontal drains (inclined 5 degrees from the horizontal) and 100 mm in diameter. The length of these drains is 2 m with a horizontal spacing of 2 m.

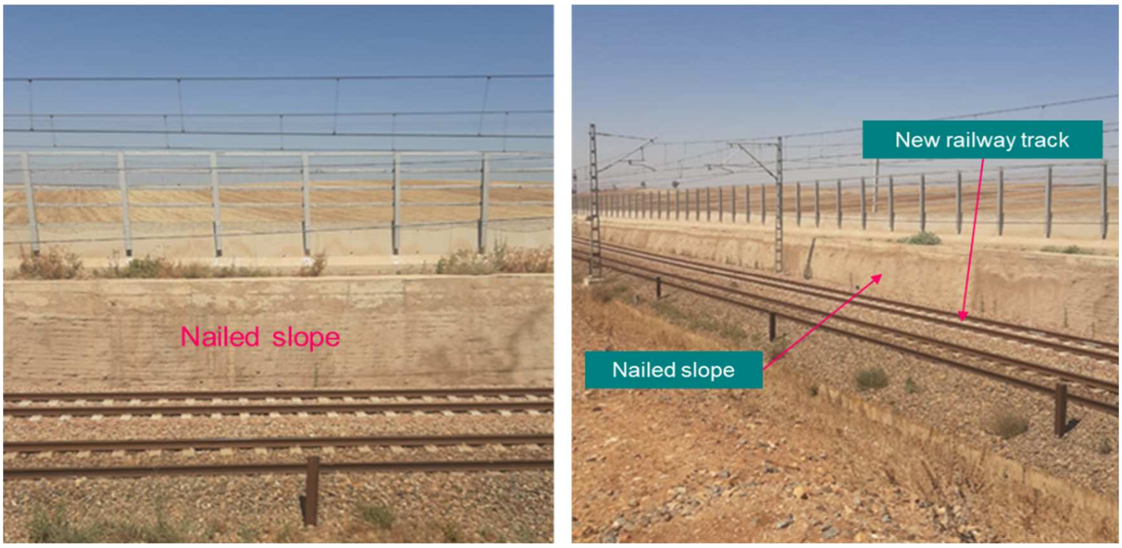

Fig. 11 Nailed slope and new railway track

IV. CONCLUSION

In-place soil reinforcement by the nailing method is widely used to stabilize slopes. The purpose of the study presented in this article was to analyze the stability and performance of a nailed embankment in a section of the road and rail infrastructures twinning. The simulations carried out within the framework of this study made it possible to highlight the effectiveness of the technique of nailing in this section. This arrangement has the advantage of being able to widen the right-of-way on the cutback side while maintaining traffic on the N9. The nailed walls in the twinning section, between KP 105+938 and KP 106+263, also have the advantage of protecting the marl-limestone slope from external effects and thus allowing this formation to retain its intrinsic shear parameters for as long as possible. Several parameters can be involved in the behavior of a soil reinforced by nailing, namely the geometry of the site, the length and inclination of the nails and the nature of the soil. Generally, the implementation of nailed walls is performed in several successive stages as the work progresses. In-situ soil support by the nailing technique has several advantages, notably the speed of execution, the reduced and light equipment for construction and the very competitive cost compared to other reinforcement solutions.

NOMENCLATURE

KP	Kilometer point
Φ	Internal friction angle
γ	Volume weight
c	Cohesion
SF	Safety factor
Tmax	Maximum shear stress
Tm	Mobilized shear stress

REFERENCES

[1] B. R. Srinivasa Murthy, G. L. Sivakumar Babu, and A. Srinivas, "Analysis of prototype soil-nailed retaining wall," *Gr. Improv.*, vol. 6, no. 3, pp. 129–136, 2002, doi: 10.1680/grim.6.3.129.39049.

[2] L. Wang, G. Zhang, and J. M. Zhang, "Nail reinforcement mechanism of cohesive soil slopes under earthquake conditions," *Soils Found.*, vol. 50, no. 4, pp. 459–469, 2010, doi: 10.3208/sandf.50.459.

[3] X. Ye, S. Wang, Q. Wang, S. W. Sloan, and D. Sheng, "Numerical and experimental studies of the mechanical behaviour for compaction grouted soil nails in sandy soil," *Comput. Geotech.*, vol. 90, pp. 202–214, 2017, doi: 10.1016/j.compgeo.2017.06.011.

[4] A. Pak, J. Maleki, N. Aghakhani, and M. Yousefi, "Numerical investigation of stability of deep excavations supported by soil-nailing method," *Geomech. Geoengin.*, 2019, doi: 10.1080/17486025.2019.1680878.

[5] T. T. Bui, M. Bost, A. Limam, J. P. Rajot, and P. Robit, "Modular precast concrete facing for soil-nailed retaining walls: laboratory study and in situ validation," *Innov. Infrastruct. Solut.*, vol. 5, no. 1, 2020, doi: 10.1007/s41062-019-0250-z.

[6] Y. Kim, S. Lee, and S. Jeong, "The effect of pressure-grouted soil nails on the stability of weathered soil slopes," *Comput. Geotech.*, vol. 49, pp. 253–263, 2013, doi: 10.1016/j.compgeo.2012.12.003.

[7] M. W. Bo, M. Fabius, A. Arulrajah, and S. Horpibulsuk, "Environmentally Friendly Slope Stabilization Using a Soil Nail and Root System in Canada," in *Ground Improvement Case Histories: Chemical, Electrokinetic, Thermal and Bioengineering Methods*, 2015, pp. 629–654.

[8] M. Yazdandoust, "Experimental study on seismic response of soil-nailed walls with permanent facing," *Soil Dyn. Earthq. Eng.*, vol. 98, no. February, pp. 101–119, 2017, doi: 10.1016/j.soildyn.2017.04.009.

[9] S. Alsubal, I. S. H. Harahap, and N. Muhammad Babangida, "A Typical Design of Soil Nailing System for Stabilizing a Soil Slope: Case Study," *Indian J. Sci. Technol.*, vol. 10, no. 4, 2017, doi: 10.17485/ijst/2017/v10i4/110891.

[10] N. Kotake and E. Sato, "Bearing capacity of a flexible plastic plate for soil nailing," *Int. J. Phys. Model. Geotech.*, vol. 21, no. 1, 2021, doi: 10.1680/jphmg.18.00102.

[11] W. R. Azzam and A. Basha, "Utilization of soil nailing technique to increase shear strength of cohesive soil and reduce settlement," *J. Rock Mech. Geotech. Eng.*, vol. 9, no. 6, pp. 1104–1111, 2017, doi: 10.1016/j.jrmge.2017.05.009.

[12] S. Hirschmüller, R. Marte, and A. Englberger, "Applicability of finger jointing to circular laminated veneer hollow sections for temporary soil nailing," *Eur. J. Wood Wood Prod.*, vol. 78, no. 5, 2020, doi: 10.1007/s00107-020-01577-y.

[13] A. Sharma and R. Ramkrishnan, "Parametric Optimization and Multi-regression Analysis for Soil Nailing Using Numerical Approaches," *Geotech. Geol. Eng.*, vol. 38, no. 4, 2020, doi: 10.1007/s10706-020-01230-8.

[14] I. E. Zevgolis and Z. A. Daffas, "System reliability assessment of soil nail walls," *Comput. Geotech.*, vol. 98, no. July, pp. 232–242, 2018, doi: 10.1016/j.compgeo.2017.10.020.

[15] S. Dewedree and S. N. Jusoh, "Slope stability analysis under different soil nailing parameters using the SLOPE/W software," in *Journal of Physics: Conference Series*, 2019, vol. 1174, no. 1, doi: 10.1088/1742-6596/1174/1/012008.

[16] J. de Sauvage, M. Blanc, T. Dubreucq, and J. P. Rajot, "Centrifuge modelling of a soil-nailed wall," *17th Eur. Conf. Soil Mech. Geotech. Eng. ECSMGE 2019 - Proc.*, vol. 2019-Septe, 2019, doi: 10.32075/17ECSMGE-2019-0323.

[17] W. Han, G. Li, Z. Sun, H. Luan, C. Liu, and X. Wu, "Numerical investigation of a foundation pit supported by a composite soil nailing structure," *Symmetry (Basel).*, vol. 12, no. 2, 2020, doi: 10.3390/sym12020252.

[18] M. Ben Ouakkass, L. Ouadif, A. Akhssas, and L. Bahi, "Etude de la dégradation de la géométrie de la voie ferrée entre les PK80 et 105 au niveau du plateau de Settat (Maroc)," in *MATEC Web of Conferences*, 2018, vol. 149, pp. 1–8, doi: 10.1051/matecconf/201714902021.

[19] H. Tokhi, G. Ren, and J. Li, "Laboratory pullout resistance of a new screw soil nail in residual soil," *Can. Geotech. J.*, vol. 55, no. 5, pp. 609–619, 2018, doi: 10.1139/cgj-2017-0048.

[20] H. Y. Hu, Y. C. Zhang, and C. Y. Chen, "Discussion on the Displacement and Stability of the Soil Nailing," in *IOP Conference Series: Earth and Environmental Science*, 2020, vol. 510, no. 5, doi: 10.1088/1755-1315/510/5/052012.

[21] F. A. Villalobos and S. A. Villalobos, "Effect of nail spacing on the global stability of soil nailed walls using limit equilibrium and finite element methods," *Transp. Geotech.*, vol. 26, 2021, doi: doi.org/10.1016/j.trgeo.2020.100454.

[22] J. Garzón-Roca, V. Capa, F. J. Torrijo, and J. Company, "Designing Soil-Nailed Walls Using the Amherst Wall Considering Problematic Issues during Execution and Service Life," *Int. J. Geomech.*, vol. 19, no. 7, p. 05019006, 2019, doi: 10.1061/(asce)gm.1943-5622.0001453.

[23] M. Ben Ouakkass, L. Ouadif, L. Bahi, and A. Akhssas, "Predictive risk mapping related to the shrink-swell of clays under the railway track in the Settat plateau (Morocco)," *ARPN J. Eng. Appl. Sci.*, vol. 14, no. 13, pp. 1–10, 2019.

[24] D. A. Mangnejo, S. J. Oad, S. A. Kalhoro, S. Ahmed, F. H. Laghari, and Z. A. Siyal, "Numerical Analysis of Soil Slope Stabilization by Soil Nailing Technique," *Eng. Technol. Appl. Sci. Res.*, vol. 9, no. 4, 2019, doi: 10.48084/etasr.2859.

[25] M. Sharma, M. Samanta, and S. Sarkar, "Soil nailing: An effective slope stabilization technique," in *Advances in Natural and Technological Hazards Research*, vol. 50, 2019, pp. 173–199.

[26] T. Yang, J. F. Zou, and Q. J. Pan, "Three-dimensional seismic stability of slopes reinforced by soil nails," *Comput. Geotech.*, vol. 127, no. February, p. 103768, 2020, doi: 10.1016/j.compgeo.2020.103768.

[27] V. Nappa, R. Ventini, V. Ciotta, D. Asprone, F. De Silva, and S. Fabozzi, "A new frontier of BIM process: Geotechnical BIM," 2019, doi: 10.32075/17ECSMGE-2019-0682.

[28] M. H. Mohamed, M. Ahmed, J. Mallick, and P. V. Hoa, "An experimental study of a nailed soil slope: Effects of surcharge loading and nails characteristics," *Appl. Sci.*, vol. 11, no. 11, 2021, doi: 10.3390/app11114842.

[29] M. Sabermahani and H. Nuri, "Studying the effect of geometrical nail layout on the performance of soil-nailed walls: Physical and numerical modeling," *Acta Geodyn. Geomater.*, vol. 18, no. 1, 2021, doi: 10.13168/AGG.2021.0003.

[30] M. Alemyparvin, "Deformations Analysis and Finite Element Numerical Modeling of Soil' s Excavations Improved by Soil Nailing," vol. 16, no. December, pp. 395–401, 2020.

[31] J.-P. GIGAN, "Applications du clouage en soutènement–Paramètres de conception et de dimensionnement des ouvrages,". *Bulletin de Liaison des Laboratoires des Ponts et Chaussées. Vol 143.*, pp. 51–64, 1986.