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M. A. R. Morsli*[1]**,**
orcid.org/0000-0001-5242-986X,
S. Berdoudi[1]**,**
orcid.org/0000-0002-3612-6823,
A. Hafsaoui[2]**,**
orcid.org/0000-0002-1720-9527,
A. I. Kanli[3]**,**
orcid.org/0000-0001-5642-5866,
M. Ferfar[4]**,**
orcid.org/0000-0002-2028-5213

1 – LAVAMINE Laboratory,Mining Department, Faculty of Earth Sciences, Badji Mokhtar University, Annaba, Algeria
2 – Naturel ressources and planning Laboratory, University of Annaba, Annaba, Algeria
3 – Istanbul University-Cerrahpasa, Istanbul,Turkey
4 – Environmental Research Center (C.R.E), Annaba, Algeria
* Corresponding author e-mail: abdelraoufmorsli@gmail.com

ANALYSIS AND PREDICTION OF SURFACE SETTLEMENTS DURING THE DIGGING OF UNDERGROUND MINING WORKS (ALGERIA)

Purpose. To analyze, study and predict surface settlements during the digging of a tunnel in an urban area located in the Algerian capital and to take the necessary measures.

Methodology. Based on the physical and mechanical parameters and the geological characteristics of the actual traversed layer, and taking into account the geometric parameters of the tunnel, the mechanical model is established, and the numerical simulation is designed to determine the settlement deformation and displacement of the overlying zone under mining disturbance.

Findings. Due to the impact of the excavation works, the land will undergo large deformations such as collapse. So, it is necessary to take corrective measures to limit its effect on the surrounding environment and protect urban areas.

Originality. The application of a complex of methods allowed providing a predictive assessment of the safety of mining workings in urban conditions. The study was conducted in two main stages; a geotechnical characterization in situ and in the laboratory to determine the necessary properties of the soil and rock mass used in our model, and in a second step, the development of feedback analysis using numerical modelling based on the data collected.

Practical value. From this study, the results obtained seem to show vertical displacements that exceed international standards in urban areas (1/1000, which can induce significant ground movements and therefore an influence on the surrounding environment. As a solution, there is a possibility of reducing the deformations by improving the mechanical properties of the soil carrying the project using the Jet-Grouting technique – the technique has shown its effectiveness in reducing settlements with a reduction rate of 78 %.

Keywords: *ground movement, underground structure, finite element method, stability modelling, geotechnical parameters*

Introduction. For many infrastructure projects, uncertainties regarding subterranean soil and rock conditions contribute significantly to the overall technical and financial risks of the project. In this sense, the construction of underground structures poses the problem of stability during the work, particularly at the face [1], and the type of support to be implemented to guarantee deformations at the level of the tunnel walls.

Underground works may lead to ground subsidence. They may induce important loading of structures which may be damaged, which can go so far as to jeopardize the stability of the excavation carried out [2], or to cause intolerable disorders in the ground and the environment of the work itself.

In order to make an assessment of the effects induced in the terrain by the construction of the underground structures, an analysis is proposed to ensure the stability of the structure and control the deformations of the massif taking into consideration the characteristics of the terrain crossed by the structure (geological and geotechnics) and the characteristics of the structure itself (geometric and geotechnical).

Numerical methods have experienced a very significant development in geotechnical research, their use is very common today and the design of large projects necessarily involves analyses of this type in order to verify the stability of structures in interaction with their environment; new methods of numerical calculation of tunnels have completely replaced the old methods. These powerful tools make it possible to control the displacements and the constraints so that they are acceptable and to help with the dimensioning of the works.

According to Alkhdour (2020), the numerical approach based on finite elements offers a much more effective solution and allows one [3], among other things, to calculate the field of displacements and stresses in the massif by allowing the simulation of the excavation phases and taking into account elaborate soil behavior laws and complex boundary conditions.

The object of our research is to highlight the impact of geotechnical parameters on the modeling during the digging of a tunnel in a mine form, located in the Algerian capital. This study is of great importance, as it will allow a better understanding of the specific geotechnical behaviors of the region and the development of more precise and efficient excavation models.

Based on this objective, a calculation code was chosen (Geo5). The code works with finite elements; it is specially designed to solve the problems of deformations during works in underground mode.

Materials and Methods. ***General characteristics of the studied area.*** Our study area is located in the city of Algiers (Algeria). It is about the realization of a tunnel of 430 meters (Fig. 1). It passes under the infrastructures of a very important urban life, this tunnel is characterized by a diameter of 9.82 m and a radius of 4.9 m.

Geotechnical characterization of the studied area. The identification of all geotechnical parameters was carried out by conducting in-situ and laboratory tests, with borehole depths ranging from 40 to 60 meters.

For an in-depth study, Douib (2023) and Khan (2022) show that the establishment of these tests is very necessary before any construction on the surface [4, 5] or in depth. During the execution phase of the project, several surveys (coring and pressuremeter survey) and the SPT test were carried out in order to specify the nature of the land crossed and consequently determine all the geotechnical parameters of the site studied.

Prospecting work shows the presence of the following lithological complex:

Fig. 1. Project location

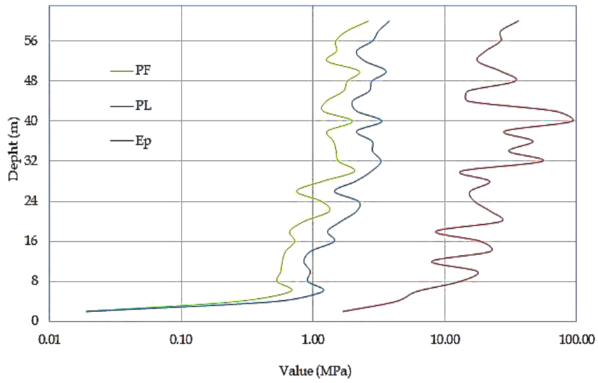

Fig. 3. Variation of creep pressure (PF), limit pressure (PL) and strain modulus (Ep) as a function of depth

- an alluvial bedrock that appears in boreholes at 60 m depth;

- gray marls firm clay sometimes sandy in places, the thickness of this formation varies from 10 to 20 m. Fig. 2 gives an overview of the different layers crossed by the tunnel.

Characterization and classification. The characterization of the soil for the site in question requires the determination of several parameters. That is why in situ tests of static loading of the ground were made to characterize the behavior and the mechanical characteristics and the plastic state of the soil on the basis of three parameters: the pressuremeter modulus of deformation, the creep pressure and the limit pressure.

Using the samples from the core drilling, we carried out laboratory tests to determine the geotechnical characteristics of each of the units detected and thus have a geotechnical profile all along the route.

In-situ tests. The pressuremeter tests require the realization of several surveys, of which the Menard pressuremeter survey is the most consequent test [6] of all the geotechnical tests in situ.

Fig. 3 shows the test results for the different parameters of the ground crossed by the tunnel.

In the context of our study, from the analysis of curve in Fig. 3, substantial fluctuations in the limit pressure (*PL*) were observed, ranging from 0.02 to 4.00 MPa, with an observed average value of 2.00 MPa. Simultaneously, the pressuremeter modulus (*Ep*) exhibited considerable variations, ranging from 1.80 to 95.00 MPa, and with an average value of 25.00 MPa.

It is worth noting that a significant correlation can be established between the undrained shear strength and the cohesive properties of the clay. In accordance with the findings of various studies [7], when the ultimate pressure reaches 2.00 MPa, in conjunction with a horizontal stress σ_h of 0.15 MPa, an undrained cohesion of approximately 160 kPa becomes relevant.

A notable aspect is the increase in the ultimate pressure with respect to the pressuremeter modulus as the depth increases. This trend suggests a more responsive reaction of the ultimate pressure to the specific geotechnical conditions encountered at greater depths.

Regarding the creep pressure (*PF*), an average value of 1.10 MPa was determined, which is highly representative of our case study.

These results highlight the remarkable diversity of the mechanical characteristics of the studied soil, characterized by significant fluctuations in both ultimate pressure and pressuremeter modulus. Furthermore, they underscore the imperative need to consider depth and specific geotechnical stresses in order to thoroughly understand the behavior of this clay.

Standard Penetration Tests. Standard penetration test (SPT) is mainly used to determine the strength and deformation parameters of soils [8].

In-situ analysis and the values of S.P.T. (N30 value) provide valuable information on the degree of consistency of the materials studied, although the limitations of SPT penetration testing in cohesive materials should be noted. N30 values vary between 4 and 60, with an average value of 15, which allows us to generally evaluate the consistency of these materials. Overall, the consistency of the materials ranges from stiff to hard, with an average state of very stiff consistency. These indications help us to better understand the mechanical characteristics of the materials studied.

Concerning the strength parameters in drained conditions, the following values can be adopted: an angle of internal friction Φ′ of 30° and a cohesion *c*′ of 43 kPa. However, the variability of the data as well as the specific characteristics of the material must be taken into account.

Regarding the drained strain modulus, a representative value of 38 MPa is adopted, taking into account both the variability of the data and the intrinsic characteristics of the material.

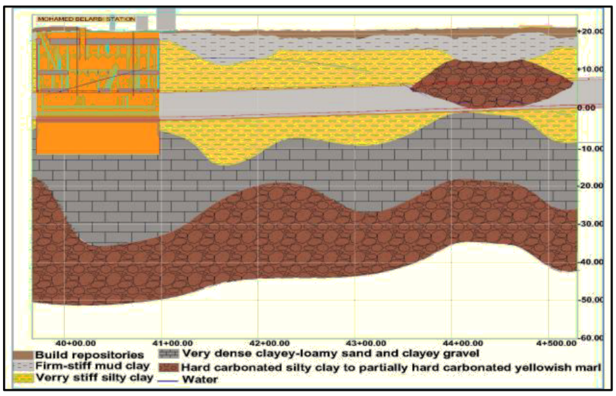

Fig. 2. The different geotechnical units crossed by the tunnel

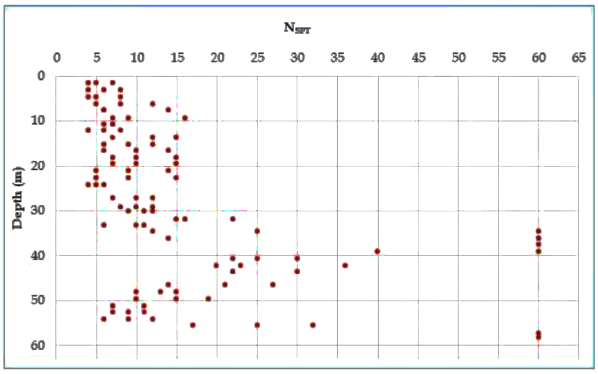

Fig. 4. Penetration test results (N_{spt}) as a function of depth from the ground surface

In addition, the analysis of the grain size characteristics of the material reveals a very low permeability, which makes it possible to consider these materials as practically impermeable. The average permeability value is established at $k = 3.9.10^{-7}$ m/s.

This information provides a better understanding of the geotechnical properties of the materials studied, including their consistency, strength, deformation, and permeability. It is essential to take these parameters into account for an accurate evaluation of the geotechnical behaviour of these materials for our study.

Laboratory tests. Laboratory tests were started once the in-situ reconnaissance had been carried out to determine the soil condition (particle size, Atterberg limits, humidity, density, aggressiveness, etc.).

Classification and characteristics:

1. The particle size analysis reveals that the material studied is mainly composed of particles with a diameter of less than 2 mm, representing approximately 92 % of the particle size fraction. Moreover, about 89 % of the particles have a diameter less than 0.08 mm. These results indicate a fine grain size and a predominance of small particles.

2. Regarding the Atterberg limits, the liquidity limit has an average value of 40 %. This indicates the water content from which the material changes from a plastic state to a semi-solid state. In addition, the plasticity index shows an average value of 22 %, which reflects the ability of the material to change shape without breaking when subjected to stress.

3. The dry density, ρ_d, is measured at 19.5 kN/m^3, as for the natural water content, W_n, it is established at 16 %.

By agreeing with the empirical correlations and studies proposed for the determination of soil properties on the basis of standard penetration test values and the pressuremeter test [9, 10] and their comparison with those obtained in the laboratory to characterize the geotechnical units, the materials crossed by the tunnel are clayey silts, slightly marly to marly taking into account the USCS system (Unified Soil Classification System).

The reconnaissance campaigns and various tests have highlighted the homogeneity of the terrain crossed by the structure at point PK 4+155 (the area studied). Table 1 summarizes the main calculation parameters resulting from the analysis and interpretation of the field data and the laboratory data for the two reconnaissance boreholes.

Analysis methods. The choice of the construction method to be used in a tunnel must be conditioned, first, by the geometric characteristics of the tunnel [11], the geotechnics of the terrain and by the construction limits with regard to the execution of the tunnel in an urban area.

Many factors affect the excavation process such as tunnel geometry, regional geology, structural geology and properties of the surrounding materials with its geotechnical characteristics. To facilitate the distribution of the tensions in the ring of ground which surrounds the tunnel, one defines the sections type of retaining with rounded forms in vaults, by avoiding the angular points.

In our case, the tunnel is made using the NATM method (New Austrian Tunneling Method), it is an excavation by half-sections, it promotes stability [12].

The support will be placed so that it allows the ground to deform, always within the stability limit of the tunnel, so that the ground develops its self-supporting capacity [13].

In the resolution of the numerical models for the design of the standard sections, a calculation was carried out using the mode of Mohr-Coulomb behavior. The simulation was performed under drained conditions for clay materials. The presence of the water table in the calculations is taken into account because the system adopted for the drainage of the tunnel allows the ground to be drained during the excavation, so that the hydrostatic pressures are generated on the support.

Numerical Study. Finite element method (FEM) was employed in this work, using Geo5 software. Modeling allows us to analyze the effects of specific geotechnical parameters on the behavior of underground structures. This allows us to obtain more accurate predictions of strains, stresses, and stability degree. Noting that the program includes the analysis of the rock slope stability and the settlement of surfaces due to the construction of tunnels.

All parameters necessary for the application of the model are presented in Table 1. Before starting the work, it is essential to be able to have a zero state of the movements of the proximity of the underground structure to be built; this state completes the preliminary investigations on the building and its previous movements. In the case of buildings of mediocre

Table 1

Test results in-situ and in the laboratory of the geotechnical unit crossed by the project

Geological-geotechnical unit	Build repositories	Firm-Stiff Mud Clay	Very stiff silty clay	Very dense clayey-loamy sand and clayey gravel	Hard carbonated silty clay to partially hard carbonated yellowish marl
SPT number of blows (penetration of 30 cm) N_{30}	–	13	22	82	29
Particle size < 0.08 mm (%)	45	89	91	24	94
Density γ_h (KN/m^3)	19	20.8	21.5	20.9	20.8
Liquid limit *LL* (%)	–	56	44	water table	41
Plasticity index *IP* (%)	–	27	21	water table	18
Undrained cohesion Cu (KPa)	–	80	150	–	175
Cohesion C' (KPa)	5	30	40	10	50
Angle of internal friction φ(°)	28	25	25	35	27
deformation modulus E' (MPa)	6	15	20	50	35
Poisson ratio n'	0.3	0.3	0.3	0.3	0.3
Recharge/unload deformation module *Eur* (MPa)	12–24	30–45	40–60	100–150	70–105
Pressuremeter modulus E_p (MPa)	–	15	20	40	30
Limit pressure *Pl* (MPa)	–	0.71	1.4	2.8	2.48
Creep pressure *Pf* (MPa)	–	0.4	0.8	1.62	1.45
Permeability *K* (m/s)	–	10	10	10	10

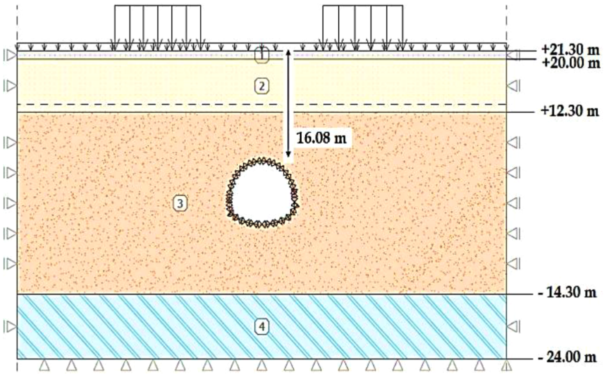

Fig. 5. Structure layout

quality and/or foundations of low bearing capacity, it allows one to know the possible evolutions of the building under its own weight without any influence of future works. Fig. 6 shows the stress distribution in the initial state and after digging along the two axes *x* and *y*.

According to Fig. 6, the stresses around the structure immediately after the excavation seem well distributed; according to Md Shariful Islam [14] and Kuanda Fang [15] whatever the construction technique used to build an underground structure, displacements around the excavation occur and propagate in the rock mass and can reach the surface.

Results and discussion. Results of the modeling of the transverse and longitudinal settlements resulting from the numerical calculation according to the *x* and *z* profiles are presented in graphic form (Fig. 7).

Fig. 7 shows remarkable deformations at the right foot and the tunnel key along the two axis *X* and *Z* respectively. The evaluation of the deformations and the stress states of the adjacent medium of the tunnel make it possible to control the settlements [16]. These displacements, depending on their amplitude, extension, direction, and speed of propagation, can cause disorders in the building located in the environment

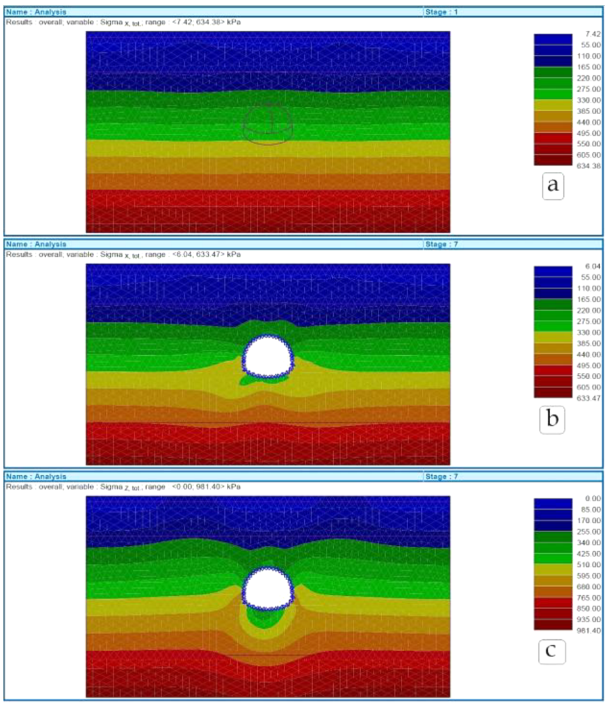

Fig. 6. Stress distribution:

a — the initial state; b — after excavation along axis X; c — after excavation along axis Y

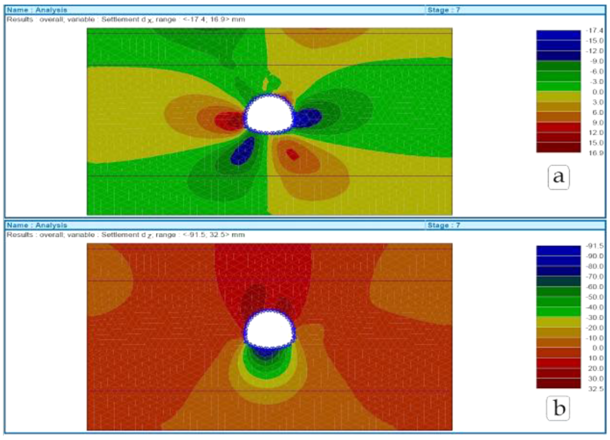

Fig. 7. The displacements recorded:

a — along the axis x; b — along the axis y

of the structure. Fig. 8 shows the surface settlements around the reconnaissance borehole.

According to Fig. 8, a maximum settlement of the value of 20 mm located at a depth of 16 m, i.e. below the excavation zone and this during the excavation phase. According to the recommendations of AFTES (1995); the surface deformations tolerated for underground structures [17] in urban sites do not exceed 1/1000 (0.1 %) of deformation as a limit, i.e. 16 mm for our case study. On the other hand, the settlement was reduced to 4.4 and 16 mm for stages 6 and 7, i. e., a reduction rate of 78 and 20 % for the two stages respectively.

Limitation of settlements and support. The limitation of surface settlements can be ensured by applying the recommendations of AFTES (1995). To minimize settlements, we are more interested in improving the behavior of the soil carrying the project. Protection using umbrella arch with Jet-Grouting column is a technology provided an improvement in the mechanical properties of the treated ground occurs, by the injection of a fluid, generally cement slurry, at high pressure, breaking the structure of the ground and forming columns of soil-cement. Depending on the grain size of the natural terrain, the column may look like mortar or concrete.

Fig. 9 shows the Jet-Grouting technique used for the different materials according to their grain sizes.

This technique can be used for the stabilization and sealing of all types of soils and various sediments to clay [18], as it also applies to non-homogeneous soil formations.

The support will be carried out by the projection of a sealing layer with concrete covering the excavated surface (30 cm thick) and the installation of metal hangers. Jet-Grouting umbrellas and columns have been modelled using Geo5 for the improvement of geotechnical parameters in the perimeter of the excavation (with a thickness of 0.60 m) and in the working face of the excavation in elements of the model equivalent to the 0.60 m diameter jet-Grouting columns that will be executed during the works.

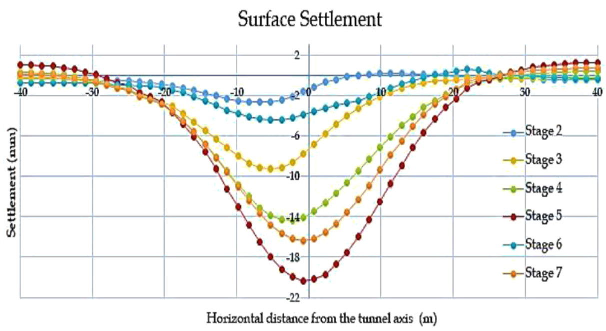

Fig. 8. Settlement basin for the different stages

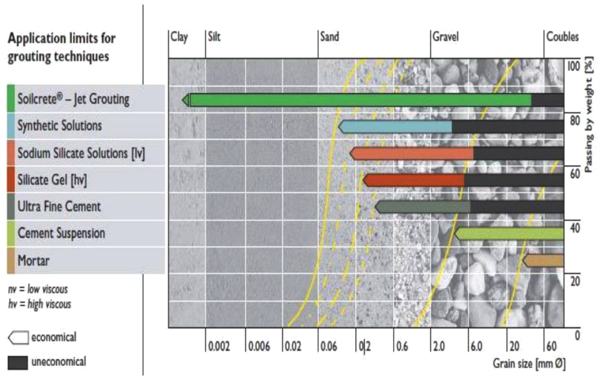

Fig. 9. Procedure of the Jet-Grouting technique (Keller, 2019)

B/Right and left side-wall

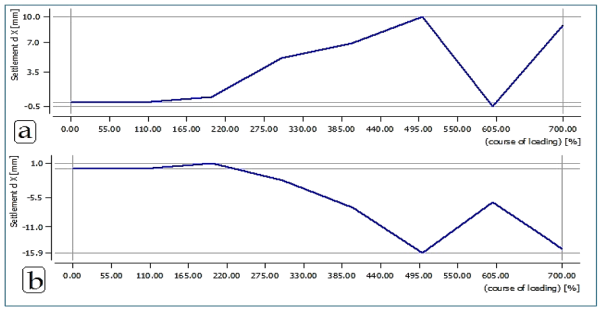

Fig. 11. The settlements recorded according to the loads applied: a – on the right side wall; b – left side-wall

The numerical model used makes it possible to obtain the field of displacements and stresses at any point of the mass around the excavation and to deal with a wide range of problems which are difficult or even impossible to solve with other methods. The undeniable advantage of numerical methods is to address analytically insoluble theoretical problems by replacing them with an approximate numerical solution [19]. 2D simulations are more adequate and give more precision than 3D in the determination of the deformations around a tunnel in view of their simplicity of calculation [20].

For the resolution of the numerical models, a series of steps were followed that simulate the phases followed in the excavation and the support of the tunnel. With the help of this program, it is possible to evaluate the stresses on the elements of support and even the deformations in the walls for each of the excavation phases with the installation of monitoring points, in particular at the key, slab and the two side walls.

Results of loading tests. When the surfacing has been carried out, a new equilibrium of the surrounding ground will tend to be established, generally corresponding to a certain progressive re-compression of the ground. The results of the settlements recorded at the key, slab, right side-wall and left side-wall of the tunnel are shown in Figs. 10 and 11 respectively.

We also traced the evolution of the horizontal displacements in the transverse direction in the right foot (*a* and *b*) in order to compare them with the results of the modeling (Fig. 7). First of all, we notice a slight difference between the horizontal displacements obtained. Indeed, they are weaker.

From Figs. 10 and 11 and in accordance with AFTES recommendations (French Association of Tunnels and Underground Space), the results obtained are within the range of acceptable settlements in urban areas, the greatest value of which was noted at right foot A with 15.9 mm of settlement,

A/At the slab and the Tunnel key

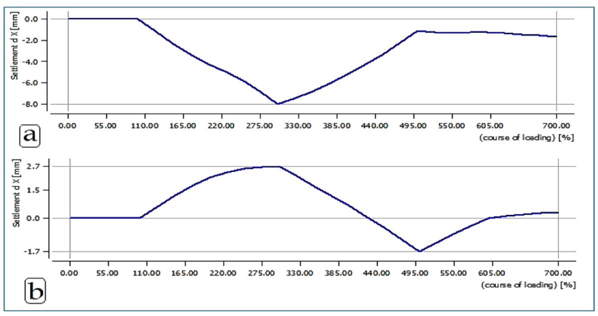

Fig. 10. The settlements recorded according to the loads applied: a – on the tunnel key; b – at the slab

whereas our work is at a depth of 16 m, i.e., 16 mm of tolerance.

Conclusion. In this study the prediction of the maximum settlement is made by a numerical approach in order to have a reliable and effective estimate of a real phenomenon by ensuring the stability of the constructions on the surface and in depth, the results obtained illustrate an acceptable and reliable accuracy of the model used.

From this study, we can therefore draw the following:

1. The section studied was carried out in homogeneous but very difficult terrain. The movements generated by the excavation of the structure are linked to a complex phenomenon which depends on the nature of the soil, the excavation methods, and the geometry of the work to be done.

2. The digging work has caused a change in the balance of stresses in the environment. Although the structure is dug at a shallow depth, the deformations produced are reflected to the surface.

3. The results obtained in terms of stresses in the ground are very sensitive to the isotropy of the ground crossed by the tunnel.

4. The study showed that it is possible to minimize settlement based on the monitoring of deformations by improving the behavior of the soil carrying the project, thus using the Jet-Grouting technique.

5. The load tests carried out show a reduction in the deformations recorded by the digital model, thus respecting international standards when digging underground structures.

6. Finally, this work has improved the understanding of the effects of improving the behavior of the soil carrying the project on the phenomenon of surface settlements and on the relative forecasting methods. This result was possible thanks to the numerical approach used.

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Аналіз і прогнозування поверхневих просідань під час проходки підземних гірничих виробок (Алжир)

М. А. Р. Морслі[*1], *С. Бердуді*[1], *А. Хафсауі*[2], *А. І. Канлі*[3], *М. Ферфар*[4]

1 – Лабораторія LAVAMINE, Департамент гірничої справи, Факультет наук про Землю, університет Баджі Мохтара, м. Аннаба, Алжир
2 – Лабораторія природних ресурсів і планування, Університет Аннаби, м. Аннаба, Алжир
3 – Стамбульський університет-Черрахпаша, м. Стамбул, Туреччина
4 – Центр екологічних досліджень (C.R.E), м. Аннаба, Алжир
[*] Автор-кореспондент e-mail: abdelraoufmorsli@gmail.com

Мета. Аналіз, вивчення та прогнозування поверхневих просідань під час виконання проєкту із проходки підземної міської зони, розташованої у столиці Алжиру, та застосування необхідних заходів.

Методика. На основі фізико-механічних параметрів і геологічних характеристик фактично пройденого шару, ураховуючи геометричні параметри тунелю, створена механічна модель і проведене чисельне моделювання визначення деформацій просідання та зміщення надземної зони в умовах гірничих виробок.

Результати. Унаслідок впливу розкривних робіт земля зазнає значних деформацій, таких як обвали. Тому необхідно вжити коригуючих заходів для обмеження їх впливу на навколишнє середовище й захистити міські території.

Наукова новизна. Застосування комплексу методів дозволило дати прогнозну оцінку безпеки проходження гірничих виробок у міських умовах. Дослідження проводилося в два основні етапи: геотехнічна характеристика на дільниці та в лабораторії для визначення необхідних властивостей ґрунту й гірничих порід, що використовуються в нашій моделі, а на другому етапі – розробка аналізу зворотного зв'язку з використанням чисельного моделювання на основі отриманих даних.

Практична значимість. Із цього дослідження видно, що отримані результати показують вертикальні зміщення, які перевищують міжнародні стандарти в міських умовах (на 1/1,000), що може спричинити значні зсуви ґрунту і, отже, вплив на навколишнє середовище. Як рішення, існує можливість зменшення деформацій шляхом покращення механічних властивостей ґрунту, на якому виконується проєкт, за допомогою методу струменевого цементування – цей метод показав свою ефективність у зменшенні просідань зі швидкістю зменшення на 78 %.

Ключові слова: *зрушення ґрунту, підземна споруда, МКЕ, моделювання стійкості, геотехнічні параметри*

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