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MAXIMUM SURFACE SETTLEMENT INDUCED BY SHALLOW TUNNELING IN LAYERED GROUND

Purpose. To improve the prediction of maximum surface settlement induced by tunneling in multi-layered soils. At the design stage, geotechnical experts tend to use simplified formulas for evaluating the ground response.

Methodology. To examine the accuracy of empirical equations in predicting maximum surface displacement, two widely adopted formulas are considered for the current study: "*Volume Loss"* and *"Farmer and Attewell"*. Moreover, because both equations are *"inflection ratio"* dependants, all existing expressions of the inflection parameter are taken in consideration. Finally, the obtained results are compared with field measurements, and the best pair of the expressions (*"MSS"* and *"inflection ratio"*) is chosen.

Findings. Prediction of the maximum surface settlement due to shallow tunneling in soft grounds is a valuable indicator in ensuring safe operations, particularly in urban areas. The current paper clarifies the advantage of the *VL method over Farmer and Attewell* for all scenarios (variable overburden); high values of the *VL* improve the predictions significantly when it is combined with Dindarloo formulation of inflection ratio.

Originality. The originality of this work is the examination of the most adopted empirical methods and all inflection point formulas, to estimate the maximum surface settlement induced by the construction of 'Algiers Subway System' tunnel project; also, the paper demonstrated the weakness of some mostly used approaches through practical measurements.

Practical value. Because of the lack of data in geotechnical engineering, this paper is a rich resource for tunneling projects in future because it covers over sixty measurement transverse profiles, and suggests numerical values for better assessment.

Keywords: *Algiers Subway, maximum surface settlement, layered soils, tunneling, SCL method, NATM method, volume loss*

Introduction. "Algiers Subway" is a relatively new subway system in Algiers (the capital of Algeria) in respond to growing demand for public transport.

Such tunnels are generally built in shallow depth in order to reduce the costs. Tunneling projects lead inevitably to ground movements which appear in most cases as surface settlement and consequently may affect overlying buildings and services. For that, it is peremptory to estimate the magnitude of these displacements at the early stages of tunnels design in order to define the potentially affected structures.

For predicting ground movement extent at the preliminary design stage, analytical and empirical relations are considered more suitable for their simplicity [1]. In analytical methods (closed-form solutions), two widely used approaches exist. One of the earliest attempts for initially isotropic and homogeneous incompressible soil is to estimate the strain field. After that, Verruijt and Booker [2], generalized the above solution to include tunnels in homogeneous elastic half spaces arbitrary values of Poisson's ratio and the effect of tunnel lining deformation in the long term.

Those solutions are derived from empirical relations and are applicable only for few cases, because similar conditions to original models are not usually fulfilled, and are not widely adopted for their over-simplification approach. Moreover, the "Algiers Subway" project passes through multi-layered soil with heterogeneous characteristics.

For those gained from empiricism, the literature is rich and they represent the first tries to predict ground movement and results obtained generally from practice (field observation) or in laboratory tests (physical modelling, centrifuge tests).

The most realistic approximation of surface settlement is given by *Peck* [3] who stated that the transverse settlement trough can be described by a Gaussian error function, and this relation has been confirmed and adopted by many authors since then. The form and the width of this mathematical function is governed by the distance from the tunnel centerline to the inflexion point of settlement trough known as *"i parameter"*, *"trough width parameter"* or *"inflection ratio"* [3]. Yet those methods are not suitable for predicting maximum surface settlement "MSS", but only the shape of surface settlement.

At the definitive design stage, the numerical calculation as bi-dimensional (2D) and three-dimensional (3D) is more adequate but harder to use due to a large number of parameters needed in order to perform the computation and requires excessive computational resources. Even with the recent advances in numerical modelling, a wider and shallower than measured settlement trough is still reported by Maji and Adugna (2016) [4], Kwong, et al. (2019) [5].

Site characterization. Two segments are adopted for the analysis: A section from Hai El-Badr to Ain Naadja line and

Table 1

The Characteristic values of ground layers

	Description	Unit weight, kN/m^3	Young modulus, MN/m^2	Poisson ratio	Cohesion, kN/m^2	Friction angle (degrees)	Plasticity index, (%)
EM	Embankment and recent deposits	19.0	15	0.17	5	28.0	27.00
CS	Silty-sandy clays	20.6	30	0.30	30	30.0	16.42
SC	Silty clayey sand	21.0	50	0.23	10	32.5	17.00
CM	Clayey friable marl and slightly sandy	20.7	45	0.32	35	25.1	20.48
SCS	Silty clayey sands	21.0	60	0.25	50	27.5	11.23
GSC	Gravelly and sandy clays	22.0	100	0.35	15	32.5	19.48

another section from Ain Naadja to Barraki line of "Algiers Subway" subway system with a total of 65 MSS measuring profiles. The geotechnical site investigation indicates six (06) main soil layers characterized and summarized in Table 1.

Based on geotechnical parameters, Sprayed Concrete Lining (SCL) is adopted as an excavation method respecting the sequencing order and geometry shown in Fig. 1. Prior to excavation, an umbrella of steel pipes is installed with a 6 dip in a truncated conic shape made on the crown of the tunnel. The umbrella length is 12 m of which excavation is carried on under 9 m. Truncated cone shape allows the 3m overlapping of two adjacent umbrellas.

From a construction view point, the NATM tunneling method is differentiated by:

1. The tunnel is sequentially excavated and supported in every slice, and the excavation sequences can be varied according to geological conditions.
2. The ground pre-support is provided by an umbrella of metallic tubes or forepolling.
3. The initial support is assured by shotcrete in combination with fiber or welded-wire fabric reinforcement, steel arches and sometimes ground reinforcement.
4. The permanent support is usually a cast in place lining.

Settlement analysis using empirical approach. Predicting tunnel induced settlement and assessing the risk of damage is an essential part of planning, design and construction of tunnels in an urban environment.

Vu, et al. (2016) [6] summarized the main causes of surface movements of soil due to tunneling into:

1. Change in stress state: The stress relief mechanism causes a reduction in soil weight concomitant to an upward movement of soil.

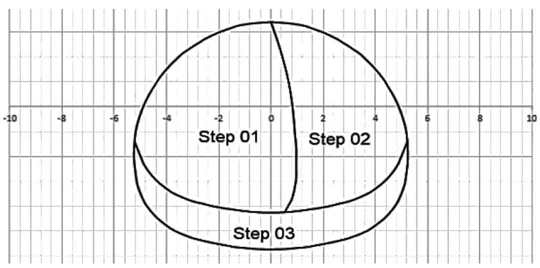

Fig. 1. Transverse cross-section and tunneling order adopted for "Algiers Subway"

2. Subsidence due to the removal of natural support during excavation: this causes a downward movement due to the lack of support after the excavation.

The three primary design criteria of underground tunnels from a geotechnical perspective are stability during construction, long and short-term settlement, and determination of lining structural loading [7].

In transverse direction, Martos and Peck [3] described the surface settlement trough as an error function (1), and since then it has been widely accepted.

$$Sv(x) = MSS\,exp\,(-x^2/2i^2). \tag{1}$$

Where Sv is the vertical settlement at a horizontal distance $\boldsymbol{x}$ from the tunnel centerline, ***MSS*** denotes the maximum settlement that is at the tunnel centerline and $\boldsymbol{i}$ is referred to as the trough width parameter.

In order to obtain a better fit to the observed tunneling-induced settlement data in sand, cases are considered where volume loss causes volumetric deformation, Broere and Bosch (2016) [6], the modified Gaussian curve is more accurate (2), Vorster, et al. (2005) [7]. Additionally to ***MSS*** and $\boldsymbol{i}$ dependency, the modified curve is determined also by another parameter defined as shape parameter $\boldsymbol{a}$, that gives an additional degree of freedom and therefore gives more flexibility to the curve shape.

$$Sv(x) = MSS\,n/(n-1+exp\,[a(x^2/i^2)]), \tag{2}$$

where n is the shape function parameter defined by

$$n = exp\,(a)(2a-1)/(2a+1)+1.$$

The settlement trough width obtained using the standard (1) and modified Gaussian curve (2) is usually governed by the inflexion ratio that is the distance from the tunnel centerline to the trough inflexion point (assumed symmetric) (Fig. 2). It should be noted that both equations describe only the form of transverse settlement not the maximum surface settlement "*MSS*".

The MSS depends on many parameters including:

- excavation method and its parameters such as NATM, TBM or cut and cover;
- support and pre-support method such as shotcrete, lining, forepolling, umbrella arching;
- geological and conditions such as unit weight, Poison's ratio, friction angle, Young's modulus, cohesion, seismological Tashayo, et al. (2019) [15];
- geometrical shape of the tunnel and advancing rate including tunnel diameter and depth, the number and distance between the tunnels and geotechnical parameters such as groundwater and permeability.

To estimate the ***MSS*** empirically, two main methods are widely adopted due to their simplicity and reliability; ***Attewell and Farmer*** and using the ***Volume Loss factor***.

Attewell and Farmer method. Attewell and Farmer [8] suggested (3) for the estimation.

$$MSS = (D/1000).(kD/H)^{1/n}. \tag{3}$$

Where $\boldsymbol{k}$ and $\boldsymbol{n}$ are parameters governing the shape of the (3), with values of 10 and 0.67 respectively.

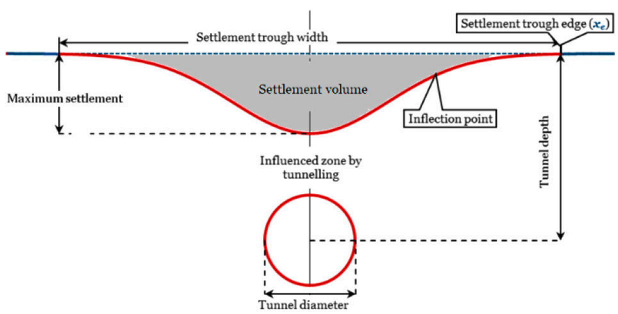

Fig. 2. Schematic of the surface settlement parameters

Fig. 3 demonstrates the predicted MSS via Attewell & Farmer against the measured values during the construction of tunnel.

Three domains are to be distinguished on axis C/D; 0 to 2, 2 to 3 and over 3.

The first domain is $C/D < 2$, where measured *MSS* are under the graph and the method is completely valid; this domain is known in the literature as "shallow tunnels". More precisely the *MSS* values are exaggerated where $C/D < 1$.

The second domain; $2 < C/D < 3$ where the points are located under and above the graph and the method is questionable.

Moreover, the last domain $C/D > 3D$, where all field measurements disagree with expected values completely.

Volume loss factor "VL" method. This method is also widely adopted for surface settlement estimation, Peck [1], Dindarloo and E. Siami-Irdemoosa (2015) [3], Vu, et al. (2016) [6] and many others.

The main concept of the *VL method* is that: in tunneling projects in clayey soil, the maximum vertical displacement registered during tunneling work usually occurs in undrained conditions (without change in the volume), hence it is assumed that the loss of soil volume at the contour of excavation is equal to the ground surface settlement volume.

Based on practical data, Wang, et al. (2020) [14] suggested that the presence of volume loss could be observed primarily in three main stages as the tunnel advances in the soil: 1) ahead of the face; 2) above the construction; 3) upon the erection of the lining. Furthermore, consolidation, creep, and variations in hydraulic conditions in the surrounding soil can all contribute to additional volume loss.

The volume loss is usually adopted to describe the effect of tunneling. There are two main types of volume loss for tunneling-induced ground displacements, the volume loss of tunnel, and the volume loss of soil (are expressed as the percentage).

Because (1) represents the Gaussian error function, ***MSS and i*** are independent variables, so the area enclosed by the curve can have a value expressed by (4)

$$VS = \int_{-\infty}^{+\infty} Sv(x)\,dx = \sqrt{2\pi} i MSS, \quad (4)$$

where *VS* is the volume of the settlement trough per unit length. For the tunnel excavation diameter *D*, the volume loss factor *VL* (%) is expressed by

$$VL = VS/(\pi D^2/4). \quad (5)$$

By combining (4) and (5), the MSS can be expressed by

$$MSS = 0.313 VL\, D^2/i.$$

Typical values of the VL could be obtained from other similar projects, Table 2.

Other measured VL of United Kingdom tunneling projects ranges from 1 to 3 % for all construction methods [10, 11], Table 3.

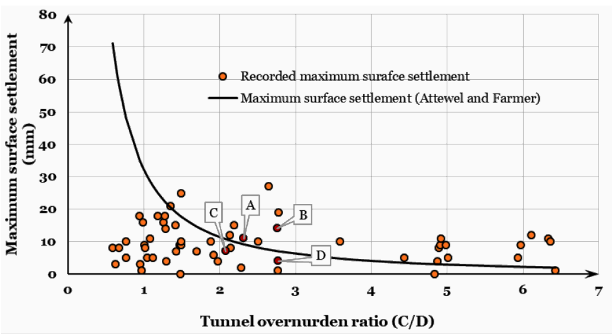

Fig. 3. Maximum surface displacement Attewell & Farmer versus recorded MSS

Table 2

Relationship among Volume Loss, Construction Practice, and Ground Conditions [9]

Case	*VL*(%)
Good practice in firm ground; tight control of face pressure within a closed face machine in slowly raveling or squeezing ground	0.5
Usual practice with closed face machine in slowly raveling or squeezing ground	1.0
Poor practice with closed face in raveling ground	2.0
Poor practice with a closed face machine in poor (fast raveling) ground	3.0
Poor practice with little face control in running ground	4.0 or more

Table 3

Recorded Volume Losses in tunneling projects of UK

Case and construction technique	*VL*(%)
Open faced shield tunneling in (London Clay)	1–2
Construction of the Jubilee Line beneath Green Park, London	1.4
Jubilee Line Extension in St. James's Park, London	3.3 and 2.9
Heathrow Express tunnel construction using a tunnel shield	1.0 and 2.9
Sprayed concrete lining (SCL) for the Heathrow trial tunnel, which was constructed in (London Clay)	1.0 –1.3

In addition to the *VL*, the inflection parameter "*i*" has a significant role in the estimation and has a variety of expressions in geotechnical engineering, the main existing formulas are summarized in Table 4.

Table 4 represents all existing inflexion parameter expressions regardless of case study but confirms the dependence on tunnel depth and, in some cases, soil condition.

To evaluate the effect of the volume loss and inflection parameter on *MSS*, and based on tunneling practice (Tables 2 and 3) three values of *VL* are adopted for detailed examination: 0.8, 1.6 and 2.4 %.

Those values are chosen in a way that represents a good approximation to projects around the world and include all tunneling techniques.

For VL = 0.8 % Fig. 4, the best fit is obtained via equation a expressed by *Dindarloo*, yet the predictions underestimate the MSS, and in some points reach only 21.33 % of the field measurements; furthermore, the predictions obtained by other researchers are so far from the measurement reaching only 6.6 % of the field data.

For *VL* = 1.6 % (Fig. 5), the predictions are improved significantly and the best fit is obtained also by the same researcher *Dindarloo*; this estimation is improved and agrees with most points, and is not valid for all overburden ratios (C/D).

The value 2.4 % (Fig. 6) represents optimal value when assessing maximum vertical displacement.

Summing up the analysis, we can claim that Dinadarloo' equation of inflection ratio represents the optimum expression, when it is combined with high value of *VL* (2.4 %). This equation is characterized by narrower Gaussian error curve defined by low value of "*i*"; the variation of *i*-parameter for "Algiers Subway" tunneling project is illustrated in Fig. 7.

Choosing between the two approaches of "*Farmer and Attewell*" and "*Volume Loss*", we find it clear that adopting *VL* with recommended values (*VL* > 2.4 % and Dindarloo's ex-

Table 4

Adopted inflection parameter formulas

	Researcher		Equation	Notes
A	Peck (1969) [3]		$i = R(Z_t/2R)^n$	Basing on field observation, $n = 0.8$ for cohesionless and $n = 1$ for cohesive soils
B	Attewell and Farmer/Wang, Miao, Yang & Liang (2016) [12]		$i = Ra(Z_t/2R)^n \quad a = 1$	London Clay case when the shield-tunneling method is used ($n = 0.8–1.0$)
C	Cording & Hansmire (1975)/ Schmidt & Clough (1981) [13]		$i/R = (Z_t/2R)^{0.8}$	cohesionless soils to demonstrate the shear strength distribution around tunnel excavated in medium dense to dense sands and gravel
D	Atkinson [14]	*a*	$i = 0.25(1.5Z_t + 0.5R)$	for loose sand
		b	$i = 0.25(Z_t + R)$	for dense sand and over consolidated clay
E	Glossop, et al./Mair, et al./ Rankin, et al. [13]		$i = 0.5Z_t$	basing on site measurement for tunneling in soft alluvial clay/both finite element and centrifugal modelling in soft clay case/from centrifuge tests, valid for all tunneling techniques
F	O'Reilly & New [14]	*a*	$i = 0.43Z_t + 1.1$	for cohesive soils with, $3 < C < 34$ m
		b	$i = 0.28Z_t - 0.12$	for granular soils with, $6 < C < 10$ m
G	Herzog [13]		$i = 0.40Z_t + 1.92$	for all types of soils
H	Arioglu [13]	*a*	$i = 0.40Z_t + 0.6$	for excavation in clays by shield machines
		b	$i = 0.386Z_t + 2.84$	for excavation of all types of soils
		c	$i = 0.9(R)(Z_t/2R)^{0.88}$	for excavation of all types of soils by shield machines
I	Lee, Shen and Bai [14]		$i/R = 0.58(Z_t/R) + 1$	construction of Shanghai Metro Tunnel-Line 2 in soft silty clay
J	Hamza, Ata and Roussin [14]		$i = 0.43Z_t + 1.1$	for tunneling by shielded mechanics
K	Dindarloo and Siami-Irdemoosa (2015) [10]	*a*	$i_{Low} = (2R/5)(Z_t/2R)^{0.8}$	Basing on 34 cases worldwide and using decision tree classification method for shallow tunneling
		b	$i_{Up} = R(Z_t/2R)^{1,2}$	
L	Selby (1988) , New and O'Reilly (1991) [14]		$i = \sum K_i Z_i$	$\boldsymbol{K_i}$ values should be 0.4–0.5 for stiff fissured clay, 0.5–0.6 for glacial deposits, 0.6–0.7 for soft silty clay and 0.2–0.3 for sands above the water table. Mair and Taylor suggested that K_i should be 0.5 for clay and 0.25–0.45 for sands and gravels

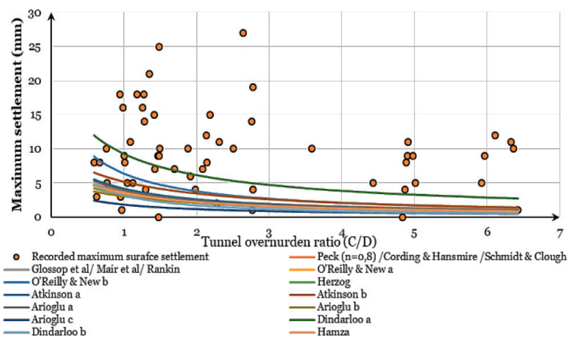

Fig. 4. variation of predicted MSS versus field measurement for VL = 0.8 %

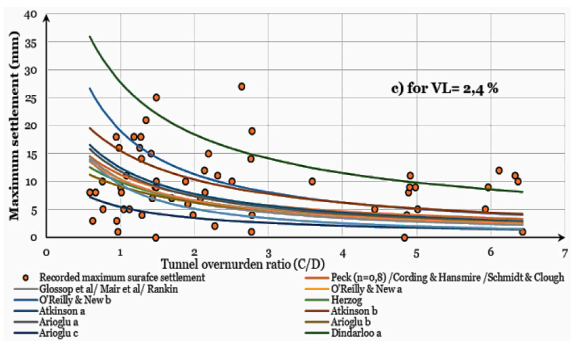

Fig. 6. Variation of predicted MSS versus field measurement VL = 2.4 %

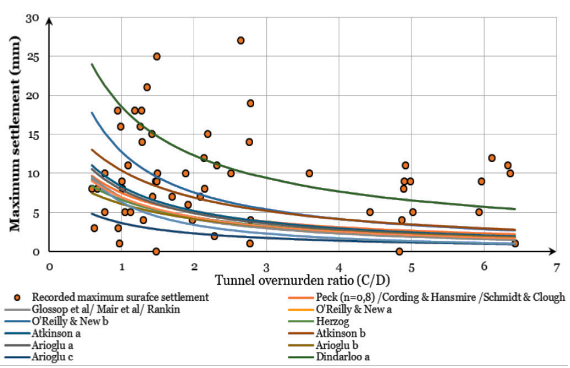

Fig. 5. Variation of predicted MSS versus field measurement for VL = 1.6 %

pression) gives better fit for multi-layered ground with cohesive soils and valid for cover to diameter categories (C/D).

A possible explanation is that Dindarloo's expression for inflection point is obtained by analyzing a variety of tunneling projects worldwide (34 cases) and using decision tree classification method for shallow tunneling.

Dindarloo, 2015 [10], stated that the proposed model was able to predict the maximum settlement induced by tunneling in soft grounds. Tunnel depth, diameter, volume loss, and normalised volume loss demonstrated to be the most effective/explanatory variables for classification of the tunnels in his study. Moreover, the VL was the most important parameter in his model.

Conclusions. Tunneng in an urban area leads inevitably to ground movement that appears in most cases as surface settlement. An exact quantification of such displacements in

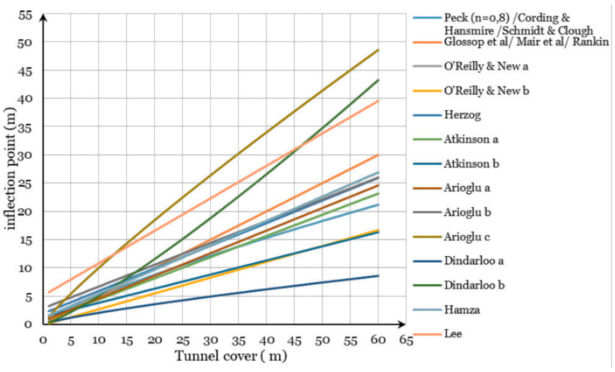

Fig. 7. Variation of inflexion parameter position

the first stages of tunnels design is of utmost importance. For that, the empirical approach is the simplest yet reliable way to describe the surface settlement extent. The complexity of surface displacement assessment lays in the heterogeneity of soil layers. A suitable method must give a close approximation and should not underestimate the displacements.

The current paper examined ability of the most adopted empirical methods and all inflection point formulas, to estimate the maximum surface settlement induced by the construction of "*Algiers Subway*" tunnel project.

Recommendations. The obtained results recommend the use of Volume Loss over Farmer and Attewell formula for all overburden ratios. More precisely the recommended method should be adopted with high volume loss value ($VL > 2.4$ %) and narrow surface settlement trough.

The results recommend for future studies: the use of machine learning methods such as Artificial Neural Networks to understand better the effect of geotechnical soil parameters on deformation.

Another hybrid model (empirical and numerical) is highly advisable to quantify the magnitude of the stress and displacements around the tunnel.

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Максимальне осідання поверхні внаслідок неглибокого тунелювання шаруватих порід

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Мета. Покращення прогнозування максимального осідання поверхні, спричиненого тунелюванням у багатошарових ґрунтах. На етапі проектування технічні експерти, як правило, використовують спрощенні формули задля оцінки реакції породи.

Методика. Для вивчення правильності емпіричних рівнянь у прогнозуванні максимального просідання поверхні, у даному дослідженні розглядаються дві широко застосовувані формули: «втрати об'єму ґрунту» та формула Фермера та Аттевела. Більш того, із-за того, що обидва рівняння є залежними від «відношення перегину», враховуються всі існуючі вирази параметра перегину. У кінцевому підсумку, отримані результати порівнюються з польовими дослідженнями та обирається найкраща пара виразів («максимальне осідання поверхні (МСС)» і «відношення перегину»).

Результати. Прогнозування максимального просідання поверхні внаслідок неглибокого тунелювання м›яких порід – важливий показник у забезпеченні безпечних операцій, особливо в міських зонах. Дана робота роз'яснює переваги методу «втрати об'єму ґрунту» в порівнянні з методами Фармера та Аттевеля для всіх сценаріїв (різний тиск порід); високі показники методу «втрати об'єму ґрунту» значно покращують прогнозування, коли він поєднаний із формулюванням «відношення перегину» Діндарлу.

Наукова новизна. Новизною даної роботи є розгляд найбільш розповсюджених емпіричних методів і всіх формул точок перегину, для оцінки врегулювання максимального осідання поверхні, викликаного будівництвом тунелю проекту «Algiers Subway»; також за допомогою практичних вимірювань робота продемонструвала слабкість деяких найбільш часто використовуваних підходів.

Практична значимість. Через відсутність даних у геотехнічній інженерії, ця робота є гарним ресурсом для тунельних проектів у майбутньому, оскільки охоплює понад шістдесят профілів вимірювань, і передбачає чисельні значення для кращої оцінки.

Ключові слова: *алжирський метрополітен, максимальна площа осідання, шаруваті породи, тунелювання, метод SCL (метод облицювання із бетону, що розпорошується), метод NATM (послідовних земляних робіт), втрата обсягу*

Максимальное оседание поверхности вследствие неглубокого туннелирования слоистых пород

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Цель. Улучшение прогноза максимального оседания поверхности, вызванного туннелированием в многослойных породах. На этапе проектирования геотехнические эксперты, как правило, используют упрощенные формулы для оценки реакции пород.

Методика. Для изучения правильности эмпирических уравнений в прогнозировании максимального оседания поверхности в данном исследовании рассматриваются две широко применяемые формулы: «потеря объема грунта» и формула Фармера и Аттевеля. Более того, из-за того, что оба уравнения являются зависимыми от «отношения перегиба», учитываются все существующие выражения параметра перегиба. В конечном итоге, полученные результаты сравниваются с полевыми исследованиями и выбирается лучшая пара выражений («максимальное оседание поверхности (МСС)» и «отношения перегиба»).

Результаты. Прогнозирование максимального оседания поверхности вследствие неглубокого туннелирования мягких пород – важный показатель в обеспечении безопасных операций, особенно в городских зонах. Данная работа разъясняет преимущества метода «потери объема грунта» по сравнению с методами Фармера и Аттевеля для всех сценариев (различное давление пород); высокие показатели метода «потери объема грунта» значительно улучшают прогнозирование, когда он совмещен с формулировкой «отношения перегиба» Диндарлу.

Научная новизна. Новизной данной работы является рассмотрение наиболее принятых эмпирических методов и всех формул точек перегиба, для оценки урегулирования максимального оседания поверхности, вызванного строительством туннеля проекта «Algiers Subway»; также с помощью практических измерений работа продемонстрировала слабость некоторых наиболее часто используемых подходов.

Практическая значимость. Из-за отсутствием данных в геотехнической инженерии, эта работа является богатым ресурсом для туннельных проектов в будущем, поскольку охватывает более шестидесяти профилей измерений, и предполагает численные значения для лучшей оценки.

Ключевые слова: *алжирский метрополитен, максимальная площадь оседания, слоистые породы, туннелирование, метод SCL (метод облицовки из распыляемого бетона), метод NATM (последовательных земляных работ), потеря объема*

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