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Determination of ground deconfinement for Motorway A8 Targu Neamt-Iasi-Ungheni tunnels in soft ground conditions in Romania

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Abstract: After decades of tunnelling scarcity, Romania has restarted its major infrastructure projects, resulting in a significant increase in tunnel design and construction. One of the challenges in designing the conventional tunnels for Motorway A8 Targu Neamt-Iasi-Ungheni is the determination of the deconfinement effect of in-situ stresses due to tunnel excavation and support sequencing. A 3-step approach is analysed, using the analytical Convergence-Confinement Method (Marc Panet), a 2D Axisymmetrical Finite Element Model, and a 3D Finite Element Model. The first two methods simulate the 3D effects generated by the construction sequence in a 2D model, whilst the third method models the tunnelling steps in 3D. This paper aims to compare the three methods, outline the difference in results, and calibrate the 3D effects in the 2D model, thus adding more clarity to the ground deconfinement determination process for conventional tunnels in soft ground conditions.

Keywords: Conventional Tunnelling; Finite Element Modelling; Ground Deconfinement; Romania

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1. Project Background

1.1. Location

The proposed A8 Motorway Targu Neamț-Iasi-Ungheni crosses the Moldavian Hills per-pendicularly, in the East of Romania (see Fig. 1), generating a series of small to medium cover motorway tunnels. Based on a preliminary geotechnical study, the geology of the Moldavian Hills generally comprises of a combination of granular and cohesive deposits, predominantly with weak clays and thin sand layers. The groundwater table typically re-sides in the sand layers, varying in depth, and is recorded to be absent at locations where boreholes indicate the existance of clay only.

Fig. 1. Map of Romania illustrating the motorway system, including the A8 Motorway project.

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1.2. Moimesti Tunnel overview

The Moimesti Tunnel is a proposed twin-tunnel located on Section 3 of the A8 Motorway, between km 72+960 – 73+480, and accommodating 2 lanes of traffic (see Fig. 2). The tunnel underpasses agricultural lands and has a total underground length of 470 m, a maximum cover of 36 m and an approximate 140 m^2 excavated tunnel cross-sectional area. The cross-section of the Moimesti Tunnel is presented in the figure below, illustrating one of the two tunnel tubes and the internal dimensions of the tunnel. The Moimesti Tunnel is currently in tender for construction.

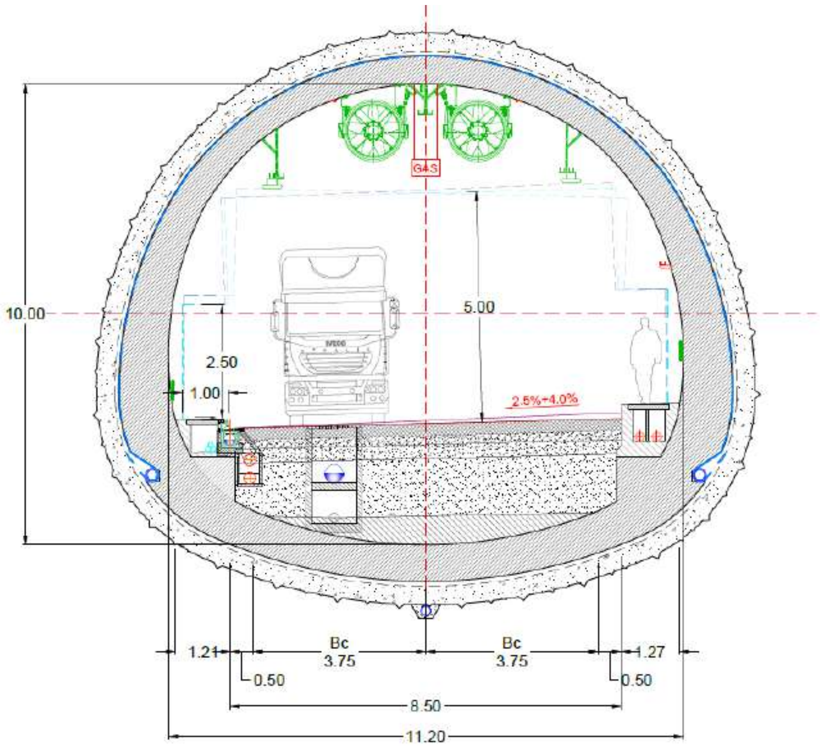

Fig. 2. Cross-section of the Moimesti Tunnel Tube 1 with internal dimensions in meters.

Due to its relatively short length, the tunnel is proposed to be excavated conventionally, using the Sequential Excavation Method (SEM), in a series of excavation steps (top heading, bench, invert) and supported by a 350 mm thick primary sprayed concrete lining (SCL). Additional ground support measures such as pipe umbrella for the low cover, forepoling and radial bolts are included in the design. A waterproofing membrane is installed prior to the construction of a cast in situ secondary reinforced concrete lining.

The geotechnical investigation conducted for the Moimesti Tunnel included 5 boreholes reaching below the tunnel invert, geophysics, in-situ and lab testing. The results of the investigations showed that the geology is generally homogenous and tunnel passes predominantly through a thick layer of clay, characterised as firm or stiff, with a fairly low Modulus of Elasticity (12-15MPa) and the groundwater table is reported to be below the tunnel invert. The geotechnical parameters are presented in Figure 3 of the following chapters. Unexpected, local variability of the geology (i.e. the presence of sand lenses) could result in local face instability, producing higher deformations and therefore increasing the ground relaxation; this paper however, focuses on the determination of the ground relaxation parameter for the predominant clay layer, following the results of the geotechnical study.

2. The ground relaxation parameter

One of the governing factors in the design of tunnel primary linings is the deconfinement of the ground, also known as the ground relaxation, which accounts for the stress redistribution in the ground after the excavation and before the installation of the tunnel support system. The deconfinement factor therefore plays a crucial role in the two-dimensional simulation of the three-dimensional effects generated by the excavation of the tunnel.

In order to determine the deconfinement factor for the Moimesti Tunnel, a number of analyses were undertaken, considering the 350 mm thick SCL primary lining, without taking into account the effects of any additional ground support measures. This methodology was chosen to ease the comparison between the different ground relaxation analysis methods.

The deconfinement factor obtained is introduced in finite element models using Plaxis 2D and the results are compared at the end of the paper.

3. Method 1: the convergence-confinement method (Marc Panet)

3.1. Methodology

The first method used to determine the deconfinement factor is the well-known Convergence-Confinement Method (CCM) developed by Marc Panet. The CCM is based on the analysis of a circular tunnel in homogeneous ground and on the assumptions that the tunnel is deep and the stresses in the ground are isotropic. A deconfinement factor (λ) be-tween 0 and 1 is determined using the unsupported advance length and the tunnel radius as presented in the empirical equation provided below (Panet, 2001):

$$\lambda_d = 1 - 0.75\left[\frac{0.75R}{0.75R+d}\right]^2 \quad (1)$$

where d = Unsupported tunnel length from working face; R = Radius of circular tunnel;
λ_d = Deconfinement at distance d from working face.

Once the deconfinement of the ground is calculated, the stresses in the lining can be obtained by multiplying the deconfinement factor with the initial stresses in the ground, as shown in the equation below (Jones, 2022):

$$\sigma = (1-\lambda)\sigma_0 \quad (2)$$

σ = lining stress; λ = Ground deconfinement; σ_0 = initial ground stress.

3.2. Application to Moimesti Tunnel

The application of the CCM to the Moimesti Tunnel is considered to be partial, as the 3-diameter tunnel cover is not considered deep enough and the SEM tunnel shape isn't circular. However, the calculations can be performed using an equivalent tunnel radius to determine the ground deconfinement and then compare it against the other results to assess the suitability of the CCM for medium cover SEM tunnels. As the shape of the Top Heading-Bench-Invert is too different from a circular shape, the full face deconfinement factor will be used throughout the calculation.

A deconfinement factor of λ=0.48 is obtained using the CCM for a 1m advance and a 6.7 m equivalent tunnel radius for the 140 m2 excavated tunnel area. The deconfinement factor is introduced in the numerical analysis using Plaxis 2D as (1- λ) for the top heading, bench, and invert sequences. Because of the early ring closure, the deconfinement factor remains unchanged while progressing through the excavation phases.

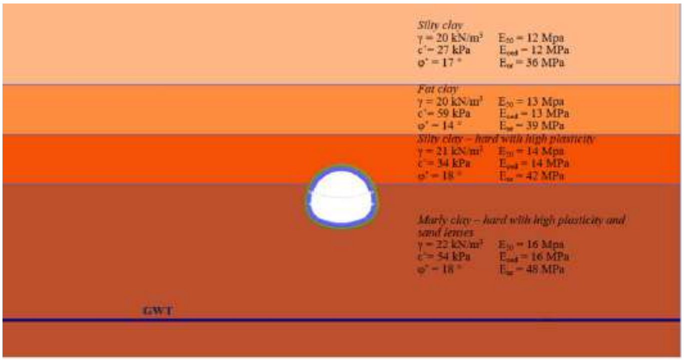

Fig. 3. Extract of Moimesti Tunnel in Plaxis 2D showing the geotechnical parameters.

3.3. Method 1 Results

The results of the numerical analysis using the deconfinement factor obtained through the CCM for the Moimesti Tunnel are listed in Table 1 below. The calculation results indicate high bending moments and deformations, which are primarily associated with the low stiffness of the ground.

Table 1. Method 1 CCM 2D Finite Element results for Moimesti Tunnel for 1m advance.

Method	Deconfinement factor (λ)	Horizontal Deformation u_x (cm)	Vertical Deformation u_y (cm)	Max. Axial Force (kN)	Max. Bending Moment (kNm)
2D SEM Tunnel Tunnel with deconfinment from CCM (panet-full face)	0.48	7.88	25.75	2236.00	313.70

4. Method 2: the axisymmetric finite element model method

4.1. Methodology

A second analysis is carried out using the method of axisymmetry with fixed field stress conditions. Two Plaxis models are created in 2D to calibrate the deconfinement factor. The first model is created using a circular tunnel, similarly to the CCM conditions, while the second model is created with axisymmetric conditions, vertical, similarly to a shaft, thus the model conditions, including the field stress, are effectively rotated, in order to allow for the simulation of the tunnel advance effects in 2D. The deconfinement is determined once the two models are calibrated, when the hoop force and the deformation is similar in both models. Finally, a third 2D model is created using the SEM tunnel shape and the excavation steps, using the deconfinement factor determined previously. Similarly to the CCM, the deconfinement factor is calculated only for the full cross-section of the tunnel.

4.2. Application to Moimesti Tunnel

The first Plaxis 2D model is created, assuming a circular tunnel with 6.7 m radius, homogenuous ground conditions and fully fixed boundaries in all directions. Then, a field stress is assigned to the ground, with a vertical stress $\sigma_{1(v)}=\gamma h=760$ kPa, and a $\sigma_{2(h)}=523$ kPa, corresponding to $k_0=0.7$.

A second, axisymmetric model is created in Plaxis 2D, with the same tunnel radius, the tunnel is modelled vertically, with 1m advances and simulating the strength gaining of the shotcrete at 1 days, 3 days, and 7 days (see Figure 4). The ground is assigned a field stress, inverse to the first 2D model, with σ_1=523 kPa and σ_2=760 kPa. Thus, the model conditions are effectively rotated in order to allow for the simulation of the tunnel advance effects in 2D. The sequential advances are modelled for the first 20 m, then a "wished-in-place" tunnel is created, independent of the sequential advances. This is done by creating a new Phase linked straight to the Initial Phase, where the primary lining is activated first, then a second Phase is created and the ground is deactivated, thus not allowing any confinement loss in the ground.

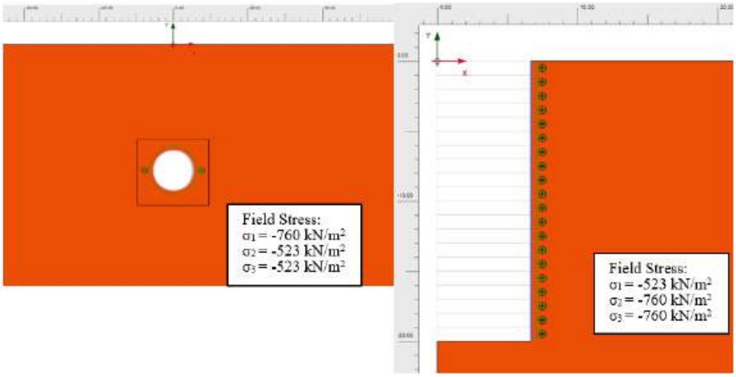

Fig. 4. Plaxis 2D FE of (a) circular and (b) axisymmetric models with field stress conditions.

Further on, the deconfinement factor is determined using two methods: A) the average hoop force of the 7 days strength SCL is divided by the hoop force of the "wished-in-place" SCL (also 7 days strength), then the deconfinement (λ) is equal to 1 minus the hoop force ratio (see Figures 5 and 6 below); B) the horizontal deformation in the axisymmetric model at the tunnel face is used as a reference for the 2D SEM model, then a deconfinement factor is determined in the 2D SEM model by trial and error, until the vertical crown deformation obtained in the 2D SEM model is similar to its correspondent in the axisymmetric model. The hoop force or deformation near the boundary are not considered.

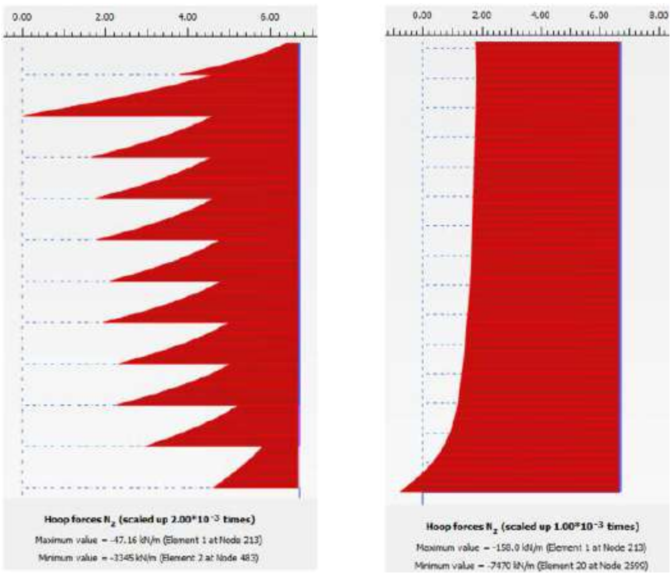

Fig 5. Method 2A showing the (a) sequential (left) and (b) "wished-in-place" (right) Hoop Force results.

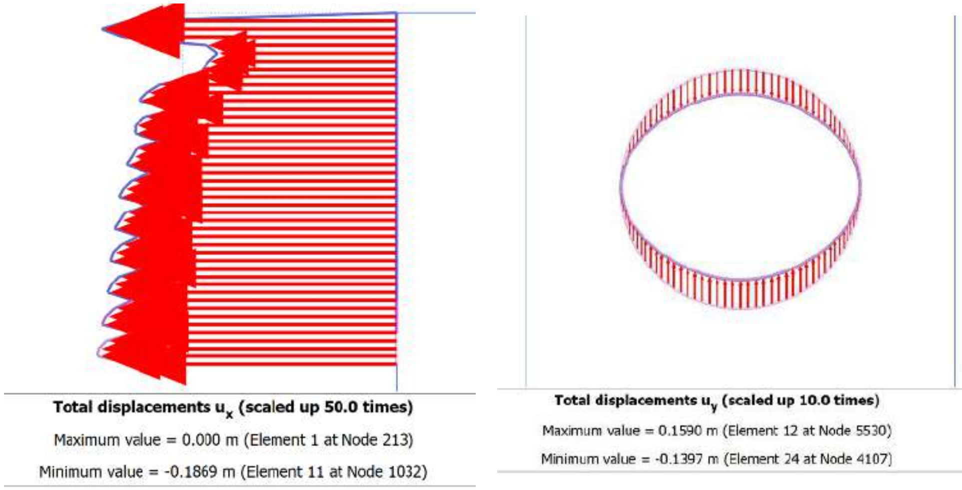

Fig 6. Vertical crown displacement at the front in the (a) 2D Axisymmetric and (b) circular models after calibration with λ=0.64.

4.3. Method 2 Results

A deconfinement factor of λ=0.64 is obtained using the Hoop Force ratio (method A), and a deconfinement factor of λ=0.49 is obtained using the Tunnel Crown Deformation (method B). The results are presented in Tables 2 and 3 below.

Table 2. Determination of Deconfinement using the Hoop Force ratio and the Vertical Crown Deformation.

Determination of Deconfinement factor using the Hoop Force ratio (method A)							
Analysis Method	Tunnel cross-section	Advance Length (m)	Face area (m^2)	Equivalent Radius (m)	Sequential Excavation	Wished- in-place	Deconfinement (%)
					Hoop Force (kN) average	Hoop Force (kN)	
Axisymmetric model	Full face	1.00	139.93	6.67	1752.5	4890	64.16
Determination of Deconfinement factor using the Vertical Crown Deformation at tunnel face (Method B)							
Analysis Method	Tunnel cross-section	Advance Length (m)	Face area (m^2)	Equivalent Radius (m)	Axisymmetric model	SEM Tunnel model	Deconfinement (%)
					Crown deformation at the face - u_x (cm)	Crown deformation at the face - u_y (cm)	
Axisymmetric model	Full face	1.00	139.93	6.67	17.80	17.50	49.00

The two deconfinement factors are used in two different 2D models of the SEM tunnel, obtaining the results presented in Table 3 below. The Hoop Force ratio (method A) results in higher deformations and lower bending moments than the Tunnel Crown Deformation (method B), because of the higher deconfinement factor. The high bending moments and deformations are also due to the relatively low cover of the tunnel and the reported low ground stiffness.

Table 3. Method 2 FE results for Moimesti Tunnel using the Axisymmetric method with 1m advance.

Method	Deconfinement factor (λ)	Horizontal Deformation u_x (cm)	Vertical Deformation u_y (cm)	Max. Axial Force (kN)	Max. Bending Moment (kNm)
2D SEM Tunnel Tunnel with deconfinement from Axisymmetric Model (Axial force derivation-Method 2A)	0.64	22.74	55.14	2033	259.60
2D SEM Tunnel Tunnel with deconfinement from Axisymmetric Model (Axial force derivation-Method 2B)	0.49	8.40	26.79	2220	309.10

5. Method 3: THE full 3d finite element model method

5.1. Methodology and application to Moimesti Tunnel

A full-scale 3D model is created in Plaxis 3D, modelling a 50 m long stretch of the SEM tunnel, with 1m sequential advances of top heading, bench, and invert, using the progressive 1 day, 3 days, and 7 days SCL strength gain (see Figure 7). The ground conditions are the same as for the 2D SEM models and the groundwater table is below the tunnel. After the sequential stages are modelled, an independent stage is created, modelling the "wished-in-place" tunnel conditions, as described previously.

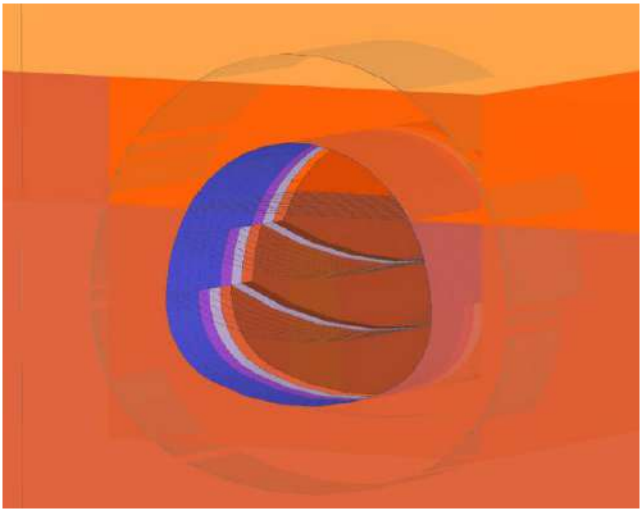

Fig 7. 3D model of Moimesti Tunnel showing the sequential excavation with top heading, bench, and invert.

The deconfinement factor is determined using the same methods as used in the axisymmetric analysis: A) the average axial force of the 7 days strength SCL is divided by the axial force of the "wished-in-place" lining (also 7 days strength), then the deconfinement (λ) is equal to 1 minus the axial force ratio. B) the vertical crown deformation at the front of the tunnel is used as a reference for the 2D SEM model, then a deconfinement factor is determined by trial and error, until the vertical crown deformation obtained in the 2D SEM model is similar to the one in the 3D model. The forces or deformations at the boundary are not considered.

5.2. Method 3 Results

The results of the 3D analysis are presented in the table and figures below. A deconfinement factor of λ=0.40 is obtained using the Axial Force ratio (method A), and a deconfinement factor of λ=0.50 is calculated using the Vertical Crown Deformation (method B) of the fresh (1day strength) SCL at the front of the tunnel. These two factors are used in two different 2D models of the SEM tunnel, and the results are included in the table below. The results are summarised in Table 4 and Figure 8 below.

Table 4. Finite Element results for the Moimesti Tunnel using the 3D model with 1m sequential advance.

Method	Deconfinement factor (λ)	Horizontal Deformation u_x (cm)	Vertical Deformation u_y (cm)	Max. Axial Force (kN)	Max. Bending Moment (kNm)
3D Model	N/A	7.60	23.30	2578	271.6
2D SEM Tunnel Tunnel with deconfinement from Axisymmetric Model (Axial force derivation-Method 3A)	0.40	4,61	19,16	2617	358.30
2D SEM Tunnel Tunnel with deconfinement from Axisymmetric Model (Axial force derivation-Method 3B)	0.50	9,55	27,89	2204	304.80

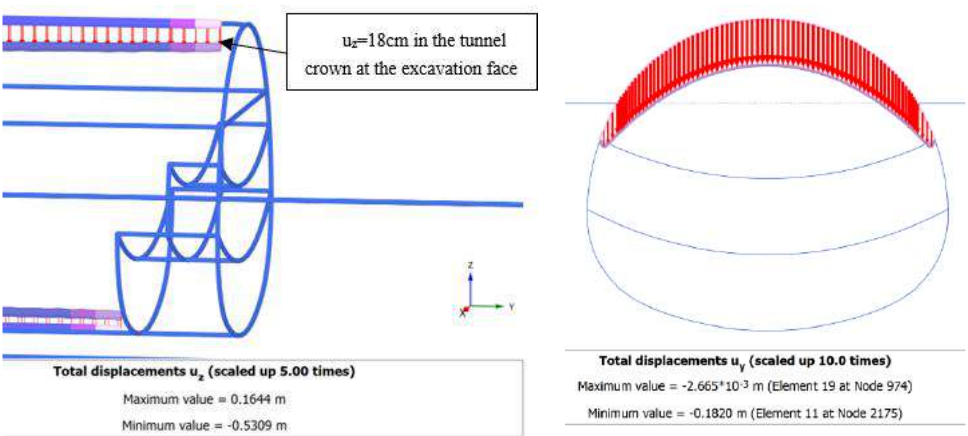

Fig. 8. Vertical crown displacement at the front in the 2D and 3Ds models after calibration with λ=0.50.

6. The three method deconfinement results comparison

The three methods utilised for the determination of the deconfinement factor (λ) have resulted in a range of results between 0.40 to 0.62, confirming that high deconfinement factors result in high deformations and lower support pressures. In the absence of real-life monitoring data, the 3D model created is considered to be the reference for the effects of the stresses in the ground acting on the primary lining, in the form of deformation, axial force, and bending moments. Table 5 below summarises the results obtained using the deconfinement factor (λ) resulted from each method (CCM, Axisymmetric, and 3D derivations).

Table 5. Summary table of the 2D and 3D Finite Element Analysis results for the Moimesti Tunnel.

Method	Deconfinement factor (λ)	Vertical Deformation u_y (cm)	Max. Axial Force (kN)	Max. Bending Moment (kNm)
2D SEM Tunnel with deconfinement from CCM (Panet-full face)	0.48	25.75	2236	313.70
2D SEM Tunnel with deconfinement from Axisymmetric Model (Axial Forces derivation-Method 2A)	0.64	55.14	2033	259.60
2D SEM Tunnel with deconfinement from Axisymmetric Model (Deformation derivation-Method 2B)	0.49	26.79	2220	309.10
2D SEM Tunnel with deconfinement from 3D Model (Axial Forces derivation-Method 3A)	0.40	19.16	2617	358.30
2D SEM Tunnel with deconfinement from 3D Model (Deformation derivation-Method 3B)	0.50	27.89	2204	304.80
3D Model	N/A	23.30	2578	271.60

It is observed that all three methods have generally obtained similar results, with the exception of the case when the deconfinement factor was determined using the Axial Forces ratio, referred to as method A, which resulted in higher deformations (55 cm) and bending moments (358 kNm) compared to the 3D model results. On the other hand, when the deconfinement factor was obtained using the CCM and the Axisymmetric and 3D models with the Vertical Crown Deformation (method B) as reference, the axial forces, bending moments, and deformations are consistently closer to the 3D model, corresponding to a deconfinement of approximately 50%.

7. Conclusion and further development

The aim of this paper was to present a three-step methodology for the determination of the deconfinement factor in soft ground, necessary for tunnel design. The methodology was applied to the proposed Moimesti Tunnel, part of the A8 Targu Neamt-Iasi-Ungheni Motorway project in Romania, which will be constructed using the sequencial excavation method. The three-step methodology comprised of using the Convergence-Confinement Method, a 2D Axisymmetric model, and a 3D model, each of them obtaining different deconfinement factors, that were in turn introduced in a 2D model, corresponding to each method.

The first two methods can be used successfully in early-stage or tender design, to reduce the duration of the evaluation and then confirmed by 3D numerical analysis and further one, compared and validated by convergence monitoring during construction. A back analysis should be conducted during construction to determine the real ground relaxation parameter.

The results, presented in the previous chapter, indicated that the CCM can be reliable for a 3 diameter cover SEM tunnel in soft ground conditions, and can be used at least as a tool for preliminary design stages. The axisymmetric method is also reliable, particularly when the deconfinement factor is determined by trial and error, using the fresh SCL vertical crown deformation near the tunnel front.

Finally, the analysis that used the deconfinement factor obtained from the 3D model, also using the fresh SCL vertical deformation near the tunnel front, has also provided results similar to those of the 3D model. This proved that the 2D and 3D models were calibrated successfully.

In conclusion, the results showed that the three-dimensional effects of the tunnel excavation can be successfully simulated in a two-dimensional analysis, using the Convergence-Confinement, 2D

Axisymmetric, and 3D numerical methods, and it is recommended to be done so, in order to check the accuracy and consistency of the deconfinement calibration.

It is acknowledged that although the analysis was successful, the results still indicate high deformations and bending moments, which is primarily due to the low stiffness of the ground. Therefore, additional geotechnical investigation is required to confirm the geotechnical parameters, particularly the Elastic Modulus. A further development step in the analysis is to determine the effects of the additional ground support in the form of bolts, spiles, lattice girders, in the determination of the ground deconfinement factor. Another further development step is to carry out the assessment in more competent ground, with longer advances and different deconfinement factors for the excavation sequences.

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