SCIENTIFIC MINING JOURNAL
The Publication of the Chamber of Mining Engineers of Türkiye
Original Research
www.mining.org.tr

Estimating support pressure with finite element and convergence-confinement method for different rock masses

Hüseyin Onur Dönmez[a,*], Hakan Tunçdemir[a,**]

[a] *Istanbul Technical University, Faculty of Mines, Mining Engineering Department, Istanbul, TÜRKİYE*

*Received: 6 September 2023 * Accepted: 3 October 2023*

A B S T R A C T

Support pressure is a key factor in the stability of the excavation area during mining and tunneling. The vital thing desired in an underground engineering structure is to ensure that the structure survives safely throughout its lifetime. For this reason, choosing the right support system at the planning stage is very important for the pressure that will affect the support system must be determined with a certain convergence. This article aims to discuss the support pressures by the finite element method and convergence-confinement method and compare the results. A series of two-dimensional finite element models are established to analyze support pressure with different rock masses selected from the literature. The results reveal that the convergence-confinement method and the finite element method have high-order relationships regarding support pressures and displacements for weak rock masses. Therefore, it shows that support pressures and displacement values for similar conditions can be estimated by the convergence-confinement method, which is more practical than the finite element method.

Keywords: *Support pressure, Finite element method, Convergence-confinement method, Underground mining, Tunneling*

Introduction

Today, the increasing population and urbanization rate cause people to live in large masses in limited areas. This situation brings with it some problems. Areas on earth are becoming increasingly inadequate and negatively affect people's living standards. Transportation is one of these negatively affected living standards. For this reason, road and railway tunnels are of great importance for safer and more comfortable transportation. At the same time, production amounts are increasing to meet the needs of the increasing population. Our underground resources, which are our most important source of raw materials, are scarce resources by nature, so the production levels are getting deeper. This causes underground mining to become more widespread and work at deeper levels. These two cases show that the need for underground structures is extremely high and increasing.

The main issue sought in an underground structure is to ensure that the structure survives safely throughout its lifetime. Thus, choosing the right support system at the planning stage is significant.

To select and dimension the correct support system, first of all, the pressures that will affect the support system must be revealed with a certain convergence.

Theories for the estimation of support pressure began to emerge in the early 20th century (Protodyakonov, 1907). Theories started with the engineers working in this field converting their experiences into numerical data and equations and then continued with the classification of the different environments studied and the estimation of the support pressure by making use of them (Terzaghi, et al., 1946; Lauffer, 1958; Deere, 1964; Deere et al., 1970; Wickham et al., 1972; Bieniawski, 1973; Barton et al., 1974; Rose, 1982; Stille et al., 1982; Birön and Arıoğlu, 1985; Ünal and Özkan,

*Corresponding author: donmezhu@itu.edu.tr • https://orcid.org/0000-0002-5567-0824
**tdemir@itu.edu.tr • https://orcid.org/0000-0001-9244-6728
https://doi.org/10.30797/madencilik.1356042

1990; Goel et al., 1995; Palmstrom, 1995; Goel et al., 1996; Hoek and Brown, 1997; Singh et al., 1997; Palmstrom, 2000; Aydan et al., 2014).

The finite element method (FEM), which was first used in the aerospace industry in the 1960s and quickly found use in every branch of engineering, was also applied to underground structures and is a good tool for analyzing the support pressure of mine galleries and tunnels. Therefore, many researchers have been using FEM in their analysis (Seshagiri Rao, 2020; Sharma et al., 2020; Taghizadeh et al., 2020; Aygar, 2022; Huang, et al., 2022; Zhang et al., 2022; Cui et al., 2023; Kumar and Sahoo, 2023; Niu et al., 2023).

The convergence-confinement method (CCM) is an analytical tool for estimating the support pressure and displacements in a tunnel by applying a hypothetical pressure to the tunnel wall. The basic components of the CCM are the ground reaction curve (GRC), the longitudinal displacement profile (LDP) of the tunnel walls, and the support reaction curve (SRC) (Panet et al., 2001).

This study presents a numerical analysis of the support pressure estimation of the tunnels bored for 3 different rock masses selected from the literature as weak, medium, and good. 2D finite element software named RS2 (Rocscience, 2020a) was used to perform FEM, and RocSupport (Rocscience, 2020b) was used to perform CCM. Analyses with FEM were made for a horseshoe section tunnel or gallery. However, CCM only allows the modeling of full circular cross-section openings. For this reason, in order to avoid any problem in the comparison of the models created, the circular cross-section tunnels with the same opening as used in the CCM model were remodeled in FEM for the same rock masses. A total of 591 points in 9 models were analyzed and the results of two different analysis methods were examined. Finally, this paper discusses the estimation of support pressures for different rock masses.

1. Materials and Methods

1.1. Analyzed Rock Masses

The geomechanical parameters given in Table 1 are from the Yacambú Quibor tunnel in Venezuela for the weak rock mass (Hoek, 2000), the underground power room in the Nathpa Jhakri Hydropower project in India for the medium rock mass (Jalote et al., 1996), and the power station tunnels in Argentina for the good rock mass (Moretto et al., 1993). The reason for using the data obtained from these studies is that they are also referenced by the RS2 software due to their high representation power of the rock masses in which they are located (Hoek, 2000).

The tunnel shape and dimensions chosen are in the form of a horseshoe, 5x5 m in size, which is given in Figure 1, which is the most frequently used in mine galleries in Turkey.

Table 1. *Geomechanical parameters of different rock masses used in the analyses (Hoek, 2000)*

Parameters		Weak	Medium	Good
Intact rock strength (MPa)	σ_{ci}	50	30	110
Geological Strength Index	GSI	25	65	75
Hoek-Brown constant	m_i	10	15	28
Hoek-Brown constant	m_b	0.481	4.3	11.46
Hoek-Brown constant	s	0.0002	0.02	0.062
Constant	a	0.53	0.5	0.501
Deformation modulus (MPa)	E_m	1000	10000	45000

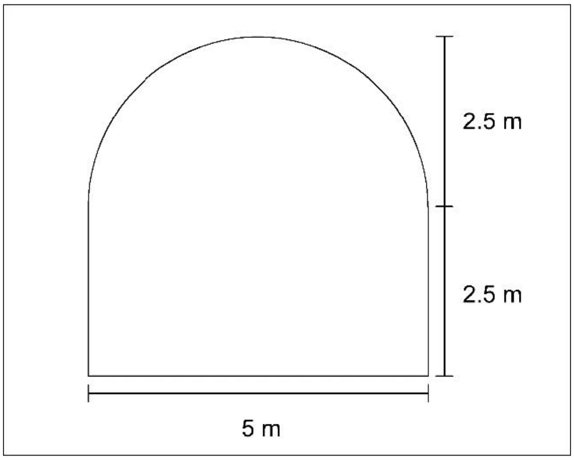

Figure 1. *Shape and dimensions of the analyzed tunnel*

1.2. Convergence-Confinement Method

The convergence-confinement approach developed by Panet and Guellec in 1974 is frequently used to evaluate tunnel wall deformations and offer recommendations for the design of rock supports (Brown et al., 1983; Carranza-Torres and Fairhurst, 2000; Panet and Sulem, 2022).

According to Figure 2, a circular tunnel with hydrostatic field stresses is excavated in an isotropic material, and the plane strain requirement is satisfied by the stress condition at a cross-section sufficiently removed from the tunnel face (for instance, section B-B). The pressure that rock supports carry when they are positioned behind the tunnel face is less than the initial pressure p_0 and they do not carry the complete support load from the rock mass. This is brought on by the tunnel face's supportive role in carrying some of the loads of the rock mass. The support from the face effect is represented by a fictitious internal pressure p_i. With the advancement of the tunnel face, the radial displacement on the walls increases as the face effect p_i on the section under study decreases (Wang and Cai, 2022).

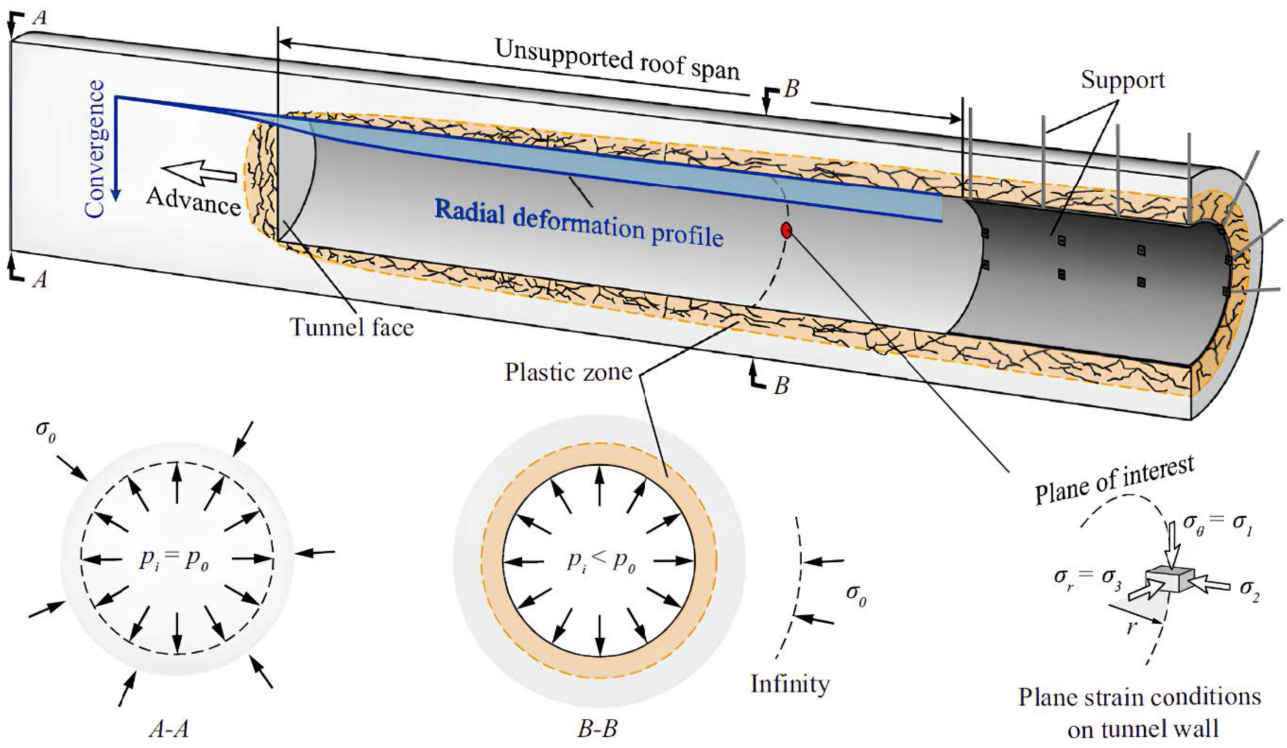

Figure 2. *Stress profiles and radial displacement variations along the tunnel axis (Wang and Cai, 2022)*

The relationship between this hypothetical pressure and the radial displacement at the tunnel wall is explained by the ground reaction curve (GRC), and the longitudinal displacement profile (LDP) is used to describe the relationship between the change in radial displacement along the tunnel due to the advancement of the tunnel face (Figure 3). For any section along the tunnel, the pressure and displacement at the tunnel wall can be estimated if the LDP and GRC of the tunnel are known.

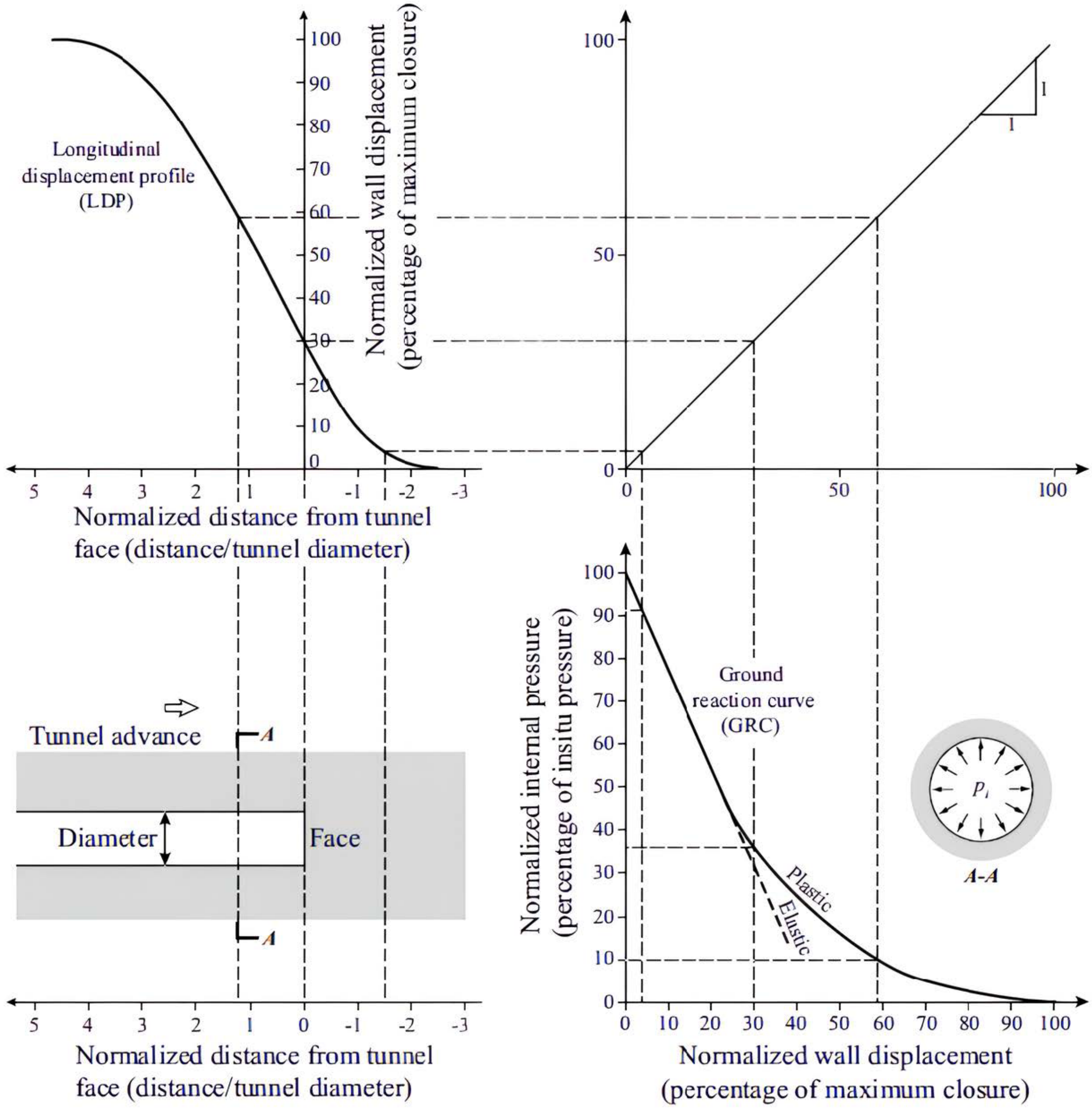

Figure 3. *The convergence-confinement method (Wang and Cai, 2022)*

1.3. Finite Element Modeling

Based on the data described in the previous subsection, tunnels in different rock masses were modeled in RS2 as summarized in Table 1. The analysis type is plane strain, the solver type is the "Gaussian Elimination Method", and units are metric and MPa for stresses. For stress analysis, the maximum number of iterations was determined as 500 and the tolerance was 0.01. The "Generalized Hoek Brown" failure criterion was chosen while selecting the properties of the rock mass. Since the depth of the modeled tunnels is quite deep from the surface (the nearest tunnel is 130 m), movements are restricted on all sides. GRCs were obtained from RS2 for comparison with CCM. For this reason, using the stress reduction method, the pressures that will affect the support are added in 10 stages in a way that will decrease analytically. The mesh type is graded, and the element type is a 3-node triangle. The finite element model of the tunnel is created in RS2 as shown in Figure 4.

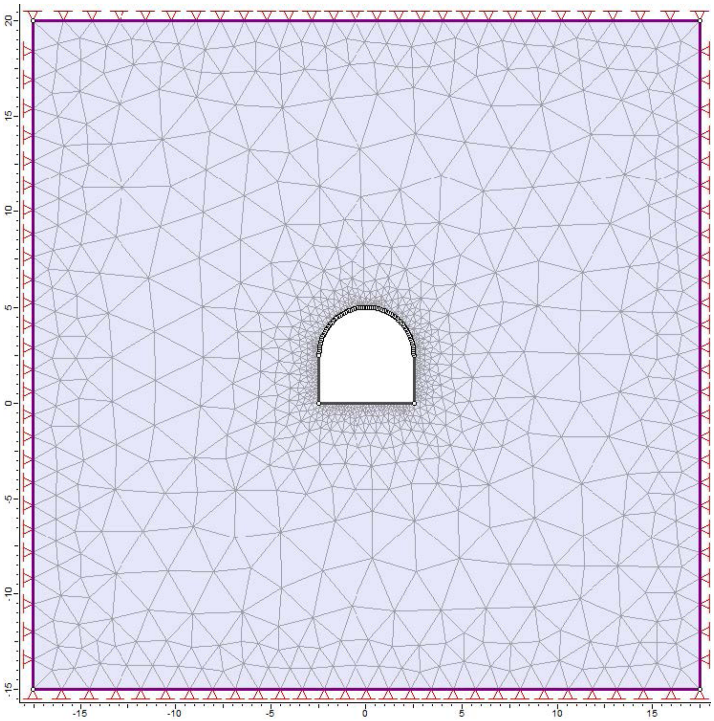

Figure 4. *Finite element modeling*

2. Results and Discussion

The radius of the plastic zone was determined according to the finite element model. According to the maximum displacement amount obtained from the model, the displacement amount corresponding to the pressure that will affect the support was calculated by using the LDP curves drawn by the equations of Vlachopoulos and Diederichs (2009). These values obtained for three different rock masses are given in Table 2.

Table 2. *LDP parameters of different rock masses used in the analyses*

Parameters		Weak	Medium	Good
Plastic zone radius (m)	R_p	6.73	3.93	3.58
Tunnel radius (m)	R_t	2.5	2.5	2.5
R_p/R_t		2.7	1.6	1.4
Maximum displacement (m)	U_{max}	0.118	0.0038	0.0024
Displacement (m)	U	0.059	0.0024	0.0017
U/U_{max}		0.5	0.63	0.72

In order to make a comparison between CCM and FEM in terms of GRCs, GRCs were obtained by constructing the hypothetical p_i pressure in the FEM model. Since CCM is only recommended for fully circular underground openings, GRCs were obtained by constructing circular-section FEM models with the same opening as horseshoe-section galleries. All GRCs generated for 3 different rock masses are given in Figures 5 to 7.

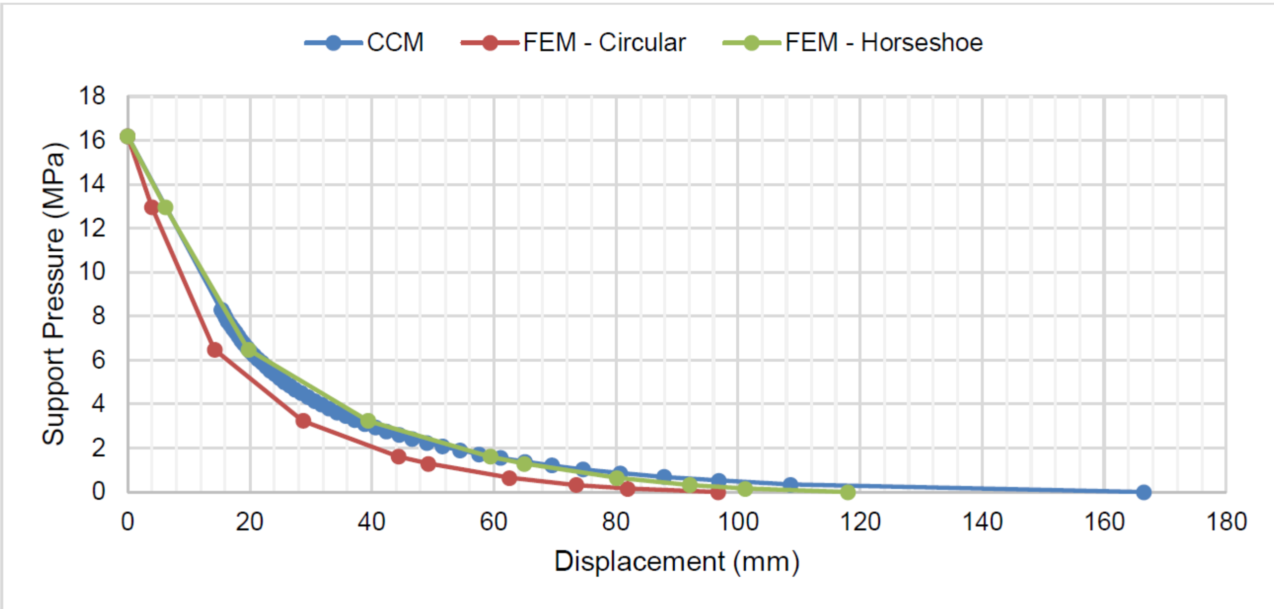

Figure 5. *Ground reaction curves for weak rock mass*

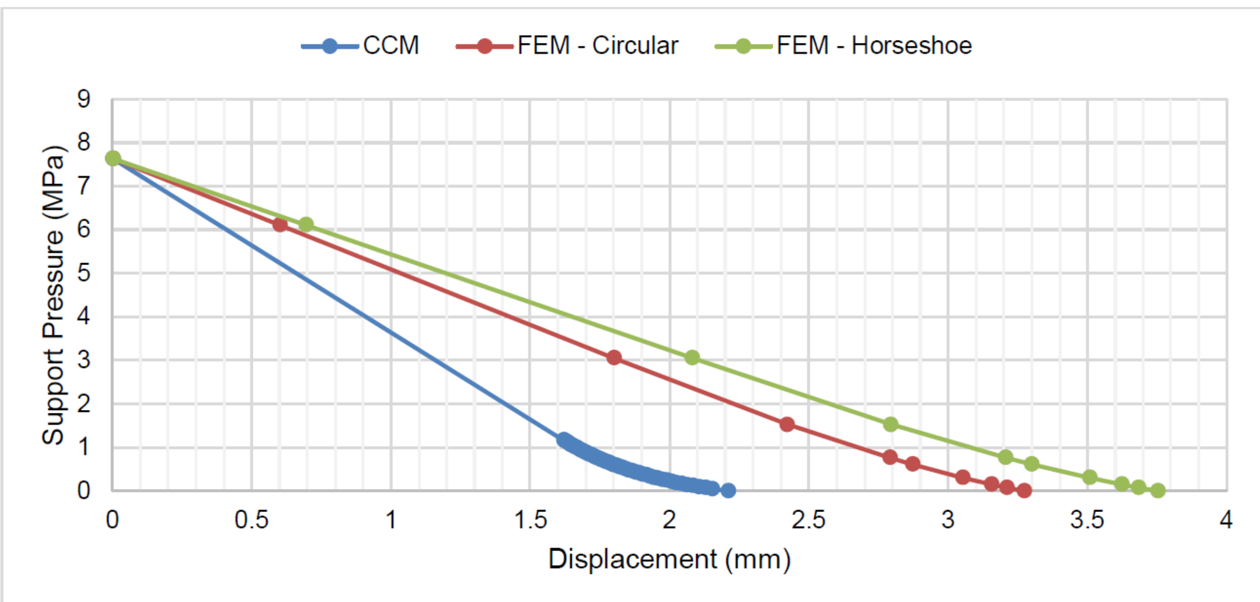

Figure 6. *Ground reaction curves for medium rock mass*

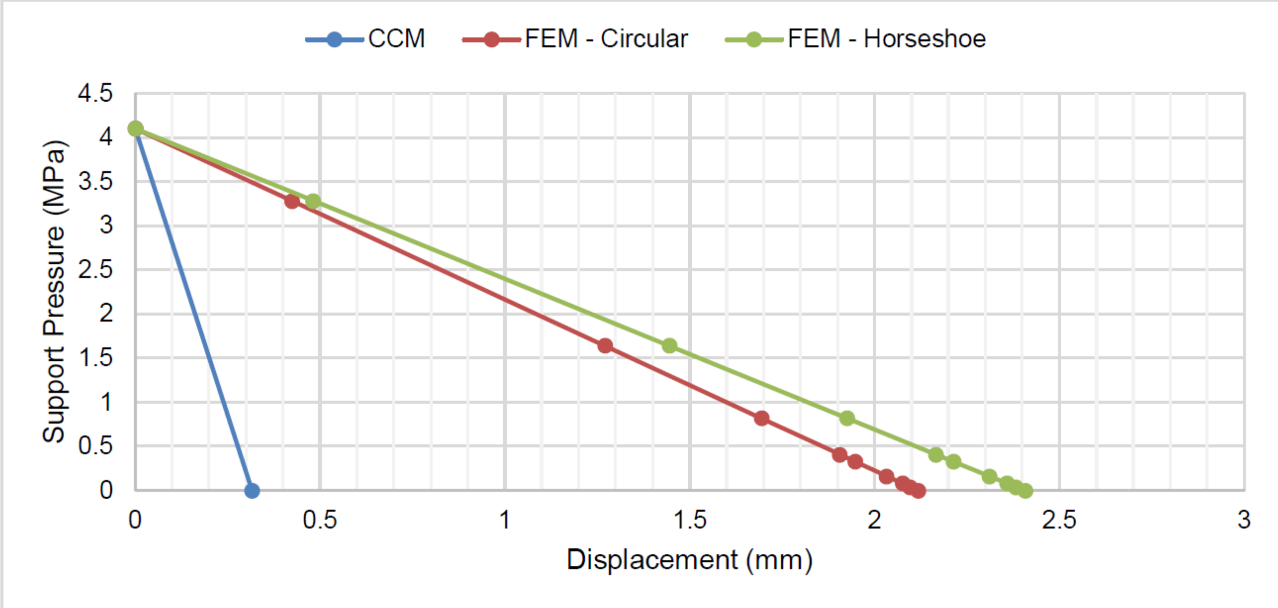

Figure 7. *Ground reaction curves for good rock mass*

Support pressures corresponding to the displacement amounts in Table 2 were calculated for all generated GRCs and the results are given in Table 3. The displacement amounts obtained from the FEM model for medium and good rock masses are greater than those calculated in the CCM and are therefore expressed as 0 in the table. It seemed that from Table 3, there is a correlation between the support pressures in the CCM and the horseshoe section FEM model. Based on this phenomenon, CCM and FEM support pressures corresponding to the same displacements for the weak rock mass were compared. As a result of the comparison in Figure 8, it is seen that the support pressures obtained from CCM and FEM have a relationship with a high and reliable coefficient of determination. CCM and FEM displacements corresponding to the same support pressures were compared from the same point of view. A strong coefficient of determination has been found in the relationship among the displacements produced from CCM and FEM as an outcome of the comparison in Figure 9.

Table 3. *Support pressures for different rock masses*

Analyze	Support Pressure (MPa)		
	Weak	Medium	Good
CCM	1.60	0	0
FEM - Horseshoe	1.60	2.40	1.20
FEM - Circular	0.80	1.50	0.80

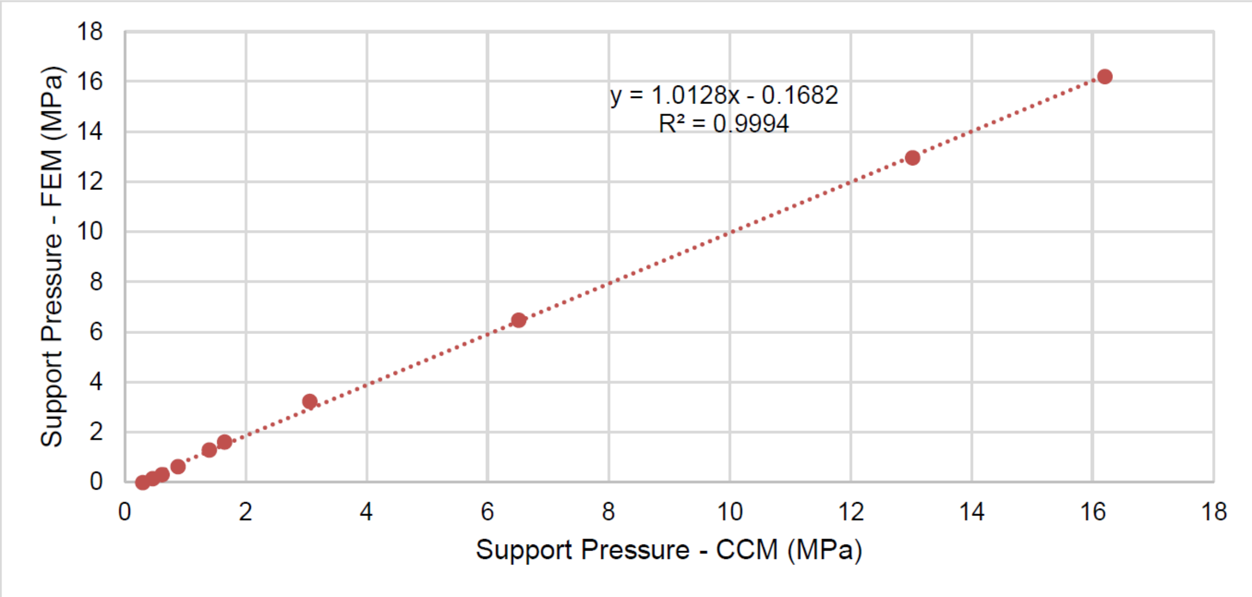

Figure 8. *Relationship between CCM and FEM model in terms of support pressures for weak rock mass*

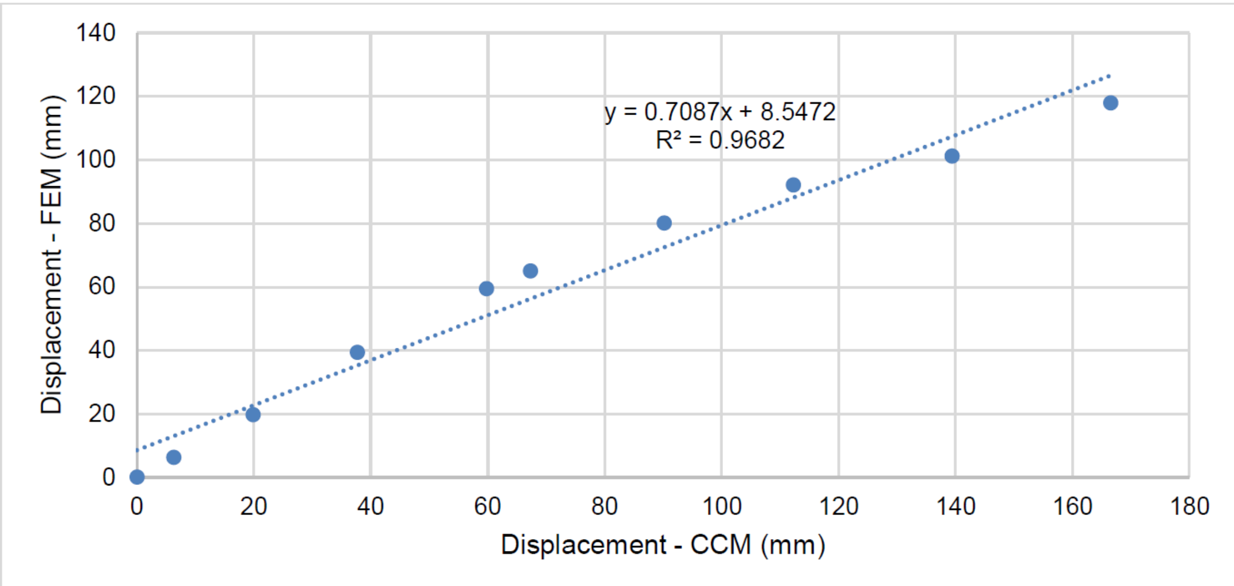

Figure 9. *Relationship between CCM and FEM model in terms of displacements for weak rock mass*

3. Conclusion

The finite element method and convergence-confinement method were used to estimate the support pressures in three different rock masses. The results obtained from the two methods are compared and the remarkable results are summarized below.

• It has been revealed that there is a high correlation in terms of support pressures and displacements between the horseshoe section FEM model created for the weak rock mass and the CCM.

• FEM models for medium and good rock masses estimated more displacement than CCM. For this reason, it was not possible to make a comparison for good and medium rock masses.

• In order to make a better comparison with the CCM, circular cross-section FEM models were created with the same opening as the horseshoe cross-section models, but the horseshoe cross-section FEM model with the CCM gave more consistent results.

• It is seen that for rock masses with properties similar to the weak rock mass modeled in this study, the support pressures and displacements can be estimated with CCM, which is more practical than FEM.

Acknowledgments

This study is a part of the first author's MSc. Thesis and was supported by Scientific Research Projects Coordination Unit of the Istanbul Technical University (ITU BAP) with a grant number in MYL-2021-43070. The authors thank to ITU BAP for financial support.

References

Aydan, Ö., Ulusay, R., & Tokashiki, N. (2014). A new rock mass quality rating system: rock mass quality rating (RMQR) and its application to the estimation of geomechanical characteristics of rock masses. Rock mechanics and rock engineering, 47, 1255-1276.

Aygar, E. B. (2022). Zayıf zeminlerde açılan büyük çaplı çift tüp tünellerde tünellerin birbirine olan etkisinin 3 boyutlu sayısal analizler ile incelenmesine bir örnek, Bolu Tüneli destek sistemlerinin değerlendirilmesi.Scientific Mining Journal, 61(3), 157-168.

Barton, N., Lien, R., & Lunde, J. J. R. M. (1974). Engineering classification of rock masses for the design of tunnel support. Rock Mechanics, 6, 189-236.

Bieniawski, Z. T. (1973). Engineering classification of jointed rock masses. Civil Engineering= Siviele Ingenieurswese, (12), 335-343.

Birön, C., Arıoğlu E. (1985). Madenlerde Tahkimat İşleri ve Tasarımı, Birsen Kitabevi, İstanbul.

Brown, E. T., Bray, J. W., Ladanyi, B., & Hoek, E. (1983). Ground response curves for rock tunnels. Journal of Geotechnical Engineering, 109(1), 15-39.

Carranza-Torres, C., & Fairhurst, C. (2000). Application of the convergence-confinement method of tunnel design to rock masses that satisfy the Hoek-Brown failure criterion. Tunnelling and underground space technology, 15(2), 187-213.

Cui, L., Yang, W., Zheng, J., & Sheng, Q. (2023). Improved equations of ground pressure for shallow large-diameter shield tunnel considering multiple impact factors. Tunnelling and Underground Space Technology, 138, 105166.

Deere, D. U. (1964). Technical description of rock cores for engineering purpose. Rock Mechanics and Engineering Geology, 1(1), 17-22.

Deere, D. U., Peck, R. B., Parker, H. W., Monsees, J. E., & Schmidt, B. (1970). Design of tunnel support systems. Highway Research Record, (339).

Goel, R. K., Jethwa, J. L., & Dhar, B. B. (1996). Effect of tunnel size on support pressure. International Journal of Rock Mechanics and Mining & Geomechanics Abstracts, 33(7).

Goel, R. K., Jethwa, J. L., & Paithankar, A. G. (1995). Indian experiences with Q and RMR systems. Tunnelling and Underground Space Technology, 10(1), 97-109.

Hoek, E., & Brown, E. T. (1997). Practical estimates of rock mass strength. International journal of rock mechanics and mining sciences, 34(8), 1165-1186.

Hoek, E. (2000). Practical rock engineering (2023 ed.). Rocscience, Toronto, available online at: http://www.rocscience.com.

Huang, M., Li, Y., Shi, Z., & Lü, X. (2022). Face stability analysis of shallow shield tunneling in layered ground under seepage flow. Tunnelling and Underground Space Technology, 119, 104201.

Jalote, P.M., Kumar A., Kumar V. (1996). Geotechniques applied in the design of the machine hall cavern, Nathpa Jhakri Hydel Project, N.W. Himalaya, India. J. Engng Geol. (India) XXV(1-4), 181-192.

Kumar, B., & Sahoo, J. P. (2023). Lining pressure for circular tunnels in two layered clay with anisotropic undrained shear strength. Geomechanics and Geoengineering, 18(2), 91-104.

Lauffer, H. (1958). Gebirgsklassifizierung für den stollenbau. Geologie und Bauwesen, 24(1), 46-51.

Moretto O., Sarra Pistone R.E. and Del Rio J.C. 1993. A case history in Argentina - Rock mechanics for underground works in the pumping storage development of Rio Grande No 1. In Comprehensive Rock Engineering. (Ed. Hudson, J.A.) 5, 159- 192. Oxford: Pergamon.

Niu, Y., Ren, T., Zhou, Q., Jiao, X., Shi, J., Xiang, K., ... & Satyanaga, A. (2023). Analysis of Excavation Parameters on Face Stability in Small Curvature Shield Tunnels. Sustainability, 15(8), 6797.

Palmstrom, A. (1995). Characterizing the strength of rock masses for use in design of underground structures. In International conference in design and construction of underground structures (Vol. 10).

Palmstrom, A. (2000). Recent developments in rock support estimates by the RMi. Journal of Rock Mechanics and Tunnelling Technology, 6(1), 1-19.

Panet, M., & Guellec, P. (1974). Contribution to the problem of the design of tunnel support behind the face. Progres en mecanique des roches-comptes rendus du 3eme congres de la societe internationale de mecanique des roches, Denver.

Panet, M., & Sulem, J. (2022). Convergence-confinement method for tunnel design, Switzerland: Springer.

Panet, M., Givet, P. D. C. O., Guilloux, A., Duc, J. L. D. G. N. M., Piraud, J., & Wong, H. T. S. D. H. (2001). The convergence-confinement method. AFTES-recommendations des Groupes de Travait.

Protodyakonov, M. M. (1907). Rock pressure on mine support (theory of mine support). Tipografiya Gubernskogo Zemstva, Yekaterinoslav, 23-45.

Rocscience. (2020a). RS2, Version 11. Toronto, Ontario, Canada.

Rocscience. (2020b). RocSupport, Version 5. Toronto, Ontario, Canada.

Rose, D. (1982). Revising Terzaghi's tunnel rock load coefficients. In The 23rd US Symposium on Rock Mechanics (USRMS). OnePetro.

Seshagiri Rao, K. (2020). Characterization, modelling and engineering of rocks and rockmasses. Indian Geotechnical Journal, 50, 1-95.

Sharma, S., Muthreja, I. L., & Yerpude, R. R. (2020). Application and comparison of squeezing estimation methods for Himalayan tunnels. Bulletin of Engineering Geology and the Environment, 79, 205-223.

Singh, B., Goel, R. K., Jethwa, J. L., & Dube, A. K. (1997). Support pressure assessment in arched underground openings through poor rock masses. Engineering Geology, 48(1-2), 59-81.

Stille, H., Groth, T., & Fredriksson, A. (1982). FEM-analysis of rock mechanical problems with JOBFEM. Stiftelsen Bergteknisk Forskning–BeFo, Stockholm, 307(1), 82.

Taghizadeh, H., Zare, S., & Mazraehli, M. (2020). Analysis of rock load for tunnel lining design. Geotechnical and Geological Engineering, 38(3), 2989-3005.

Terzaghi, K., Proctor, R. V., & White, T. L. (1946). Rock tunneling with steel supports. Commercial Shearing and Stamping Co, 119-140.

Ünal, E., & Özkan, I. (1990). Determination of classification parameters for clay-bearing and stratified rock mass. In Proceedings of the 9th International Conference on Ground Control in Mining. Morgantown: West Virginia University (pp. 250-259).

Vlachopoulos, N., & Diederichs, M. S. (2009). Improved longitudinal displacement profiles for convergence confinement analysis of deep tunnels. Rock mechanics and rock engineering, 42, 131-146.

Wang, M., & Cai, M. (2022). Numerical modeling of stand-up time of tunnels considering time-dependent deformation of jointed rock masses. Rock Mechanics and Rock Engineering, 55(7), 4305-4328.

Wickham, G. E., Tiedemann, H. R., & Skinner, E. H. (1972). Support determinations based on geologic predictions. In N Am Rapid Excav & Tunnelling Conf Proc (Vol. 1).

Zhang, H., Zhang, G., Pan, Y., Hao, Z., Chen, S., & Cheng, F. (2022). Experimental study on the mechanical behavior and deformation characteristics of lining structure of super-large section tunnels with a small clearance. Engineering Failure Analysis, 136, 106186.