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Field Observations and Numerical Back-Analysis of an Excavation in Marl Rock Supported by a Strut-Free Buttress Pile Wall

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Abstract

Marl, as a transitional soft rock, exhibits complex geotechnical behavior due to its heterogeneous structure, fissuring, and variable cementation. The difficulty of obtaining undisturbed samples makes field-based calibration essential for realistic modeling of excavation performance. This paper presents field observations and a numerical back-analysis of a strut-free excavation in marl supported by buttress pile walls. A monitoring program, including inclinometer and geodetic survey measurements, provided a reliable basis for model calibration. The excavation was predominantly in marl, ensuring consistent ground conditions and minimizing the influence of other layers. A three-dimensional finite-element back-analysis was performed to simulate the staged excavation and reproduce the observed deformation response. Both shear strength and stiffness parameters were varied: strength bounds were adopted from independent large-scale direct shear tests on intact marl and discontinuities, while stiffness ranges were based on geophysical testing. The calibrated parameter sets successfully reproduced the measured wall displacements and overall deformation patterns. The results highlight the importance of combined calibration of strength and stiffness and provide a practical reference for modeling and design of excavations in marl and similar transitional weak rock formations.

Keywords

Marl, Back-analysis, Strut-Free Buttress Pile Wall, Monitoring, Numerical modelling.

1 Introduction

Deep excavations in urban areas require reliable predictions of ground and retaining-structure deformations to ensure safety and protect nearby infrastructure. The behavior of support systems depends strongly on ground stiffness and strength, which can be determined with reasonable confidence in soils but remain uncertain in weak or transitional rock formations. Marl is a geomaterial with complex behavior due to its heterogeneous composition and transitional nature between soil and rock. Fissures, bedding, and discontinuities may significantly influence the mechanical response of excavations in rock masses (Berisavljević et al., 2022). Previous studies have shown that earth pressures in jointed rock masses can differ considerably from those predicted using conventional soil assumptions, depending on rock type, joint conditions, groundwater presence, and support

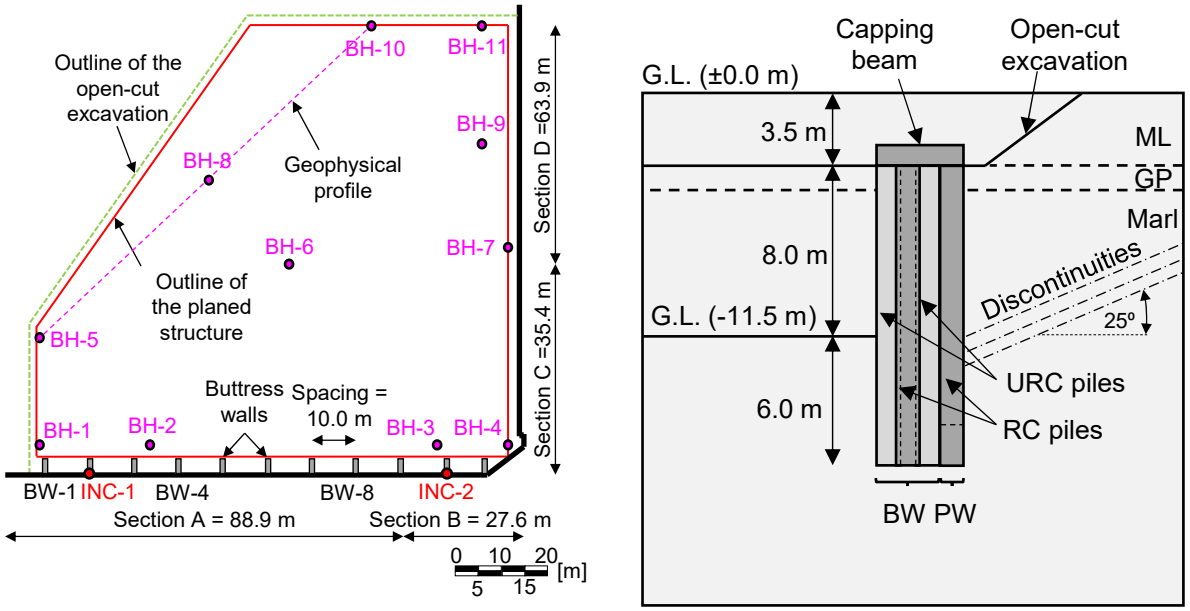
characteristics. For example, physical model tests and numerical analyses conducted by Son and Park (2014) demonstrated notable deviations in both the magnitude and distribution of earth pressures. In parallel, studies on strut-free systems with buttress walls have shown their effectiveness in reducing wall deflections and settlements through increased system stiffness and mobilized friction (Grubić et al., 2025; Lim et al., 2017). However, their combined behavior in transitional materials such as marl remains insufficiently documented. To better understand excavation performance in such conditions, field observations and monitoring data are essential. Inclinometer measurements provide valuable insight into the development of displacement and serve as a reliable basis for numerical back-analysis.

This paper presents field observations and a 3D numerical back-analysis of a deep excavation in marl supported by a strut-free buttress pile wall. Marl was modeled using the Hardening Soil (HS) model, considering both a homogeneous representation and an alternative with weak discontinuities. Shear strength bounds were adopted from an independent study, while stiffness ranges were derived from geophysical testing at the site. These parameters were varied to match the calculated wall displacements to the inclinometer measurements. Model performance was assessed by comparing predicted and observed deformation patterns. The calibrated parameters provide a practical reference for modeling and design of excavations in marl and similar weak rock formations.

2 Site Description and Ground Conditions

2.1 Excavation geometry and instrumentation layout

The excavation project is located in Sarajevo, Bosnia and Herzegovina. The designed structure was a three-level underground parking garage with plan dimensions of 116.5 × 99.3 m. The site is bordered on three sides by the Miljacka River and on the fourth by a road. The excavation depth ranges from 11.0 to 12.0 m. Temporary retaining structures were required along two sides, while the remaining sides were formed as open cuts with surface shotcrete protection. The retaining system is divided into four sections (Fig. 1a) Section A – pile wall (PW)at 2.5 mspacing with buttress walls (BW) at 10.0 m spacing; Section B – secant PWat 0.87 m spacing with BW at 10.0 m spacing; Section C – secant PWat 0.87 m spacing; Section D – soldier PWat 2.5 m spacing. Section A, which is the focus of this study, was initially excavated as an open cut to a depth of approximately 3.5 m, followed by construction of the pilewall. Buttress walls (BW) consist of three secant piles, two unreinforced (URC) and one reinforced concrete (RC), as shown in Fig. 1b. All piles have a diameter of 1.0 m; PW piles are 12.0 m long, while BW and adjacent piles are 14.0 m long.



a) b)

Fig. 1 Excavation layout and pile wall geometry: (a) plan view with boreholes and instrumentation; (b) cross-section of the retaining structure and idealized stratigraphy.

The BW are tangent to the PW and connected by a reinforced-concrete capping beam (b/h = 120/100 cm), with all elements constructed of C25/30 concrete. Excavation was performed in stages: the first phase covered BW-1 to BW-8, followed by foundation construction. At the time of analysis, only the initial stage had been completed; therefore, the monitoring data are limited to the inclinometer INC-1.

2.2 Subsoil conditions

A total of 11 boreholes (BH-1 to BH-11) were drilled, complemented by one geophysical profile 120 m in length, with geophones spaced at 5 m, to characterize subsurface conditions. Borehole depths were 10.0 m (8 locations) and 15.0 m (3 locations). Groundwater was encountered at approximately 4.0 m below ground level within the gravel layer, while the underlying low-permeability marl was dry. The stratigraphy can be idealized into three layers, as summarized in Table 2. All boreholes were terminated in marl, and no significant stratigraphic changes were assumed below this level, which was later confirmed during the constructionof foundation piles. Shear strength parameters of the marl are presented in a separate section. The Young's modulus was estimated from measured shear wave velocities (v_s = 220–527 m/s) and compressional wave velocities (v_p = 950–3200 m/s) at depths between 5 m and 30 m, resulting in a range of approximately 59–345 MPa (Alpan, 1970). The marl is light to dark grey in color (Fig. 2a and Fig. 2b). Based on its composition (approximately 20% $CaCO_3$ and 80% clay), it is classified as clayey marl according to Ulusay and Hudson (2007). Discontinuities are inclined at approximately 25° towards the excavation, as shown in Fig. 1b.



a) b)

Fig. 2 Site conditions: (a) excavation during construction; (b) marl discontinuity details.

Table 1. Summary of Soil/Rock Properties.

Description	Depth	Thickness	N_{SPT}	γ [kN/m^3]	φ′ [°]	c′ [kPa]	C_U	C_C	W [%]
Sandy silts - ML	0.0-3.5	3.5	11-19	18.5-19.0	25-30	10-15	/	/	3.8
Sandy gravel - GP	3.5-5.0	1.5	25-35	18.0-19.0	30-35	0	156.4	6.1	/
Marl	>5.0	>5.0	>50	19.5-21.0	/	/	/	/	17.4

2.3 Direct shear tests of marl

In a large-scale independent study by Strugar (1985), 96 direct shear tests were performed on intact marl and 68 on marl discontinuities, all at natural water content. The investigated material belongs to the Miocene marls of the Sarajevo–Zenica Basin, consistent with the marl at the study site. Specimen dimensions were 15 × 30 × 20 cm (width × length × height). The test results (Fig. 3a) indicate wide scatter in shear-strength parameters for intact marl, with effective cohesion (c′) ranging from 0 to 40 kPa and effective friction angle (φ′) from 20° to 35°. For discontinuities (Fig. 3b), effective cohesion ranges from 12 to 30 kPa and φ′ from 19° to 30°. This variability is attributed to the heterogeneity of marl and the difficulty of obtaining undisturbed samples. These ranges of c′ and φ′, for both intact marl and discontinuities, were adopted as upper and lower bounds in the numerical analysis.

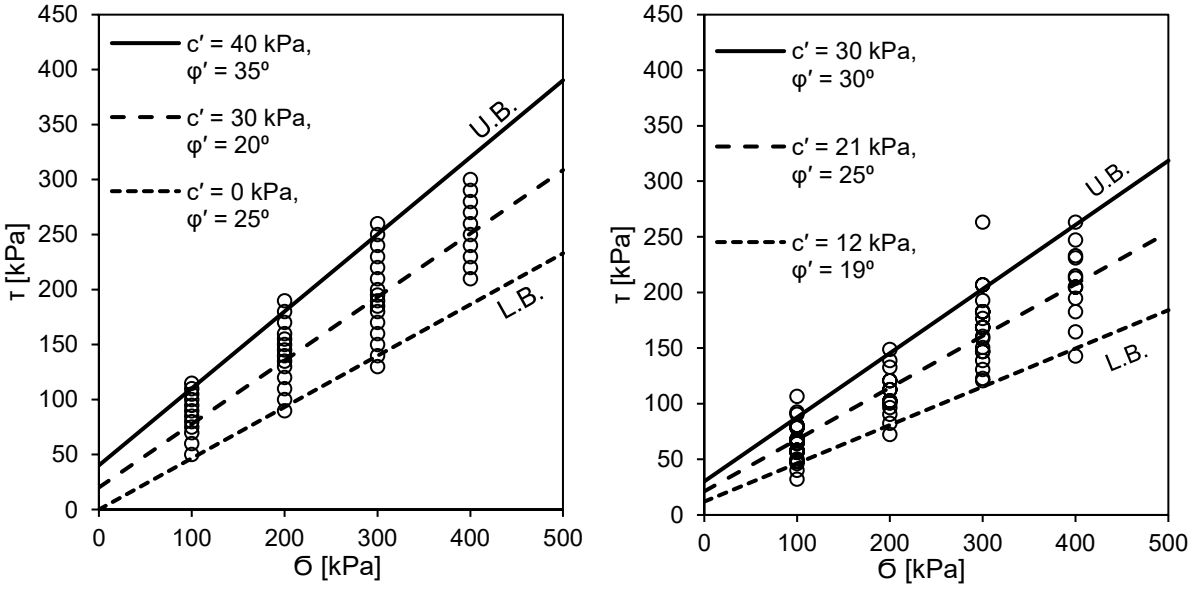


Fig. 3 Results of direct shear testing of marl at natural water content:a) intact marl, b) along marl discontinuities.

3 Numerical modeling

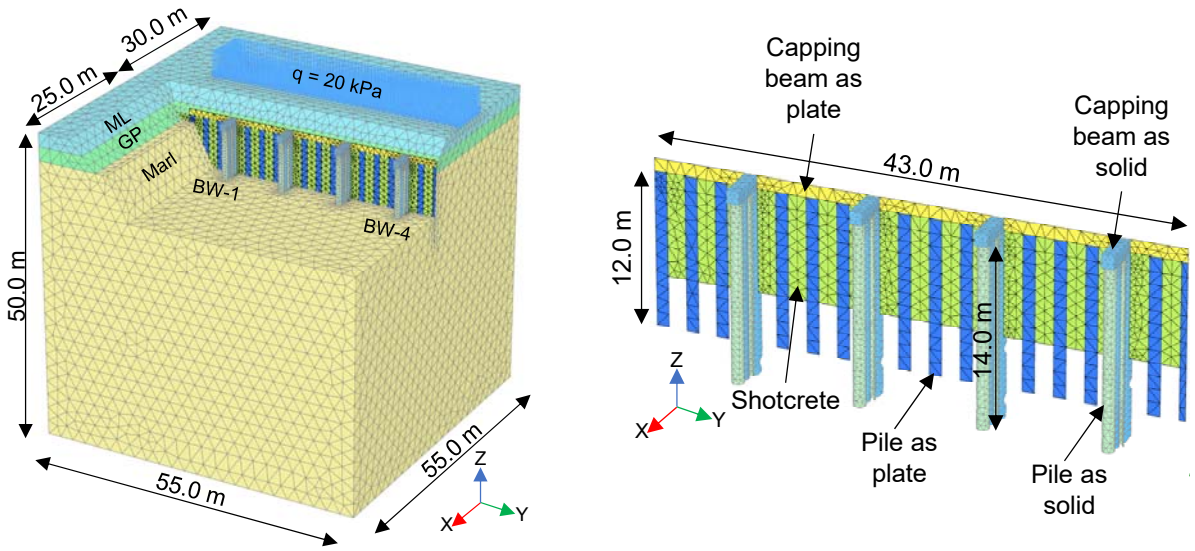
The 3D numerical back-analysis was performed using PLAXIS 3D (Brinkgreve et al., 2015), as shown in Fig. 4. Soil/rock and piles were discretized with 10-node tetrahedral elements, while plate elements were modeled using 6-node triangular elements with stiffness defined as in Skejić et al. (2023) and Bajramović & Skejić (2025).

Table 2. Material parameters used in the numerical model.

Parameters	**ML**	**GP**	**Marl**	**Marl disc.**	**RC Pile/ Capping beam**	**URC Pile**	**PW-BW interface**
Material model	HS	HS	HS	MC	LE	MC	MC
Unit weight, γ_d [kN/m^3]	19	19	21	21	25	25	25
Youngs modulus, E [MPa]	/	/	/	100	30 000	30 000	100
Poisson ratio, ν [-]	/	/	/	0.3	0.2	0.2	0.45
Tension cut-off	0	0	0	0	/	3000	0
Internal friction angle, φ [˚]	25	30	20-35	19-30	/	30	30
Cohesion, c [kN/m^2]	10	1	0-40	12-30	/	4000	30
Dilatancy angle, ψ [˚]	0	0	0-5	0	/	30	0
Reference stress, p_{ref} [kPa]	100	100	100	/	/	/	/
$E_{50,ref}$ [MPa]	15	40	100-200	/	/	/	/
$E_{oed,ref}$ [MPa]	15	40	100-200	/	/	/	/
E_{ur} [MPa]	45	120	300-600	/	/	/	/
K_0 [-]	0.577	0.50	0.65-0.42	/	/	/	/
m [-]	0.9	0.5	0.5	/	/	/	/
Poisson ratio, ν_{ur} [-]	0.2	0.2	0.2	/	/	/	/
Failure ratio, R_f [-]	0.9	0.9	0.9	/	/	/	/

The finite element mesh was refined until no further influence on the results was observed (Fig. 4a), with pile wall details in Fig. 4b. To reduce computational effort, the model included four buttress walls (BW-1 to BW-4), yielding identical displacements at INC-1 as a full model with eight walls (BW-1 to BW-8). RC piles and the corresponding capping beam were modeled as linear-elastic solids, while URC piles were represented using the Mohr–Coulomb (MC) model (Yue, 2024; Lelović &Vasović, 2020). Piles, capping beam, and shotcrete (PW) were modeled as linear-elastic plate elements, with aMohr-Coulomb (MC) interface between BW and PW. Soil and marl were modeled using the Hardening Soil (HS) model (Schanz et al., 1999). Marl discontinuities were simulated as MC interfaces spaced 1.0 m apart (Son & Park, 2014). Input parameters are given in Table 2, and a

20.0kPa surface load was applied. In total, 10 analyses were performed: five with homogeneous marl and five including discontinuities.

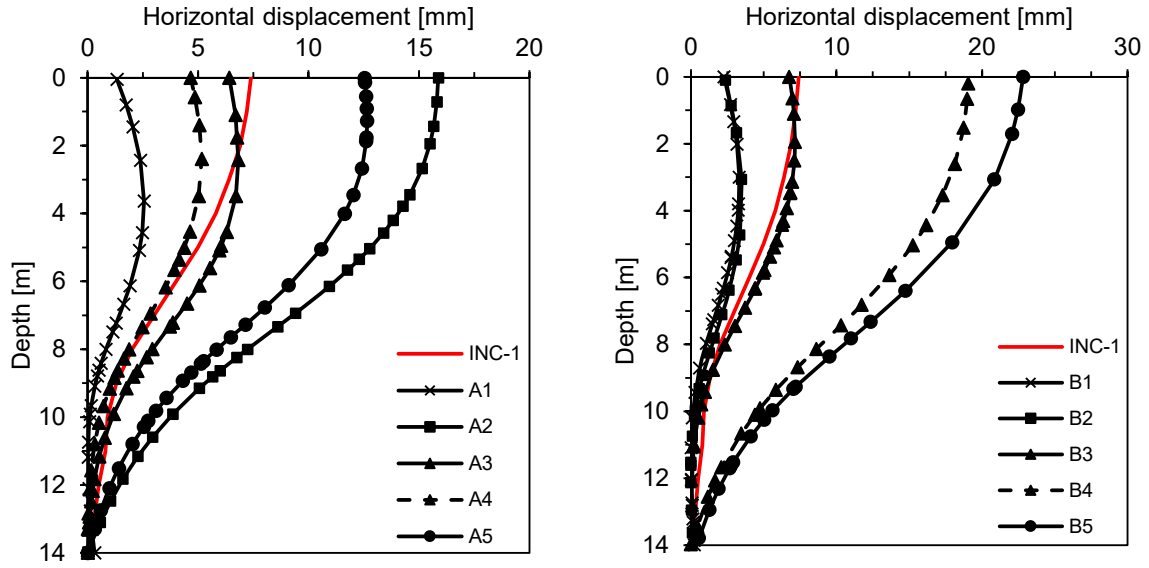


a) b)

Fig. 4 Numerical model: a) Complete 3D model, b) Details of pile wall model.

4 Back-Analysis Results and Comparison with Field Measurements

Inclinometer INC-1 recorded a maximum displacement of 7.4 mm at the pile head, confirmed by geodetic measurements, indicating no translational movement and negligible toe displacement.



a) b)

Fig. 5 Results of numerical models and comparison to inclinometer measurements: a) Marl as a homogeneous material; b) Marl withdiscontinuities.

Fig. 5compares numerical results with inclinometer data: Fig. 5a presents models with homogeneous marl (A1–A5), while Fig. 5b includes models with discontinuities (B1–B5). Both stiffness and shear strength influence displacement magnitude, with variations in shear strength within the investigated ranges producing the largest differences in model responses. The ranges of shear strength and stiffness parameters are summarized in Table 3. The agreement between calculated and measured displacement profiles was evaluated using RRMSE over the full depth profile at 1.0 m intervals, normalized by the maximum displacement. The best agreement was obtained for model B3 (RRMSE = 7.1%), followed by model A3 (RRMSE = 9.1%).

Table 3. Model variations and quantitative comparison of measured and predicted displacements based on RRMSE.

Model	IM – c [kPa]	IM – φ [˚]	IM – E [MPa]	D – c [kPa]	D – φ [˚]	RRMSE
A1	40	35	100	/	/	39.9
A2	30	20	100	/	/	82.9
A3	35	25	100	/	/	**9.1**
A4	35	25	200	/	/	15.5
A5	35	25	50	/	/	56.5
B1	40	35	100	30	30	32.7
B2	40	35	100	21	25	31.1
B3	40	35	100	12	19	**7.1**
B4	30	20	100	21	25	110.9
B5	30	20	100	12	19	137.6

5 Conclusion

A 3D numerical back-analysis of the excavation was performed and calibrated against inclinometer measurements to assess the deformation behavior of the strut-free buttress pile wall. The results showed that both shear strength and stiffness significantly influence predicted displacements. The best agreement was obtained for model B3, which includes marl discontinuities (RRMSE = 7.1%), while A3 was the closest homogeneous model (RRMSE = 9.1%), with a slightly less accurate profile. These results confirm that incorporating discontinuities improves the prediction of marl behavior, making B3 the most representative parameter set. Overall, reliable prediction requires combined calibration of strength and stiffness against field data. Despite the limitation of a single inclinometer, the RRMSE-based comparison and consistency with observed behavior support the validity of the selected parameters for future designs in similar conditions.

References

Berisavljević, D., Berisavljević, Z., Melentijević, S. (2022). The shear strength evaluation of rough and infilled joints and its indications for stability of rock cutting in schist rock mass. *Bulletin of Engineering Geology and the Environment*, *81*(3), 113. https://doi.org/10.1007/s10064-022-02580-8.

Son, M., Park,J. (2014). Physical and numerical tests of the excavation walls in jointed rock masses. Canadian Geotechnical Journal. 51(5): 554-569. https://doi.org/10.1139/cgj-2013-0081.

Grubić T, Skejić A., Kapor M, Balić A (2025). Effectiveness of the Outer Buttress Walls in Minimizing Displacements of Strut-Free Excavation: Physical and Numerical Modeling. Indian Geotech J 56, 1328–1345 https://doi.org/10.1007/s40098-025-01227-1.

Lim A, Ou C.Y., Hsieh P.G. (2017). Investigation of the integrated retaining system to limit deformations induced by deep excavation. Acta Geotech 13(4):973–995. https:// doi. org/ 10. 1007/s11440-017-0613-6.

Alpan, I. (1970).The geotehnical properties of soil. Eart-Science Reviews, 6:5-49.

ISRM Turkish National Group: The complete ISRM Suggested methods for Rock Characterization, Testing and Monitoring: 1974 - 2006. Ulusay, R., Hudson J.A. (Editors). Ankara, Turkey, 2007.

Strugar N. (1985) Otpornost na smicanje nekih kategorija “mekanih” stijena. Sarajevo (Bosnia and Herzegovina)

Brinkgreve R.B.J., Kumarswamy S., Swolfs W.M. (2015). Plaxis 3D anniversary edition manual. Delft University of Technology and Plaxis BV, Netherlands.

Skejić, A., Balić, A., Kapor, M. (2023). Case history on excessively large displacements and remediation of pile-supported excavation in a sloping ground. Engineering Failure Analysis, 143, 106856.https://doi.org/10.1016/j.engfailanal.2022.106856.

Bajramović, N., Skejić, A. (2025). Structural Failure of Strutted Soldier Pile Wall: Emergency Response, Forensic Diagnosis, and Postaccident Remediation. Indian Geotechnical Journal, 1-21.https://doi.org/10.1007/s40098-025-01433-x.

Yue, J., Wang, D., Jiang, Y., Shi, S., Huang, Y. (2024). Determination of Shear Strength Parameters of Concrete Materials Based on the Rectangular Section Splitting Method. *Materials*, *17*(24), 6141. https://doi.org/10.3390/ma17246141.

Lelović, S.,Vasović, D. (2020). Determination of Mohr-Coulomb Parameters for Modelling of Concrete. *Crystals*, *10*(9), 808. https://doi.org/10.3390/cryst10090808.

Schanz T, Vermeer P.A., Bonnier P.G. (1999). The hardening soil model: formulation and verification. Comput Geotech 281–296.