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NUMERICAL MODELLING OF TUNNELS IN BLOCK-IN-MATRIX FORMATIONS

Summary: This paper presents an automated workflow linking a voxel-based block-in-matrix (BiM) ground model to PLAXIS 2D through its Python HTTP API, focusing on finite element (FE) simulation of tunnel excavation in such heterogeneous rock. Building on prior borehole-constrained ground model and conditional random field (CRF) matrix-variability studies, the paper details the material models, excavation sequence and script logic used to transfer voxelized cross-sections, each containing thousands of block and matrix polygons, into PLAXIS 2D via batched API requests. Both block and matrix are represented with the Mohr-Coulomb elastic-perfectly plastic criterion; blocks are described with constant values of geomechanical parameters while matrix parameters vary spatially. Excavation is simulated by the convergence-confinement method in ten deconfinement stages. Results show generally reduced but scattered radial displacements relative to a homogeneous deterministic model.

Keywords: block-in-matrix, PLAXIS 2D, Python API, finite element method, tunnel excavation, Mohr-Coulomb

NUMERIČKO MODELIRANJE TUNELA U “BLOCK-IN-MATRIX” FORMACIJAMA

Rezime: Rad predstavlja automatizovan postupak za simulaciju iskopa tunela u block-in-matrix (BiM) stenskoj masi metodom konačnih elemenata, koji vokselizovani inženjerskogeološki model povezuje sa programom za numeričku analizu PLAXIS 2D putem Python HTTP API-ja. Nadovezujući se na prethodna istraživanja BiM modela uslovljenih bušotinama i simulacije varijabilnosti geomehaničkih karakteristika matrice uslovnim slučajnim poljima (CRF), rad se fokusira na metodu konačnih elemenata: materijalne modele, modeliranje iskopa i logiku skripti kojima se vokselizovani preseci, sa po nekoliko desetina hiljada poligona blokova i matrice, automatski prenose u PLAXIS 2D kroz grupisane API zahteve. Blokovi i matrica modelirani su Mor-Kulonovim kriterijumom, sa konstantnim vrednostima geomehaničkih parametara blokova i prostorno promenljivim parametrima matrice. Iskop je simuliran “convergence-confinement” metodom kroz deset faza rasterećenja. Rezultati pokazuju generalno smanjena, ali rasuta radijalna pomeranja u odnosu na homogeni deterministički model.

Ključne reči: block-in-matrix, PLAXIS 2D, Python API, metoda konačnih elemenata, iskop tunela, Mor-Kulonov model

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1. INTRODUCTION

Block-in-matrix (BiM) materials, or “bimrocks”, represent geologically complex and highly heterogeneous formations composed of relatively strong rock blocks embedded within a weaker matrix. Depending on their geological origin, these materials can be linked to sedimentary, tectonic, gravitational, or weathering processes, resulting in irregular and variable block size, shape, orientation and spatial distribution [1]. Consequently, their behaviour cannot fully be described by conventional soil or rock mass assumptions, since the mechanical response is governed both by the properties of individual components and their spatial arrangement. Since field investigations and laboratory testing can be challenging and of limited use, the main concern is how to characterize, represent and model block in matrix materials, in order to be able to make more reliable design decisions.

Pronounced block-matrix contrast as well as their interference makes them particularly demanding for underground construction, where stress concentrations at block boundaries and non-uniform ground response can compromise tunnel stability and lining design [2]. During tunnel excavation, these materials may cause significant challenges such as excessive deformation or local instabilities, stress redistribution, tool wear, overbreak and the development of irregular failure mechanisms around the tunnel opening. If not addressed adequately during investigation, characterization and design, block in matrix conditions may result in delays, increased costs, damage to equipment and structure, or the need for additional support and remediation measures.

Past research addressed the development of three-dimensional BiM ground models from borehole data, using stochastic block reconstruction constrained by field investigation, voxel-based discretisation, and geostatistical simulation of spatially variable matrix strength and deformation parameters, and their integration with numerical analysis. The present paper focuses specifically on the numerical finite element model of a circular tunnel in BiM: how the voxel-based BiM ground model is translated into a PLAXIS 2D FE model, which material models and excavation scheme are applied, and how the transfer is automated through the PLAXIS 2D Python HTTP API [3]. Since a single 2D cross-section of the voxel-based domain typically contains about ten thousand distinct soil polygons, and a full analysis campaign requires dozens of such cross-sections, manual model construction is not practically feasible. The scripting logic that makes the workflow tractable is therefore described in detail, together with the resulting tunnel response.

2. BLOCK-IN-MATRIX GROUND MODEL

Rather than treating it only as a descriptive geological feature, we model block in matrix as an individual component that directly influences the numerical interpretation of tunnel response. Our BiM ground model is reconstructed from synthetic borehole data based on block intercepts recorded along boreholes, which we convert to spherical blocks via a Bayesian chord-to-diameter relationship [1] and use to derive the volumetric block proportion parameter (VBP) that controls block-matrix spatial share. Borehole linear block proportion (LBP) is corrected by an uncertainty factor to obtain a target volumetric block proportion (VBP) range [4, 5]. Additional blocks are then generated stochastically, with diameters sampled from a truncated power-law distribution, until the target VBP is reached, while respecting the borehole-derived spheres and a minimum block spacing.

After the remaining volume is stochastically filled until reaching the target VBP, the resulting BiM geometry is discretised into a uniform voxel grid to enable compatibility with further simulations. Every voxel centroid is classified as block or matrix. Block and matrix mechanical parameters are derived individually: due to their comparably higher stiffness, blocks get assigned constant values (since blocks are markedly stiffer than the matrix and are not expected to control the overall system response [6]); and to account for the spatial variability, matrix values are simulated within a geostatistical procedure using the conditional random fields (CRF). Conditional Random Fields are generated by the randomization method and conditioned to the borehole samples through ordinary kriging [7, 8]. By directly integrating this model into numerical analysis, we aim at providing a more realistic foundation for evaluating BiM behaviour and improving the geological-geotechnical understanding of tunnel excavation in heterogeneous ground.

3. FINITE ELEMENT MODEL OF THE TUNNEL IN BIMROCK

The reference case is a circular tunnel, analysed using a set of 2D cross-sections extracted perpendicular to the tunnel axis from a 3D BiM ground model. Numerical model was developed within PLAXIS 2D FE code. PLAXIS 2D is a world-wide used code for the stress–strain, stability, and groundwater flow analysis in geotechnical engineering, that supports an easy graphical input of the models with complex geometry, as well as the illustrative presentation of the results [3]. It also features various constitutive models for soil and rock, with different levels of complexity.

The domain surrounding the excavation is extended, in every direction, by an outer buffer zone wide enough to prevent the imposed boundary conditions from affecting the deformation field around the tunnel. Since the fine, heterogeneous polygon discretization is only needed near the excavation, this buffer is represented as a homogeneous continuum, meshed at a coarser resolution and with average matrix properties assigned. This keeps the total element count and the computational cost manageable, while preserving accuracy near the excavation zone.

All external boundaries of the resulting domain are fixed against translation. The initial stress state is derived as isotropic from the assumed overburden and unit weight of the ground and the analyses is to be carried out under drained or undrained conditions, depending on the site conditions.

Both the block and matrix domains are represented by the Mohr-Coulomb elastic-perfectly plastic constitutive model. Because the blocks are stiffer and stronger than the matrix, they are assigned a single, constant set of mean geomechanical parameters. Matrix behaviour, in contrast, is kept spatially variable: each matrix voxel gets its own values of cohesion, internal friction angle and Young’s modulus by the CRF realisation, so no two matrix polygons end up with exactly the same values, while still staying consistent with the borehole data.

Each classified voxel, whether it represents the matrix or the block is translated directly into an individual soil polygon in the PLAXIS 2D geometry. Because the voxel size is small relative to the domain, a single cross-section typically yields on the order of ten thousand polygons; this fine resolution allows the model to reproduce the irregular, locally asymmetric block arrangement rather than a homogenised approximation.

Depending on the aim of the analysis, the excavation can be left unlined, therefore isolating the ground response from the lining design, or a structural lining can be modelled. Either way, it is useful to place auxiliary (“dummy”) structural elements, such as plate elements, along the excavation perimeter and along one or more reference directions crossing the excavation. These elements carry no structural role, their only purpose is to provide a fixed, ordered set of nodes from which displacement results can be extracted directly, without any manual node-sorting after the calculation.

The calculation is done in several phases: an initial phase establishes the in-situ stress field, after which the excavation is simulated using the convergence-confinement method [9]. The radial support pressure $\sigma_{r,i}$ at the excavation boundary is released gradually, over several equal increments:

$$\sigma_{r,i} = (1 - \lambda_i)\sigma_0;\ \lambda_i = i\ /\ n; i = 1 \ldots n \tag{1}$$

where σ_0 is the initial radial stress and λ_i the deconfinement ratio at stage i, and n is the total number of excavation stages chosen for the analysis.

In PLAXIS 2D, this can be accomplished in two ways: the Incomplete Staged Construction method and the Deconfinement method. The Incomplete Staged Construction method releases the resulting unbalance of deactivating soil polygons gradually through a single global stage parameter (ΣM_{stage}) that applies to the model as a whole, whereas the Deconfinement method releases the initial stress independently for each deactivated soil cluster through a local factor $(1-\beta)$, so that different tunnels can be de-confined on different schedules. The two approaches are generally equivalent for a single tunnel analysed without groundwater, but the appropriate choice depends mainly on whether groundwater is present since only the Incomplete Staged Construction method captures the accompanying change in pore pressure, and on whether multiple tunnels are modelled simultaneously, since only the Deconfinement method allows each tunnel to be de-confined independently.

For the analysed model, the soil response is evaluated from the radial displacements along the excavation perimeter and along the reference directions defined by the dummy structural elements, together with the extent and geometry of the plastic (yielding) zones developing around the excavation.

4. AUTOMATION VIA THE PLAXIS 2D PYTHON API

Manual construction of a finite element model of this kind, comprising a very large number of soil polygons, each with its own material assignment, is impractical and error prone. The entire preprocessing work is therefore automated through the PLAXIS 2D HTTP API and its Python wrapper (Figure 1).

For each model to be analysed, a Python script extracts cross section data from a voxelized ground model and splits the resulting data into two datasets: a geometry dataset, holding the identifier and centroid coordinated of every voxel, from which the soil polygons are built; and a material dataset, holding the geomechanical parameters (cohesion, internal friction angle and Young’s modulus) assigned to each matrix voxel by the corresponding CRF realisation, together with the constant reference parameters used for the blocks.

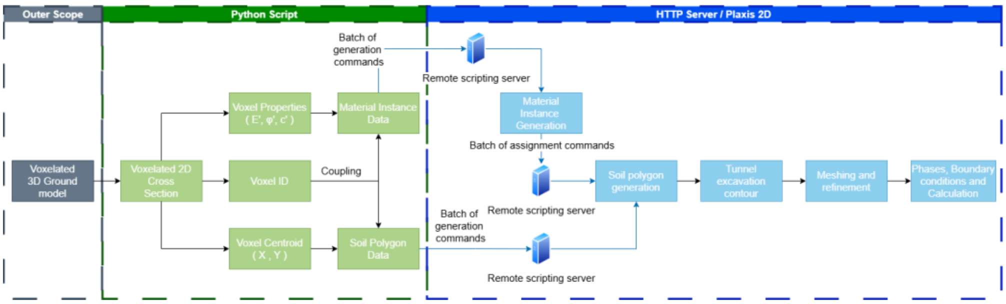

Figure 1: Flowchart of the ground-model-slice-to-FEM integration procedure [6]

Rather than issuing one API command per polygon, which would repeatedly trigger GUI refresh operations and risk congesting the HTTP scripting server, polygons are processed in batches of a fixed size. For each batch, the script assembles the associated geometry-creation, material-definition and material-assignment commands into a single request before it is sent to the PLAXIS 2D server. This batching strategy is what keeps the server responsive and the pre-processing step computationally tractable, regardless of how many polygons a given cross-section contains; the batch size itself is simply a tuning parameter, to be set according to the available server and hardware resources.

Once the geometry and materials for a cross-section have been generated, the same scripted sequence defines the tunnel excavation contour, triggers local mesh refinement around the opening, and sets up the calculation phases: an initial phase establishing the in-situ stress state, followed by the deconfinement stages. The script then launches the calculation and, once it has converged, extracts the displacement and plastic-point results required for post-processing.

Because every step of the procedure (slicing, geometry and material batching, excavation contour generation, phasing, calculation and result extraction) is fully scripted, it can be automatically reapplied to other cross-sections.

5. DEMONSTRATION EXAMPLE

The procedure described in the previous sections is illustrated on a synthetic example of a single circular tunnel with a diameter of 10 m. The ground model domain is defined with 10 boreholes, from which 10 cross sections, each of 50x50 m in extent, are subsequently extracted for FE analysis. The voxel grid is built with a uniform resolution of 0.5 m, equal to the smallest admissible block sphere diameter [6].

Spatial variability of the matrix geomechanical parameters is simulated by conditioning the random field on borehole sample points, while the block properties are kept constant. Table 1 lists the resulting parameter ranges and mean values used in the FE analyses.

Table 1: Block and matrix geomechanical parameters used in FE analyses (modified after [6])

Parameter	Statistic	Matrix	Blocks
c $[kPa]$	min	5.1	905.1
	max	14.9	1093.5
	μ (mean)	9.6	1008.1
φ [°]	min	24.0	49.1
	max	31.9	51.0
	μ (mean)	27.9	50.2
E $[GPa]$	min	1.5	7.0
	max	3.4	7.4
	μ (mean)	2.6	7.2

Following the procedure described in the previous section, each cross section is surrounded by a buffer zone extending $5L_c$ (50 m) beyond the excavation boundary, represented as a homogeneous continuum with coarser voxel resolution and average matrix properties (Figure 2).

The initial stress state is isotropic, with vertical and horizontal stress both equal to 1.74 MPa, corresponding to an overburden of approximately 80–85 m; the analyses are carried out under drained conditions, without groundwater. Given the 0.5 m voxel resolution, each cross-section comprises on the order of ten thousand distinct soil polygons. Applying the automation workflow, soil polygons and their material assignments are transferred to PLAXIS 2D in batches of 200 polygons at a time.

Excavation is simulated over ten equal deconfinement stages (n=10 in Eq. (1)), that is, in successive increments of 10% stress release per phase. Deconfinement is applied using the described Deconfinement method rather than the Staged Construction method because drained analysis is applied.

Across the analysed cross-sections, tunnel convergence is generally lower than in an equivalent, fully homogenous deterministic model using mean matrix properties, consistent with the reinforcing effect of the stiffer blocks embedded in the weaker matrix (Figure 3).

This reduction is accompanied by noticeable scatter between individual cross-sections because of the wide range of possible block arrangements. Sections with blocks favourably positioned around the excavation show markedly reduced displacement, while sections with unfavourably positioned blocks show localised amplification, occasionally exceeding the deterministic reference.

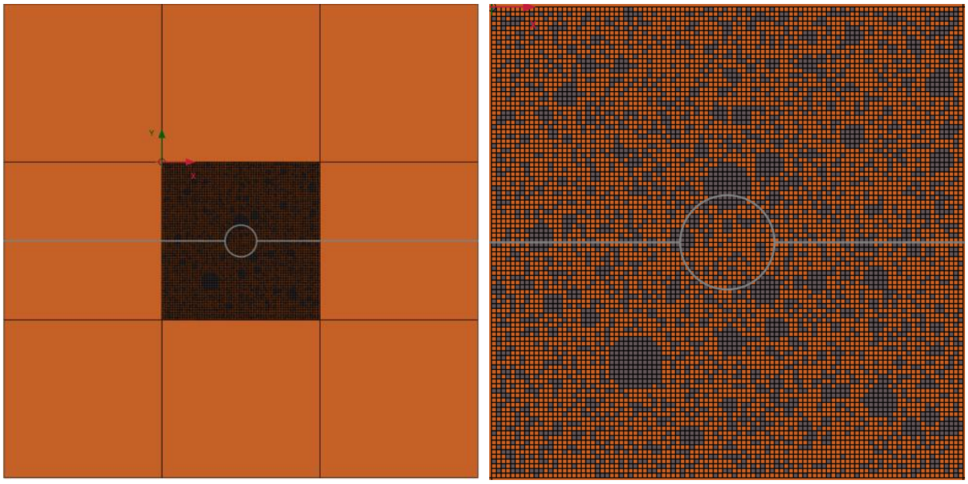

Figure 2: PLAXIS 2D model generated from a voxelized ground-model slice, with a close-up of the block/matrix polygon layout around the tunnel [6]

The resulting radial displacement profile along the tunnel perimeter is correspondingly non-uniform and non-symmetric, illustrating why a homogeneous ground assumption cannot capture the uneven loading and non-uniform bending-moment distribution relevant to lining design.

Plastic yielding is concentrated in the weaker matrix, particularly where the CRF realisation leads to local reduction of cohesion or internal friction angle near the excavation boundary, while the embedded blocks remain elastic throughout, consistent with their considerably higher strength and stiffness. In most analysed sections, the overall plastic-zone extent is smaller than that predicted by the deterministic model, again reflecting the net stiffening contribution of the blocks, although its shape follows the local block arrangement rather than the smooth, axisymmetric pattern of the homogeneous case.

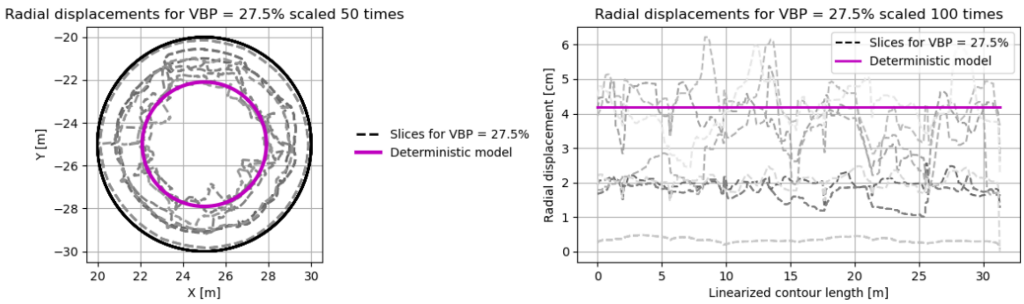

Figure 3: Radial displacement results for VBP=27.5%: tunnel cross-section (left) and perimeter displacement vs. linearized contour length (right) – modified after [6]

6. CONCLUSIONS

This paper described the automated finite element modelling workflow for simulating tunnel excavation in block-in-matrix rock, in which a voxelized, borehole-constrained ground model, with constant block properties and spatially variable matrix properties, is transferred to PLAXIS 2D through its Python HTTP API. Batching soil-polygon and material commands proved essential to make the transfer of cross-sections containing on the order of ten thousand polygons computationally tractable, allowing FE analyses to be generated and run automatically.

Modelling both block and matrix with the Mohr-Coulomb criterion and simulating excavation through staged convergence-confinement reproduced the expected stiffening effect of embedded blocks, as well as the scatter and local asymmetry in tunnel response that only a heterogeneous, data-constrained representation of the rock mass can capture, which marks the information directly relevant to tunnel lining design. Future work will extend the automated linkage to fully three-dimensional FE analyses and incorporate face-mapping observations collected during excavation to update the ground model as construction proceeds.

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REFERENCES

[1] Medley E. W. The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks). PhD Thesis. University of California, Berkeley, 1994.

[2] Napoli M. L, Barbero M, Scavia C. (2021). Tunneling in heterogeneous rock masses with a block-in-matrix fabric. International Journal of Rock Mechanics and Mining Sciences, 138, 104655, 2021, 10.1016/j.ijrmms.2021.104655.

[3] Bentley Systems. PLAXIS 2D Reference Manual, version 2024.3, Bentley Systems, 2024.

[4] Napoli M. L, Milan L, Barbero M, Scavia C. Identifying uncertainty in estimates of bimrocks volumetric proportions from 2D measurements. Engineering Geology, 278, 105831, 2020, 10.1016/j.enggeo.2020.105831.

[5] Zhang H, Huang C, Wang L, Cao Y, Boldini D. Estimation of volumetric block proportions from 1D boring of bim-materials considering different block forms. Engineering Geology, 353, 108094, 2025, 10.1016/j.enggeo.2025.108094.

[6] Micić K, Joksimović N, Marjanović M, Jovičić V, Ninić J. Towards an advanced geotechnical modelling of block-in-matrix rock for robust tunnel design and construction, 19th World Conference of the Associated Research Centres for the Urban Underground Space, Belgrade, 2025, 2.3.99, doi.ub.kg.ac.rs/doi/acuus25-2-3.

[7] Heße F, Prykhodko V, Schlüter S, Attinger S. Generating random fields with a truncated power-law variogram: A comparison of several numerical methods, Environmental Modelling & Software, 55, 2014, 32–48.

[8] Müller S, Schüler L, Zech A, Heße F. GSTools v1.3: A toolbox for geostatistical modelling in Python, Geoscientific Model Development, 15, 2022, 3161–3182.

[9] Rabcewicz L. The New Austrian Tunneling Method (NATM), Water Power, 16(8), 1964, 453–457.