

Interdisciplinary approach for groundwater flow patterns identification

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ABSTRACT: In the context of atmospheric CO₂ concentration reaching 426 parts per million and CH₄ levels being at 1929 parts per billion, there is a 1.4°C global temperature rise since preindustrial times and an Arctic Sea Ice minimum extent decrease of 12.2% per decade since 1979. Consequently, those with an interest in the field of geotechnics have also to adapt themselves to the upcoming conditions manifested as extreme weather occurrences such as heatwaves, cold waves, drought or heavy precipitation. This case study aims to identify water infiltration prone areas as critical zones for the construction of a highway tunnel that will be geographically located in the Southern Carpathians region of Romania. The importance of the given subject is given by the expected unprecedented weather conditions in relation to the geology of the area which consists of a mountainous terrain composed of a metamorphic: gneiss, amphibolite and micaceous, graphite or garnet schist basement covered with a quaternary, mostly composed of sand and gravel sedimentary cover. The area is located close to a tectonic fault system, known in the literature as Falia Oltului. The influence of the fault system and the tectonic stress of the region generated cataclastic zones within the rock mass, these in turn acting as water infiltration prone channels in the subsurface. The mapping of faults and highly fractured areas located below the surface may be achieved by combining geophysical plus borehole data and direct core observations as well as by RQD index and specific laboratory testing. Interpretation will be further verified by piezometer monitoring reports and mineralogical analysis. Mineralogy shall confirm if structures identified as water infiltration prone areas also exhibit a higher degree of alteration for their constituent minerals as it is well known that some, such as feldspar, undergo alteration in contact with water during geological time.

KEYWORDS: climate change, geotechnics, geology, mineralogy, tectonics, groundwater.

1 INTRODUCTION

Anthropogenically induced variations in atmospheric chemistry imply a destabilization of air current movements at planetary scale. Also, the storage of so-called greenhouse gases within the atmosphere promotes a process wherein less radiant heat being reflected from the earth's surface escapes into outer space, as it is being absorbed and then released by the molecules of these gases. Therefore, more energy from the sun is stored, while more evaporation in the oceans and more sea ice melting in areas such as the Poles or Greenland takes place. The atmosphere is able to contain more water vapor because its capacity increases by 7% when the atmospheric temperature rises by 1°C (Chang et al. 2019).

In the context of atmospheric CO₂ concentration reaching 426 parts per million and CH₄ levels being at 1929 parts per billion, there is a 1.4°C global temperature rise since preindustrial times and an Arctic Sea Ice minimum extent decrease of 12.2% per decade since 1979 (12.10.2024, 15:36, <https://science.nasa.gov/climate-change/>).

For the geotechnical engineer, this directly translates as potential discrepancies between the expected weather conditions and the actual ones, for a given site. Geotechnical infrastructures like soil embankments, slopes, retaining walls, foundations, engineered landfills, overburden dumps, and pavements get continuously exposed to environmental conditions which are climate dependent (Kandalai et al. 2023).

Many researchers in the field realized this fact and therefore a considerable number of scientific articles were written with the purpose of predicting how these changing conditions would affect many of the now stable, soil or rock masses.

It was proved that different evolutions of pore pressure fields and seepage channels play important roles in forming the different failure patterns (Wang et al. 2023). When facing high mean precipitation, two major failure patterns that arise are deep seated or shallow surface failures, one corresponding to small and the latter to large rainfall intensities.

There is more of recently conducted research that was directed towards rainfall-induced slope instability (Wang et al. 2024; Wang & Xu 2025). It is stated that the process of rainfall-induced landslide is closely related to the interaction between rainfall hydrology and geomechanics. The rainfall hydrological process in slope unit will not only increase the bulk density and pore pressure of the geomaterials but also decrease their strength, which leads to the increase of sliding force and the decrease of anti-sliding force. These factors coupled with seepage force from infiltration and erosion force from surface runoff adversely affect the slope stability (Wang & Xu 2025). The authors also provide a fully developed algorithm that applies a hybrid Lagrangian-Eulerian computational method, GPU-based MPM software (CoSim-MPM), to model the influence of rainfall on slope stability, while considering all the above-mentioned factors.

For the case of Europe, the EEA (2012) has synthesised climate change predictions. Observed and predicted changes are split into six climate areas with a significant trend separating north (eastern) Europe and south (western) Europe, with an increase and decrease of mean precipitation of approximately 30–35 mm per decade (EEA, 2012; Vardon, 2015). Higher mean precipitation is expected for north (eastern) Europe where Romania is located.

Groundwater flow, driven, controlled and determined by topography, geology and climate, is responsible for several natural surface manifestations and affected by anthropogenic processes. Therefore, flowing groundwater can be regarded as an environmental agent. Fracturing and tectonic elements have an effect on the permeability field for a given site. Spatially continuous geophysical data can support groundwater flow model building: systematically combined geophysical methods can provide model input. Integration of lithostratigraphic, electrostratigraphic and hydrostratigraphic information could aid groundwater flow model construction: hydrostratigraphic units and their hydraulic behaviour, boundaries and geometry can be obtained (Tóth et al. 2016).

Even though the cited source refers to processes occurring at a larger scale than those that are treated in this paper, the same controlling factors of groundwater behavior can be assumed for the site's scale analysis.

This paper adopts the above presented ideas and adds shallow seismic survey as a potential source for site characterization. Though, it won't go as far as to model or predict the stability of any slope section or tunnel structure but rather provide a perspective from which one that intends to achieve that, obtains a clear image and understanding of the geological processes that affect or affected the studied materials and consequently determine their actual nature and behavior.

Herein: 17 geotechnical boreholes with investigation depths between 20.00 – 70.00 m, 4 of which were equipped with piezometer monitoring tubing; 4 shallow seismic profiles that in terms of processing included both Multichannel analysis of surface waves and Seismic refraction for the same alignments and 7 ERT (Electrical Resistivity Tomography) profiles were integrated with the purpose of unravelling subsurface: lithological, structural, hydrogeological, mechanical and electrical properties. The investigations plan was initially implemented for the redaction of the geotechnical study conducted for a Highway Tunnel geographically located in the Southern Carpathians region of Romania.

These measurements were complemented by: surface geological and geomorphological mapping; lithological mapping of core material; geotechnical laboratory testing and mineralogical analysis on samples from various depths or from the surface.

Field and laboratory investigations were conducted in accordance with Romanian standardized legislation which mostly follows the directions given by EN 1997-1/2: Eurocode 7 and adapts details according to local specific conditions.

This paper is concerned with the nature and behavior of the terrain in a natural state. Its purpose is to identify patterns of shallow groundwater flow, based on the investigations plan initially implemented for the geotechnical study, through an interdisciplinary approach. Herein no water table is assumed to be present, therefore the term groundwater is adapted to serve our specific purpose rather than its proper meaning in the field of hydrology and hydrogeology respectively. Consequently, the distinction between unsaturated flow and groundwater flow is not considered.

2 CASE STUDY

2.1 Geographical and geomorphological conditions

Romania is a Central, Eastern European country currently with a temperate continental climate. The site's location is part of the Southern Carpathians (Figure 1).

Figure 1. Geographic position of the site as viewed in Google Earth.

To represent the geomorphology of the area, a digital elevation model was chosen. The model was based on available topographical data and field geomorphological mapping confirmed its validity. Slope angles are in the range of 20 – 45° while ground level ranges from 320 to 410 m above the Black Sea level.

Figure 2. Digital elevation model of the study area. Contour lines delimit ground level intervals. Black lines represent the projection of the two tunnel axes. Blue lines represent erosional valleys.

The section corresponding to the middle of the tunnel's projection is of particular importance as it will be later addressed in subchapter 2.4.

2.2 Geological context

Geologically, we are treating an area of rare metamorphic rock outcrops with an irregularly displayed sedimentary cover. The scarcity of exposed bedrock is also due to the extensive development of residual soils.

The highly curved Carpathian and Balkan orogens represent the eastern continuations of the Alpine belt, consisting of a collage of pre-Alpine terranes, amalgamated and docked to Laurussia during the Variscan orogeny (Balintoni et al. 2010). Within the study area, basement formations pertain to the Sebeş-Lotru terrain of the Median Dacides. According to Badescu (1997), this tectonic unit represents a ribbon continent. The western leading margin of the European plate, that during Middle to Upper Jurassic was located between the External Dacides (Ceahlau Basin) and the Tethyan realm. The terranes constituting the Median Dacides were to be later affected by compressional tectonic processes during the closure of the Tethys Ocean. The Sebeş-Lotru terrain has a tectonic history connected to that of the Median Dacides, that nowadays are part of the Getic-Supraetic Alpine nappe system.

When talking about the Sebeş-Lotru terrane, we are referring to those basement units from the Getic-Supraetic Alpine nappe system that contain eclogites and/or Neoproterozoic igneous protoliths (Balintoni et al. 2010). The important aspect that is implied is the deep burial history of the materials in discussion. Eclogite-bearing metamorphic terranes are present in former deep crustal sections of ancient and eroded mountain belts (Möller et al. 2015). They are typically generated in high-pressure granulite or upper amphibolite facies conditions at depths of at least 30 km.

One of the intrinsic characteristics of metamorphic rocks is their schistosity or foliation. These are structural features that confer anisotropy to the rock mass. Furthermore, after their genesis during the Variscan orogeny (Balintoni et al. 2010), these formations were subjected to Alpine age large-scale fold and thrust tectonics where deformations were predominantly in the brittle domain. Most of the time they exhibit the results of the tectonic processes that modeled them through their general cataclastic character (Figure 3, Figure 4). Such tectonically induced deformations leave the material in a friable state that promotes a kind of mechanical behavior more characteristic to granular materials rather than to outcropping rock masses, for reasons that shall be briefly discussed. One is that highly fractured rock slopes for which discontinuity planes seem randomly oriented on a stereonet will exhibit circular failure (Wyllie & Mah 2004), when destabilizing forces surpass stabilizing ones. Another is that the increased permeability created by the fracture network allows meteoric water to infiltrate and chemically interact with the constituent mineral phases [(1), (2), (3)].

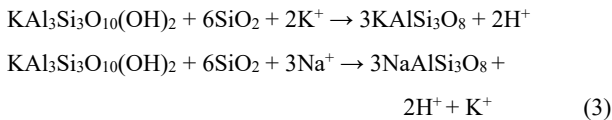
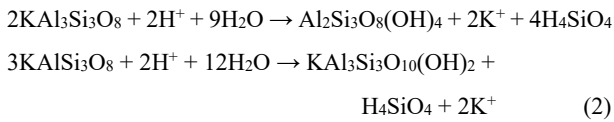
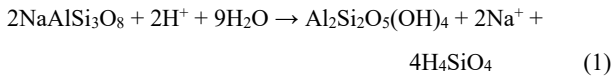
Figure 3. Tectonic breccia, primarily made up of angular quartz and feldspar fragments, set within a clay-rich matrix. Borehole investigation 301 A, investigation realized at an elevation of 342.887 m, sample retrieved from the depth of 33 m.

Figure 4. Cataclastic gneiss of the Sebes Lotru. Field point, elevation 320 m.

The Alpine age of the Carpathians does not render them ancient so one may without mistake assume a high rate of erosion that affected the Carpathian Mountains in this region. This geological process removes loads from the rock mass promoting a sort of reopening of the discontinuity planes and

maximizing the effects of water pressure in relation to effective spherical stresses.

Relaxation after unloading due to the erosion of covering layers inevitably took place, providing thus more space for consequent groundwater flow within the feldspar rich unit. By being exposed in this way, these formations are continuously subjected to the effects of the following corrosion reactions. According to Wu et al. (2023):



Where: (1) - corrosion reactions for the sodium feldspar; (2) - corrosion reactions for the potassium feldspar; (3) - corrosion reactions for micas. It is worth noting that micas are present both genetically and as a product of the reaction between orthoclase, water and positively charged hydrogen ions.

These claims are supported by experimental evidence obtained from thin sections analyzed using a polarizing (two-Nicol type) optical microscope, which revealed distinct features across different samples, therefore indicating various stages in the progression of the alteration process (Figure 5). The following stages were chosen hypothetically. Residual soils are more common within the study area than rock samples that allow the preparation of thin sections.

a) Stage 1- Feldspar specimens show staining and discoloration under plane polarized light. Birefringence shows no distinction between altered and unaltered specimens - Field point, Elevation 355 m

b) Stage 2 – Staining and discoloration are more pronounced. Birefringence shows distinct patterns for altered and unaltered specimens - Borehole investigation 299 B elevation 372.297 m, sample retrieved from the depth of 26.50 m

c) Stage 3 – Stained and discolored specimens are more common than colorless or pale unaltered ones. Birefringence shows variable properties over distances of less than 0.1 mm - Borehole investigation 298, elevation 365.484 m, sample retrieved from the depth of 24.60 m

d) Stage 4 – Individual specimens are not in direct contact and their margins show irregular shapes. Birefringence reveals high variability - Field point, Elevation 320 m

Figure 5. a) Micaceous schist, b) Garnet schist (garnet is not present in the attached section), c) Garnet gneiss, d) Cataclastic gneiss with mylonite appearance - Progressive stages of weathering. The thin sections also confirm a higher degree of constituent minerals alteration in the proximity of fractures.

The sedimentary cover within the study area is represented by Quaternary unconsolidated formations constituted by silt, sand and gravel with angular rock fragments (Figure 9). These are interpreted as deposited during the Late Pleistocene epoch due

to the activity of the Olt River. Borehole data indicate that the thickness of these ranges from 0.0 to 24.0 meters, reflecting a highly irregular paleo-geomorphological setting that influenced sediment accumulation. The Olt River flows approximately 100 m from the study site. During geological time, the hydrological process is supposed to have implied variation in discharge, especially in between ice age events (Figure 6).

The erosive bank of the river, currently advances from E towards W.

Figure 6. Study area in relation to the Olt River and its eroding bank. The magenta polygon highlights the study area. Red lines represent the projection of the tunnel's axes.

2.3 Holistic approach for investigation results interpretation

To enable an integrated visualization of data from geotechnical boreholes and geophysical measurements while facilitating the analysis of interrelationships, a 3DPanels model was chosen. What is presented could have been called imagery as well as modelling. The 3D Panels model is generated by a basic function of the Rockworks software, based purely on input data. Within this model, the major lithological units identified in the boreholes were classified based on their genesis: sedimentary formations (brown) and metamorphic terrains locally converted to residual soils (blue). Seismic data is presented as spatial distribution diagrams of primary longitudinal waves velocities V_p and secondary shear waves velocities V_s .

The model illustrates a pronounced heterogeneity in both the electrical and mechanical properties of the subsurface formations, observable in both vertical and horizontal directions (Figure 7). If needed, the user interface facilitates the mapping of contrast areas within the model and the reading of exact values for further integration into numerical models.

V_p

V_s

Figure 7. Overview of geotechnical and geophysical investigations: boreholes, Electrical Resistivity Tomography, and seismic refraction or MASW.

2.4 Groundwater flow patterns emergence

Whether we are dealing with the metamorphic basement or sedimentary unconsolidated deposits, the presence of water within the permeable spaces of geomaterials alters both the electrical and mechanical properties. This explains not only the previously mentioned heterogeneity, but also certain contrasts between the seismic tomographies that are representative of V_p and V_s parameters (Figure 8, Figure 10).

Figure 8. A quasi-horizotal distribution of mechanical properties (V_p and V_s). Borehole investigation 299, elevation 389.469 m, total depth 55.0 m.

Although both sections reveal quasi-horizotal sequences, the boundaries between them and the depths at which they appear are not identical. The observed differences likely reflect the distinct behaviors of the seismic wave types involved: compressional or P-waves herein are associated with changes in lithology; shear waves, as they do not propagate through fluids, their attenuation or the reduction in seismic signal quality is associated to the presence of water within the permeable spaces of the formations. In Figure 8, it is presented how around a depth of approximately 19 m, the seismic section no longer reveals any contrast in terms of shear wave propagation velocities that stabilize at around 410 m/s. The V_p

values obtained for the same depth, range in the interval of 1000 – 1500 m/s. In certain conditions, such as those of an extremely heterogeneous medium, in the presence of water, destructive or constructive mechanical wave interference can compromise the quality and reliability of the signal. This was assumed to be the case with the above presented example. It is worth mentioning that during the drill's execution, water was reported at the depth of 19.0 m and a small spring was observed discharging the valley from above. The presented investigations are located near the erosional valley in the middle section of the planned tunnel (2.1). At this location, rounded gravel clasts with polished surfaces were discovered in the thalwegs as well as in the drilled material of borehole 299, confirming thus the hypothesis of a riverine origin for these deposits.

Figure 9. Erosional valley corresponding to the middle of the tunnel's projection.

Borehole 299 revealed sedimentary material up to 24.0 m for which a simple granulometry sieve analysis determined no clay minerals content between 3.50 – 22.0 m. This interval was followed by RQD=0 metamorphic, altered (weathering grade V-VI, in accordance with SR EN ISO 14689:2018) schist and gneiss association till 45.0 m. The drilled material was behaving as a residual soil with rare angular centimetric size fragments and rough surfaces, rounded, slightly stronger material which showed no change in mineralogy or color. Between 45 – 55 m the RQD index got in a range between 25 – 75% indicating a less fractured state of the rock. Alteration and fracturing were observed to be correlated as the weathering grade dropped between II-III at the same depth interval.

Fluid flows into the soil at a speed equal to the infiltration capacity determined by soil permeability (Wang et al. 2023). Starting from this statement, we claim that permeability contrasts would result in groundwater flow at the superior part of the two formations interface, laminar with the direction of the hydraulic gradient dictated by the morphology of the lithological limit in relation to the gravitational pull acting on the fluid. Part of the infiltrated water would also penetrate the highly fractured metamorphic basement taking preferential paths, generating seepage force, as well as increasing pore water pressure and the whole bulk density of the rock mass. Additionally, strength reduction may occur due to a loss of matric suction. The preferential paths are reflected through the excessive degree of alteration that specific areas suffer. An example is provided by the integrated results presented in Figure 10, where the P-wave velocity distribution shows a quasi-parallel arrangement that delineates a thin, poorly compacted surface layer associated with the sedimentary deposits, underlain by a relatively homogeneous lithological sequence extending at depth. In contrast, the S-wave velocity reveals markedly different patterns along the same alignment, most likely indicating the presence of a preferential flow zone for infiltrated groundwater.

Figure 10. Spatial distribution and contrast between V_p and V_s parameters.

Figure 11. Attenuation of shear wave velocities. Borehole investigation 301, elevation 356.199 m, total depth 30.0 m.

Borehole 301 revealed only an RQD=0 metamorphic sequence, with a weathering grade V-VI, similar in terms of character and behavior to that encountered by borehole 299 between 24.0 – 45.0 m.

Within the depth range corresponding to 11.00 to 24.00 m of borehole investigation 301, the adjacent seismic section

displays V_p values ranging between 2400 – 3000 m/s and V_s between 700 – 800 m/s.

This drill was also equipped with piezometer monitoring tubing. It revealed groundwater levels between 345.999 – 349.219 m above the Black Sea level. These values were recorded over approximately two years and exhibited both long-term and short-term variations with a maximum decrease of 2.40 m over the course of 5 months, highlighting the complex nature of the water infiltration patterns in the site's terrain. The other 3 equipped drills revealed groundwater levels within the interval of 358.337 – 368.688 m.

3 CONCLUSIONS

This paper's aim was to identify groundwater flow patterns based on the coherent display of the integrated results obtained from the applied principles of different scientific fields and provide a clear image and understanding of the geological processes that affect or affected the studied materials.

Accurate characterization and description of site conditions is crucial for geotechnical engineering. Any stability analysis depends upon a correct assessment of geotechnical parameters. Robust geological understanding of site locations backed by geophysical surveys allows for a correct estimation of spatial distribution of parameters.

In this specific case the geology of the area promotes complex patterns of infiltration within alluvial deposits of riverine origin and fractured metamorphic terrains. Water played an important role in determining the actual site conditions and to this day, retains preferential channels within the subsurface that exhibit two different principal mechanisms. One is controlled by permeability contrasts between two genetically different materials and the other is discontinuous flow through preferential paths within highly fractured rocks locally converted to residual soils.

Geotechnical design implications and measures related to groundwater flow through fractured rocks are given by Zhou et al. (2023). It shows among other aspects, how clogging acts and may further induce permeability variation for materials such as the metamorphic basement described herein.

For the case of the tunnel, due to the previously described heterogeneity and the identification of hardly predictable shallow infiltrated groundwater flow patterns within the site's terrain, the geotechnical study was concluded with the recommendation of the NATM (New Austrian Tunneling Method) for the construction phase development. The method was recommended because it allows systematic monitoring and staged excavation with support measures applied for each tunnel section according to its local conditions. Considerations for tunnel construction or stabilization using NATM method are provided by Niedbalski et al. (2018).

To question, how can mechanical wave propagation patterns be integrated within regional or local scale numerical models that predict groundwater behavior, may serve as a future research direction. For now, a contrast in propagation velocity of primary or shear wave velocity would serve to identify areas of different geological origins or that were subjected to the action of different geologic or environmental agents during geological time.

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