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Editorial Address/Naslov uredništva
RMZ – Materials and Geoenvironment
Aškerčeva cesta 12, p. p. 312
1001 Ljubljana, Slovenija
Tel.: +386 (0)1 470 45 00
Fax.: +386 (0)1 470 45 60
E-mail: rmz-mg@ntf.uni-lj.si

Linguistic Advisor/Lektor
Jože Gasperič

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Historical Review

More than 90 years have passed since the University Ljubljana in Slovenia was founded in 1919. Technical fields were united in the School of Engineering that included the Geologic and Mining Division, while the Metallurgy Division was established only in 1939. Today, the Departments of Geology, Mining and Geotechnology, Materials and Metallurgy are all part of the Faculty of Natural Sciences and Engineering, University of Ljubljana.

Before World War II, the members of the Mining Section together with the Association of Yugoslav Mining and Metallurgy Engineers began to publish the summaries of their research and studies in their technical periodical Rudarski zbornik (Mining Proceedings). Three volumes of Rudarski zbornik (1937, 1938 and 1939) were published. The War interrupted the publication and it was not until 1952 that the first issue of the new journal Rudarsko-metalurški zbornik – RMZ (Mining and Metallurgy Quarterly) was published by the Division of Mining and Metallurgy, University of Ljubljana. Today, the journal is regularly published quarterly. RMZ – M&G is co-issued and co-financed by the Faculty of Natural Sciences and Engineering Ljubljana, the Institute for Mining, Geotechnology and Environment Ljubljana, and the Velenje Coal Mine. In addition, it is partly funded by the Ministry of Education, Science and Sport of Slovenia.

During the meeting of the Advisory and the Editorial Board on May 22, 1998, Rudarsko-metalurški zbornik was renamed into "RMZ – Materials and Geoenvironment (RMZ – Materiali in Geookolje)" or shortly RMZ – M&G. RMZ – M&G is managed by an advisory and international editorial board and is exchanged with other world-known periodicals. All the papers submitted to the RMZ – M&G undergoes the course of the peer-review process.

RMZ – M&G is the only scientific and professional periodical in Slovenia which has been published in the same form for 60 years. It incorporates the scientific and professional topics on geology, mining, geotechnology, materials and metallurgy. In the year 2013, the Editorial Board decided to modernize the journal's format.

A wide range of topics on geosciences are welcome to be published in the RMZ – Materials and Geoenvironment. Research results in geology, hydrogeology, mining, geotechnology, materials, metallurgy, natural and anthropogenic pollution of environment, biogeochemistry are the proposed fields of work which the journal will handle.

Editor-in-Chief

Zgodovinski pregled

Že več kot 90 let je minilo od ustanovitve Univerze v Ljubljani leta 1919. Tehnične stroke so se združile v Tehniški visoki šoli, ki sta jo sestavljala oddelka za geologijo in rudarstvo, medtem ko je bil oddelek za metalurgijo ustanovljen leta 1939. Danes oddelki za geologijo, rudarstvo in geotehnologijo ter materiale in metalurgijo delujejo v sklopu Naravoslovnotehniške fakultete Univerze v Ljubljani.

Pred 2. svetovno vojno so člani rudarske sekcije skupaj z Združenjem jugoslovanskih inženirjev rudarstva in metalurgije začeli izdajanje povzetkov njihovega raziskovalnega dela v Rudarskem zborniku. Izšli so trije letniki zbornika (1937, 1938 in 1939). Vojna je prekinila izdajanje zbornika vse do leta 1952, ko je izšel prvi letnik nove revije Rudarsko-metalurški zbornik – RMZ v izdaji odsekov za rudarstvo in metalurgijo Univerze v Ljubljani. Danes revija izhaja štirikrat letno. RMZ – M&G izdajajo in financirajo Naravoslovnotehniška fakulteta v Ljubljani, Inštitut za rudarstvo, geotehnologijo in okolje ter Premogovnik Velenje. Prav tako izdajo revije financira Ministrstvo za izobraževanje, znanost in šport.

Na seji izdajateljskega sveta in uredniškega odbora je bilo 22. maja 1998 sklenjeno, da se Rudarsko-metalurški zbornik preimenuje v RMZ – Materiali in geookolje (RMZ – Materials and Geoenvironment) ali skrajšano RMZ – M&G. Revijo RMZ – M&G upravljata izdajateljski svet in mednarodni uredniški odbor. Revija je vključena v mednarodno izmenjavo svetovno znanih publikacij. Vsi članki so podvrženi recenzijskemu postopku.

RMZ – M&G je edina strokovno-znanstvena revija v Sloveniji, ki izhaja v nespremenjeni obliki že 60 let. Združuje področja geologije, rudarstva, geotehnologije, materialov in metalurgije. Uredniški odbor je leta 2013 sklenil, da posodobi obliko revije.

Za objavo v reviji RMZ – Materiali in geookolje so dobrodošli tudi prispevki s širokega področja geoznanosti, kot so: geologija, hidrologija, rudarstvo, geotehnologija, materiali, metalurgija, onesnaževanje okolja in biokemija.

Glavni urednik

Original scientific paper

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Stochastically improved methodology for probability of success (*POS*) calculation in hydrocarbon systems

Stohastično dopolnjena metodologija računanja verjetnosti uspeha (*POS*) v ogljikovodičnih sistemih

Tomislav Malvić[1, 2, *], Josipa Velić[1]
[1]INA Plc., Field Development Sector, Šubićeva 29, 10000 Zagreb, Croatia
[2]University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb, Croatia
*Corresponding author. E-mail: tomislav.malvic@zg.t-com.hr

Abstract
Geological risk of new hydrocarbon reserves discovering is usually calculated on deterministical or expert-opinion way, and expressed as 'Probability Of Success' (abbr. *POS*). In both approaches are included selections of single probability values for each geological event organised into geological categories that define hydrocarbon system. Here is described a hybrid, i.e. stochastical, model based on the deterministical approach. Here was given example from the Croatian part of the Pannonian Basin System (abbr. CPBS), improved with stochastically estimated subcategory for porosity mapped in the Stari Gradac-Barcs Nygat Field (Drava Depression). Furthermore, there is theoretically explained how such approach could be applied for two other subcategories – quality of cap rocks and hydrocarbon shows. Presented methodology could be advantageous in clastic hydrocarbon system evaluation.

Key words: geological risk, determinism, stochastics, Neogene, Northern Croatia

Izvleček
Geološko tveganje odkritja novih zalog ogljikovodikov navadno računajo deterministično ali po metodi ekspertnih mnenj in ga izražajo z »verjetnostjo uspeha« (*POS*, Probability of Success). Obe metodi temeljita na vrednostih verjetnosti posamičnih geoloških dogodkov, urejenih po geoloških kategorijah, ki opredeljujejo ogljikovodični sistem. Tu je opisan hibridni, tj. stohastični model, ki temelji na determinističnem načinu. Obravnavani primer je iz hrvaškega dela sistema Panonske kadunje (CPBS, Croatian part of the Pannonian Basin System), ki je dopolnjen s stohastično ocenjeno podkategorijo poroznosti, kartirano v polju Stari Gradac-Barcs Nygat (v Dravski kadunji). Sledi teoretska razlaga možnosti uporabe takega načina z nadaljnjima dvema podkategorijama – kakovostjo krovnih kamnin in ogljikovodičnih pojavov. Prikazana metodologija utegne biti učinkovita pri ocenjevanju klastičnih ogljikovodičnih sistemov.

Ključne besede: geološko tveganje, determinizem, stochastičnost, neogen, severna Hrvaška

Introduction

Calculation of geological risk is a well-established tool for estimation of possible hydrocarbon reservoir in plays or prospects. Such calculations, in Croatia, are well described in the Sava and Drava Depressions [1–4]. The term 'play' in those papers is generally defined as a stratigraphical unit in the range of chronostratigraphic stage or sub-stage where hydrocarbon production already exists. The 'prospect' is a vertical surface projection of potential reservoir lateral borders. Such definition has been derived from Rose [5] or White [6] where 'play' is generally defined as an operational unit characterised by several prospects and/or fields and 'prospect' is an exploration (economic) unit. In general, any potential hydrocarbon system can be evaluated with Probability of success (abbr. *POS*) calculation.

Mathematically, calculation of *POS* is a simple multiplication of several, in most cases five, independent geological category probabilities. Of course, there are geological relations among some of them, but it is using this tool impossible mathematically expressed on any useful way. Each category is defined with several geological events, and each also has its own probability. Category probability is simple multiplication of selected event probability values, defined as discrete values in range 0–1. They are often listed in *POS* probability tables, based upon previous experience and expert knowledge from analysed subsurface. Such a table (Figure 1), defined through decades of research for the Croatian part of the Pannonian Basin System (abbr. CPBS), had been a source of detail probability values defined and applied in in the Bjelovar Subdepression as part of the Drava Depression. Sometimes such values remain as an

TRAP		RESERVOIR		SOURCE ROCKS		MIGRATION		HC PRESERVATION	
Structural		**Reservoir type**		**Source facies**		**HC shows**		**Reservoir pressure**	
Anticline and **buried hill** linked to basement	1.00	**Sandstone** clean and laterally extended; **Basement** granite, geiss, gabbro; **Dolomites and Algae reefs** (secondary porosity)	1.00	**Kerogen** type **I and/or II**	1.00	**Production** of hydrocarbons	1.00	**Higher** than hydrostatic	1.00
Faulted anticline	0.75	**Sabdstones,** rich in silt and clay; **Basement** with secondary porosity, limited extending; **Algae reefs**, filled with skeletal debris, mud and marine cements	0.75	**Kerogen** type **III**	0.75	Hydrocarbons **in traces**; **New gas** detected >10 %	0.75	**Approximately** hydrostatic	0.75
Structural nose closed by fault	0.50	**Sandstone** including significant portion of silt/clay particles, limited extending;	0.50	**Favourable palaeo-facies** organic matter sedimentation	0.50	**Oil** determined **in cores** (luminescent analysis, core tests)	0.50	**Lower** than hydrostatic	0.50
Any "positive" faulted structure, margins are not firmly defined	0.25	**Basement rocks**, including low secondary porosity and limited extending	0.25	**Regionally known** source rock facies, but not proven at observed locality	0.25	**Oil** determined **in traces** (lumin. anal., core tests)	0.25		0.25
Undefined structural framework	0.05	Undefined reservoir type	0.05	Undefined source rock type	0.05	Hydrocarbon are not observed	0.05		0.05

TRAP		RESERVOIR		SOURCE ROCKS		MIGRATION		HC PRESERVATION	
Stratigraphic or combined		**Porosity features**		**Maturity**		**Position of trap**		**Formation water**	
Algae reef form	1.00	**Primary** porosity **>15 %**; **Secondary** porosity **>5 %**	1.00	Sediments are in **catagenesis phase** ("oil" or "wet" gas-	1.00	**Trap** is located in proven **migration distance**	1.00	**Still aquifer** of field-waters	1.00
Sandstones, pinched out	0.75	**Primary** porosity **5-15 %**; **Secondary** porosity **1-5 %**	0.75	Sediments are in **metagenesis phase**	0.75	**Trap** is located **between two source rocks** depocentres	0.75	**Active aquifer** of field-waters	0.75
Sediments changed by **diagenesis**	0.50	**Primary** porosity **<10 %**; **Permeability <1x10**(-3)** micrometer**2	0.50	Sediments are in **early catagenesis phase**	0.50	**Short migration pathway** (<=10 km)	0.50	**Infiltrated aquifer** from adjacent formations	0.50
Abrupt changes of petrophysical properties (caly, different facies)	0.25	**Secondary** porosity **<1 %**	0.25	Sediments are in **late diagenesis phase**	0.25	**Long migration pathway** (>10 km)	0.25	**Infiltrated aquifer** from surface	0.25
Undefined stratigraphic framework	0.05	Undefined porosity values	0.05	Undefined maturity level	0.05	Undefined source rocks	0.05		0.05

TRAP		RESERVOIR		SOURCE ROCKS		MIGRATION		HC PRESERVATION	
Quality of cap rock				**Data sources**		**Timing**			
Regional proven cap rock (seals, isolator)	1.00		1.00	Geochemical analysis on **cores and fluids**	1.00	**Trap** is **older than** matured **source** rocks	1.00		1.00
Rocks without reservoir properties	0.75		0.75	Analogy with **close located geochemical analyses**	0.75	**Trap** is **younger than** matured **source** rocks	0.75		0.75
Rocks permeable for gas (gas leakage)	0.50		0.50	**Thermal modeling** and calculation (e.g. Lopatin, Waples etc.)	0.50	**Relation** between trap and source rocks is **unknown**	0.50		0.50
Permeable rocks with locally **higher silt/clay content**	0.25		0.25	**Thermal modeling** at just a **few locations**	0.25		0.25		0.25
Undefined cap rock	0.05		0.05	Undefined data sources	0.05		0.05		0.05

Figure 1: *Example of relevant database prepared for the Bjelovar Subdepression* [after 2, 3].

internal document, but only if published [e.g., 2, 3] they make possible further independent evaluation of local or regional petroleum systems. Oppositely, such general tables, which can be applied as a rule of thumb, are missed in case of expert opinion applied for each particular well, exploration or development plan (Figure 2). In such case, single expert or team are completely responsible for given category values. Consequently, such process is subdued to "heavy" benchmarking, i.e. corrections are done with each new dataset (especially from wells). This methodology is not discussed here.
However, it is obvious that, using deterministic approach, at least several geological events (Figure 2) can be estimated from the range, i.e. from interval defined with values, number of data and, sometimes, measurement error. Moreover, in the case of low number of inputs, the Monte Carlo sampling can be applied for generation of artificial data, but it needs to be clearly stated in statistical results. However, the key question is "can any probability value for each geological event be considered certain or not". If there is a measurable uncertainty (Figure 2), resulting in non-representative mean or variance, but the minimum and maximum could be approximated, the stochastics can be successfully applied, e.g., using 2nd introduction of uncertainty in cell-value estimations with sequential Gaussian simulations. Such application of stochastics and results are shown, for the CPBS, in estimation of the porosity, thickness and depth of hydrocarbon reservoirs [e.g., 7–9]. Similar approach obviously can be regularly applied for estimation of several events in *POS* calculation and eventually set up as standard part of that method.

Selection of stochastically mapped porosity in *POS* calculation

The hydrocarbon plays or prospects could be deterministically analysed by several, mathematically independent, geological categories. The most common are: (1) structures, (2) reservoirs, (3) migration, (4) source rocks and (5) preservation of hydrocarbons [e.g., 2, 3, 6, 10]. The values of events in the most category values can be evaluated from data collected from well files, logs, seismic, cores, descriptive geological interpretations or the comprehensive regional papers [e.g., 11–13]. Based upon those data,

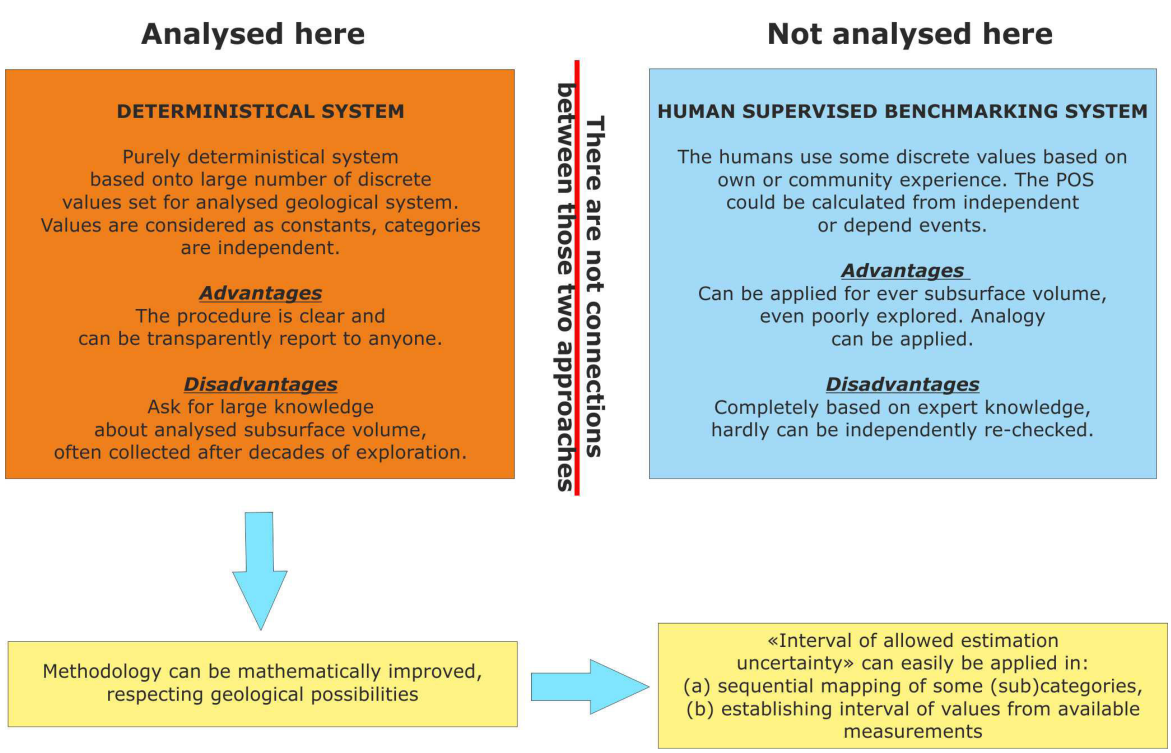

Figure 2: *Deterministical vs. human dominant benchmarking in evaluation of hydrocarbon systems.*

a value from the probability table can be easily selected, if such exists for the explored area (like Figure 1) or even from analogy based on regional geological models, especially depositional and tectonic data [e.g., 11]. In any case, *POS* table makes possible to calculate such value for any play or prospect in the area where it is defined by Equation 1:

POS = *p* (structures) × *p* (reservoir) × *p* (migration) × *p* (source rocks) × *p* (preservation)   (1)

Where are:
POS - probability value of Probability of Success for analysed hydrocarbon system,
p - probability value of each considered geological category.

All geological events, subcategories, categories and *POS* are defined with numerical values. For the part of them inputs (laboratory measurements, loggings tools ...) strictly define the results (like kerogen type, quantity of hydrocarbons during drilling) and probability can be selected without uncertainties. However, some subcategories like 'Porosity features' (in the category 'Reservoir'), 'Quality of cap rocks' ('Trap'), and 'HC shows' ('Migration') can be calculated from cores, logs and diagrams, but very often as approximations. It means they includes uncertainties, but if lithology is well-known the minimum and maximum values (e.g., for porosity) could be clearly established. The methodology had been tested with porosity maps taken from the Badenian gas-condensate reservoir in the Stari Gradac-Barcs Nyugat Field [14]. The reservoir is of massive type, trapped with combined structural-stratigraphic closure, with very complex lithology divided in four lithofacies (but single hydrodynamic unit). Porosity is geostatistically mapped in the youngest lithofacies of the Badenian clastites. The porosity distribution corresponds with structural strike NW-SE [15], and maps had been calculated using 100 realizations of sequential Gaussian simulations. It means that each cell on the map is defined with minimum and maximum values (realization), as well as 98 others between them. All of them, as equally probable, had been summed and averaged. So the minimum (3.1 %), median (3.2 %) and maximum (3.53 %) average reservoir porosities are calculated, what was base for consequently calculation of three solutions for 'Original Gas In Place' (abbr. OGIP) volume [16].

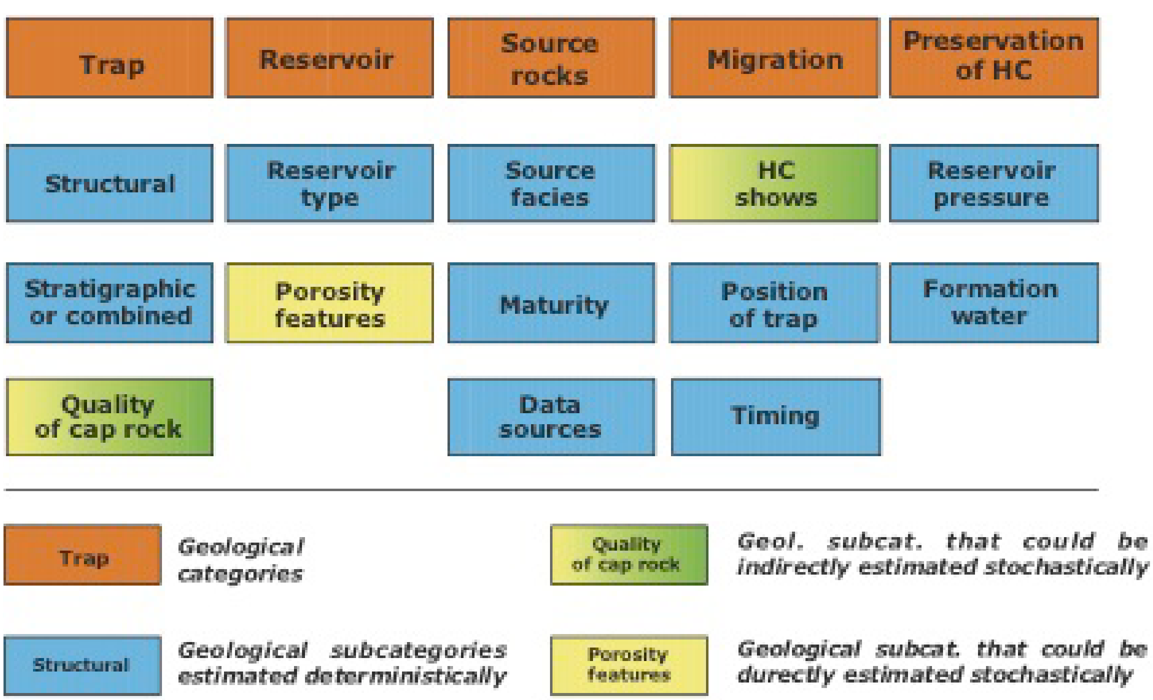

Figure 3: *Subcategories with can be determined exclusively deterministically and (in)directly stochastically.*

It is clear that all three average porosity values of the Badenian breccia reservoir in analysed gas field could be equally used as three values in 'Porosity feature' (Figure 3). If it is done so, the calculation based upon categories can be done with the following values. Structures: Trap is a faulted anticline ($p = 0.75$); Quality of cap rock is regionally proven ($p = 1.00$); Reservoir: Coarse-grained sandstones ($p = 1.00$); Primary porosity three values (3.1; 3.2; 3.53) < 5 % ($p = 0.50$); Source rocks: Kerogen type II ($p = 1.00$); Migration: Proven production ($p = 1.00$); Position of trap ($p = 1.00$); Trap is older than mature source rocks ($p = 1.00$); HC preservation: Higher than hydrostatic ($p = 1.00$); Still aquifer ($p = 1.00$). The total *POS* = 0.5 × 0.75 = 0.375. It is interesting that three 'Porosity feature' values had been used, and all three values are mathematically equally probable. However, they were all less than 5 %, which means that any chosen porosity was characterised with the same event probability (0.05), and *POS* was not changed.

However, the principle of using stochastics in deterministical calculation is clearly and correctly presented. Analyses showed that generally:

- Porosity subcategory can be easily characterised with three values, minimum, median, maximum,
- Those realizations are results of geostatistical simulations,
- Values could or could not correspond to more subcategory probabilities,
- Multiple subcategory probabilities would lead to multiple *POS* values.

Discussion about statistical basics and modifications introduced in *POS* calculation

Figure 1 summarised deterministical methodology published previously. It is opposite to the expert opinion and benchmarking based on new data. Although both approaches have pros and contras, here we consider deterministical as advantageous. The pure expertise can be too fluid and very hardly applied correctly in low to medium areas, when depending only or mostly on analogy (Figure 2). On contrary, in moderate to well explored petroleum provinces collected knowledge about hydrocarbon systems could be summarised in *POS* tables (Figure 1), where data from decades of exploration and production are summarised. In poorly explored or geological unknown hydrocarbon systems carefully analogy could be applied using *POS* tables from geologically similar areas. In any case, it is unfavourable to give expertise about any hydrocarbon system without any engineering 'support tool' and presented methodology (*POS*) is just such a tool.

Originally, the *POS* value is discrete, single value. However, if any category had more than one solution, *POS* would also be transferred into interval value. Multiple solutions could be reached using tools like geostatistical simulations or (sometimes) Monte Carlo sampling, where interpolated or estimated data can clearly reveal variable distribution (uniform, Gaussian etc.). Interestingly, if distribution is binomial it clearly indicated that mapping or estimation is wrongly applied simultaneously in: (1) two lithofacies, or (2) two plays or prospects (both are 'bimod' cases). In any case, distribution could be surely determined only from large dataset, which would be collected only in well-explored hydrocarbon systems. Intervallic expressed *POS* can be useful in reserves estimation. When proven volumes are given as probabilities, like P90 (at least 90 % of listed reserves will be recovered), P50 or P10, equiprobable *POS* values could be correlated with them.

The main advantage of stochastically calculated *POS* is set of equally probable outcomes that are all defined with continuous variable aerially distributed, like reservoir porosity. In such case, numerous statistical values can be easily calculated, like mod, median etc.

Conclusion

Hydrocarbon reservoir volume is always characterised with uncertainties, due to the limited number of available data. Evaluation of possible new hydrocarbon discoveries is often based onto *POS* methodology. The result is probability value in the range 0–1. Such methodology is well established and published for the Neogene sediments of the CPBS. In such approach (Figure 1) subcategories can be expressed exclusively deterministically with a single value. But some of them, described indirectly (descriptive, like 'HC shows' and 'Quality of cap rock') or directly (from measurements, like 'Porosity'), as interval value (Figure 3) could be evaluated with interval of values. All such interval data, for dominantly homogeneous reservoir, top or bottom layer, could be considered as equally probable values.

For example, in the case of 'Quality of cap rocks' their sealing properties cannot be directly measured without very special apparatus. However, they can be indirectly well deduced from: (a) possible 'HC shows' in the top, (b) porosity of cap rocks, or (c) regional geological model. Descriptively, they can vary between 'excellent seal' (cease migration of any gaseous molecules in subsurface) to 'temporary seal' (cease migration only of the largest molecules of heavy oil). On contrary, 'HC shows' can be directly measured along depths.

All descriptive evaluations and numerical data, if are numerous, can be transformed into event's probabilities (Figure 1). For example, new gas detected in quantity of (statistically representative) 10 % or more above seal rock will allow to select for it only two lowest probabilities (0.25 or 0.05; Figure 1), because sealing practically does not exist on geological significant period. It is often case in the Pliocene and Quaternary sands of the CPBS, where migrated thermogene or biogene ('in situ') methane cannot be efficiently trapped.

Presented stochastical approach is tested in the field located in the Drava Depression, where porosity was shown with maps (grids) constructed of numerous cells with numerical values. Other data were not analysed. The result showed relatively simple procedure how error in deterministical calculation of *POS* can be effectively decreased. The methodology can be easily and fast applied in any geological region where number of subsurface data easily allows applying deterministical approach in general (Figure 2).

All three "stochastically estimated" subcategories could be eventually described with minimum, median and maximum values. If each of such numerical values points to the different geological event (different probability; Figure 1) it would result in maximal 27 values of *POS*. In this way the pure deterministical calculation can be efficiently upgraded into a tool that gives range of maximum, median and minimum probabilities. Equiprobability is valid both for realizations as well as *POS* values and characterised with uniform distribution. In this way, potential hydrocarbon discovers would be described minimal and maximal *POS*, i.e. risk could be numerically expressed. It is why presented approach is considered as easily applying improvements of deterministical *POS* calculation.

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Compositional characteristics of the migmatite gneiss around Awo, southwestern Nigeria

Značilnosti sestave migmatitnega gnajsa pri Awu v jugozahodni Nigeriji

Mustapha T. Jimoh[1,*], Anthony T. Bolarinwa[2], Oluwanifemi O. Ashaye[1]
[1]Department of Earth Sciences, Ladoke Akintola University of Technology, Ogbomosho, Oyo state, Nigeria
[2]Department of Geology, University of Ibadan, Nigeria
*Corresponding author. E-mail: mtjimoh@lautech.edu.ng

Abstract

Migmatite gneiss within the Precambrian basement rocks around Awo, southwestern Nigeria were studied with a view to determine origin and compositional relationship of the paleosomes and neosomes. Other rocks associated with the migmatite gneiss are biotite gneiss, banded gneiss, syenite, granite, pegmatite and aplite. X-Ray Fluorescence geochemical studies reveal minor variations in the bulk chemical composition of paleosomes and neosomes. The composition is dominated by silica ($w \approx 62$ %) and alumina ($w \approx 15$ %). The migmatite gneiss magma type was high K-calc-alkaline to calc-alkaline. The Total Alkali Silica (TAS) plot shows the protolith of the migmatite gneiss to be dioritic and quartz-dioritic rocks while the xenoliths were originally gabbro. The migmatite gneisses are mostly of sedimentary parentage. Trace element data revealed high Ba content, indicating its concentration in felsic minerals. Large Ion Lithophile Elements (LILE) such as Ba, Rb and Sr generally exhibit positive anomaly while High Field Strength Elements (HFSE) notably Ta, Nb, Hf and Zr display weak anomaly. The REE geochemistry revealed strong enrichment of LREE (La, Ce, Pr and Nd) while HREE (Ho, Er, Tm, Yb and Lu) are weakly anomalous. The paleosomes and neosomes of the migmatite gneiss displayed marginal compositional variation which indicates their evolution from the same magmatic source.

Key words: Migmatite gneiss, Paleosomes, Neosomes, Geochemistry, Magmatic source

Izvleček

Migmatitni gnajs v predkambrijskih kamninah podlage v okolici Awa v jugozahodni Nigeriji smo preučevali z namenom opredelitve izvora in primerjave sestave komponent paleosoma in neosoma. Druge kamnine v povezavi z migmatitnim gnajsom so biotitni gnajs, pasoviti gnajs, sienit, granit, pegmatit in aplit. Rentgenska fluorescenčna preiskava razkriva manjša nihanja celotne kemične sestave paleosoma in neosoma. V sestavi prevladujeta silicijeva ($w \approx 62$ %) in aluminijska ($w \approx 15$ %) komponenta. Tip migmatitno gnajsove magme je bil visoko K-kalk-alkalni do kalk-alkalni. Diagram celotne alkalne silicije (TAS) nakazuje, da so bile protolit migmatitnega gnajsa dioritne in kremenovodioritne kamnine, medtem ko so ksenoliti prvotno gabrski. Migmatitni gnajsi so pretežno sedimentnega porekla. Podatki o sledeh razkrivajo visoko vsebnost Ba, očitno koncentriranega v felsičnih mineralih. Velikoionske litofilne prvine (LILE), kot so Ba, Rb in Sr, splošno izkazujejo pozitivno anomalijo, prvine visoke poljske jakosti (HFSE), in sicer Ta, Nb, Hf in Zr, pa šibko anomalijo. Geokemična sestava prvin redkih zemelj priča o znatni obogatitvi LREE (La, Ce, Pr in Nd), medtem ko so HREE (Ho, Er, Tm, Yb in Lu) šibko anomalne. Paleosomi in neosomi migmatitnega gnajsa kažejo zmerno variacijo sestave, ki priča o njihovem poreklu iz istega magmatskega vira.

Ključne besede: migmatitni gnajs, paleosomi, neosomi, geokemija, magmatski izvor

Introduction

Migmatites are heterogeneous metamorphic rocks consisting of intermingled leucosomes, melanosomes and mesosomes [1, 2]. They are also described as partially melted rocks of the continental crust which is made up of two components the neosomes and paleosomes [3].

Neosomes are crystallized products and residual materials from the melt whereas the paleosomes are the unmelted rocks. The study area which occur within the Precambrian basement complex of south-western Nigeria is located around Awo within Latitude 7° 45′ N and 7° 4′ N and Longitude of 4° 23′ E and 4° 27′ E. Field investigations showed the occurrence of diverse granitic rocks with structural features consistent with regional trend of the Nigeria basement complex. The various geological units identified around the study area are migmatite gneiss, banded gneiss, biotite gneiss, quartzite, syenite, granite and pegmatite (Figure 1).

The migmatite gneiss is located towards the central portion and the southwestern part of the study area (Figure 1). Field description revealed the migmatite gneiss as a massive outcrop. Xenoliths occur as fine grained mafic inclusions within the gneissic bodies. These inclusions are of various sizes and shapes. The shapes vary from angular, sub-angular, rounded, sub-rounded, lenticular to irregular pods (Figure 3). Odeyemi and Rahaman [4] postulated that the migmatite-gneiss of the basement complex and the meta-supracrustal rocks mark the termination of Precambrian activity in southwestern Nigeria. Migmatite gneiss complex is the oldest, most widespread and abundant rock type in the basement complex [4]. The migmatite gneiss is grayish in color and medium grained in texture, with alternation of mafic and felsic bands set in a medium to coarse grained ground mass. In some locations, pegmatite veins of variable dimensions are intruded into the gneissic bodies. These veins maintain various forms and relationship which are concordant, discordant, cross cutting and contorted with the foliation plane of the gneissic rock. The focus of this study is to investigate the migmatite gneiss with a view to highlighting the compositional characteristics of the paleosomal and neosomal components.

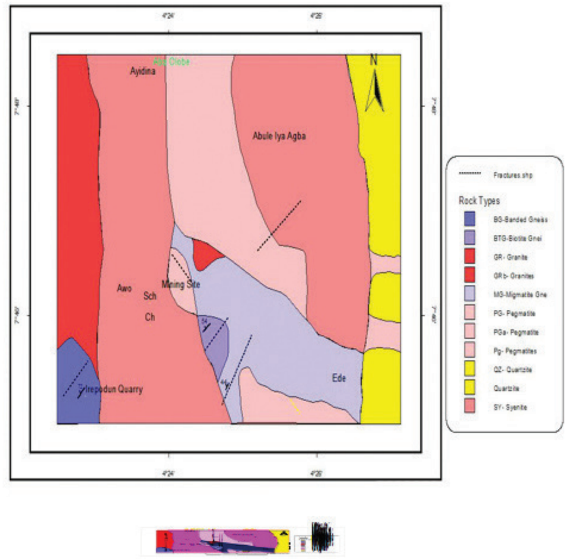

Figure 1: *Geological map of the study area.*

Geological Settings and Field Characteristics

Various geological units associated with the migmatite gneiss are banded gneiss, biotite gneiss, granite, syenite and pegmatite. Of all the rock types occurring in the study area, migmatite gneiss and biotite gneiss appear to be predominant while banded gneiss, syenite, granite and pegmatites occur in subordinate proportion. Migmatite gneisses are the oldest and most widespread lithology within the study area. They form the country rock in which all other rocks intrude. They are well exposed with mostly flat lying outcrop. They also cut across river and stream channels as highly weathered rocks. The migmatite gneisses are not treated as a single lithological unit they were segregated into paleosomes and neosomes. Neosomes are further segregated into leucosomes and melanosomes. (Table 1). The leucosomes are quartzofeldspathic in composition. Quartz appears dominant in the mode (> 70 %). The melanosomes contain varying amount of ferromagnesian minerals like platy biotite, prismatic hornblendes and equant pyroxene. Melanosomes are also identified as xenoliths. The presence of pyroxene confers a greenish tint on the rock body. The composite fabrics of paleosomes and neosomes are folded on mesoscopic scale. The paleosomes and leucosomes are concurrently folded and terminate abruptly into what appears as an enclave or tight isoclinal fold (Figure 2). The trends of the fold axis are mostly east- west. Lineation plunges usually to the north, reflecting ductile deformation. Deformations are mainly ductile. Fragments of enclaves or raft structure (competent materials) are enveloped within less competent components. The enclaves are mainly mafic subordinately felsic. These enclaves are of various shapes and sizes. Large number of shear planes was recognized in the study area, shearing was identified due to fabrics of the tectonically deformed rocks. Shearing had led to formation of various structural features like reorientation due to rotation, boudins and lenses (Figure 2). Enclaves are rock fragments that resisted migmatisation (resisters) or residual materials from which mobile materials have been extracted [5, 6].

Materials and Methods

Geological mapping of Awo area was conducted on a scale of 1 : 50 000. Particular attention was taken for the location, physical characteristics, mineral constituents, structural elements and associated rocks of the migmatite gneiss. Sampling was done to preserve various structures within the migmatite gneiss for future studies. A few samples were collected from each rock body for geochemical analysis. Various field measurements were used during the mapping. Global Positioning System (GPS) was used for geographical positioning with respect to various outcrops available in the study area. Measurement of strike, dip, plunge of structures such as foliation, lineation and fold axis were made. Field descriptions and observation were adequately recorded in a field notebook. Samples collected were properly labeled and stored prior to analyses. Representative rock samples were pulverized at Geochemistry Laboratory, Department of Geology of the University of Ibadan and analyzed at ACME Laboratory, Ontario, Canada using X-Ray Fluorescence (XRF) methods. Geochemical data were processed using Petrographic software package for different geochemical variation and discrimination diagrams.

Table 1: *Chemical composition of the Migmatite gneiss of Awo*

	NEOSOME							PALEOSOME					
	Major element concentration in mass fractions, w/%												
Analyte	**RS1**	**RS2**	**RS3**	**RS4**	**RS5**	**Mean**	**Range**	**RS6**	**RS7**	**RS8**	**RS9**	**Mean**	**Range**
SiO_2	44.5	55.5	58.7	61.5	61.5	56.34	61.5–44.5	65.1	63.8	65.3	74.2	67.1	74.2–63.8
Al_2O_3	12.54	14.77	14.93	14.49	15.16	14.38	15.16–12.54	14.96	14.39	14.43	15.50	14.82	15.50–14.39
Fe_2O_3	18.10	8.47	11.29	5.72	9.34	10.60	18.10–5.72	6.22	7.80	7.34	0.39	5.44	7.80–0.39
CaO	6.31	7.36	2.26	4.67	2.50	4.62	7.36–2.50	3.09	2.92	2.00	0.43	2.11	3.09–0.43
MgO	7.65	6.63	3.94	5.40	3.35	5.40	7.65–3.35	2.23	2.86	2.55	0.08	1.93	2.86–0.08
Na_2O	0.52	2.69	2.35	2.95	2.82	2.27	2.95–0.52	3.46	2.94	3.42	7.14	4.24	7.14–2.94
K_2O	5.32	2.20	4.15	3.15	3.66	3.70	5.32–2.20	2.57	3.03	3.15	1.90	2.66	3.15–1.90
MnO	0.39	0.17	0.21	0.16	0.15	0.22	0.39–0.15	0.12	0.15	0.15	0.11	0.13	0.15–0.11
TiO_2	2.43	2.08	1.77	0.74	1.32	1.47	2.43–0.74	1.00	1.30	1.22	0.04	0.89	1.30–0.04
P_2O_5	0.58	0.49	0.06	0.62	0.04	0.36	0.62–0.04	0.11	0.13	0.07	0.20	0.13	0.20–0.07
LOI	1.67	0.37	0.73	0.54	0.64	0.79	1.67–0.37	0.47	0.56	0.49	0.52	0.51	0.56–0.47
Total %	**100.01**	**99.73**	**100.39**	**99.94**	**100.48**			**99.33**	**99.88**	**100.12**	**100.51**		

	NEOSOME							PALEOSOME					
	Trace element concentration (× 10^{-6})												
Analyte	RS1	RS2	RS3	RS4	RS5	Mean	Range	RS6	RS7	RS8	RS9	Mean	Range
Cu	20	10	70	10	10	24	70–10	20	10	10	10	13	20–10
Ni	270	110	100	40	90	122	270–40	10	40	30	10	11	40–10
Pb	10	10	10	10	10	10	10	10	10	10	10	10	10
Zn	250	110	160	120	110	150	250–110	10	110	110	40	68	110–10
Zr	161	186	425	189	231	238	231–161	251	307	367	24	242	367–24
Ba	706	478	992	871	638	737	992–478	647	891	667	42	562	891–42
Be	2	36	7	2	51	20	51–2	4	2	4	6	4	6–2
Co	38	32	32	27	23	30	38–23	18	18	20	1	14	20–1
Cs	4	20	4	3	30	12	30–3	2	2	3	4	3	4–2
Ga	26	19	21	21	20	54	54–19	18	20	19	22	20	22–18
Rb	187	166	159	137	245	179	245–137	94	116	141	158	127	158–94
Sn	6	4	1	2	3	3	6–1	1	1	6	11	5	11–1
Sr	68	277	297	393	356	267	356–68	303	299	247	10	215	303–10
V	261	182	203	188	78	182	261–78	100	135	125	10	93	135–101
Hf	5	5	12	5	6	7	12–5	8	11	10	1	8	11–1
Nb	40	30	30	26	37	31	40–26	15	16	26	20	19	20–15
Ta	2	6	1	1	11	4	11–1	1	1	1	1	1	1
Th	2	14	32	31	20	20	32–2	25	29	16	2	18	29–2
U	2	6	2	1	10	4	10–1	1	1	2	5	2	5–1
W	1	3	2	2	5	3	5–1	2	1	1	4	2	4–1
Y	62	30	24	20	24	32	62–20	23	25	13	6	17	25–6

Figure 2: *Migmatite gneiss showing various structures: top left - basic dyke; top right - sheared boudins; middle left - rotated and folded metabasic rocks; middle right - symmetrical tail of leucosome around an enclave of melanosome; bottom left - randomly oriented raft structure of basic dykes embedded in matrix of leucosome; bottom right - tight folding of foliated paleosome, leucosome and melanosome.*

Results and Discussion

Major Element Geochemistry

Nine representative samples of the paleosomes and neosomes were selected to determine their major, trace and rare earth elements geochemistry. Five of the samples were taken from paleosomes and four from neosomes (Table 1). The xenolith expectedly has very low concentration of Na_2O (w = 0.52 %), and much higher concentrations of K_2O (w = 5.32 %) and a proportionately high concentration of Fe_2O_3 (w = 18.10 %) and MgO (w = 7.65 %) due to its mafic composition (Table 1). The paleosomes and neosomes of the migmatite gneisses are compositionally different in their mean values as revealed by major oxide data presented in Table 1.The lowest mean value of SiO_2 is w = 44.5 % which indicates the mafic nature of the paleosomes while the highest mean value of SiO_2 is w = 74.2 % which as well reveal the felsic nature of the neosomes. Low range values of oxides such as Na_2O (w = 2.95–0.52 %) and high range values of Fe_2O_3 and MgO (w = 18.10–5.72 % and w = 7.65–3.35 %) further affirm the mafic composition of the paleosomes. The overall trend for all major elements suggests that the paleosomes evolved from parent material which is intermediate between felsic and mafic sources. This is evident from the moderately high concentration of SiO_2 in the range of w = 61.5–44.5 % while a range value of w = 74.2–63.8 % for neosomes clearly indicates its felsic precursor. High contents of Fe_2O_3 (w = 18.10–5.72 %) for paleosomes attest the basic nature of the parent materials, while low Fe content (w = 7.80–0.39 %) in neosome indicates its felsic parentage. The mean values of Na_2O and K_2O (Table 1) for the paleosomes and neosomes reflect the abundance of K-rich rock forming silicates like biotite and microcline [7]. The paleosome and neosome show slight variation in their sources. The paleosomes are derived from diorite and syenodiorite sources whereas the neosomes are mostly derived from quartz diorite and granite sources (Figure 3). The AFM diagrams [9, 10] were used to determine whether the rock samples are derived from tholeiitic or calc-alkaline rock suite, the major element data were plotted on triangular diagram comprising of A (Na_2O + K_2O), F (FeO + Fe_2O_3) and M (MgO). The plot falls within calc- alkaline rock suite which is rich in Na_2O, K_2O and total Fe but low in MgO (Figure 3). The AFM diagrams were also employed to investigate the enrichments of the paleosomes and neosomes in Na_2O, K_2O, MgO and total Fe. The paleosomes are moderately enriched in MgO and total Fe while the neosomes are highly enriched in Na_2O and K_2O with low amount of total Fe (Figure 3). It is further confirmed by the plot of SiO_2 versus Na_2O + K_2O [8] which revealed that the migmatite gneiss originates from dioritic rocks (Figure 3). SiO_2 was plotted against K_2O adopting the model of Peccerillo and Taylor [13] to further determine if the rock series is high or medium calc-alkaline (Figure 3). In term of tectonic setting, following the model of Pearce et al [17] where Rb was plotted against Y + Nb, the neosome plots in the field of Volcanic Arc Granite while the paleosome plots in Within Plate Granite (Figure 3). Both components are thus product of post-collisional tectonic setting. Most of the values plot within field of high-K calc- alkaline series. Furthermore, all the major oxides were plotted against SiO_2 in Harker's diagram (Figure 4) because SiO_2 is regarded as fractionation index for the evolution of magma and the most abundant oxide in igneous rocks that exhibit a wide variation in composition [11]. Al_2O_3 and Na_2O are positively correlated with SiO_2 which is an indication of possible separation of felsic minerals like sodic plagioclase during fractional crystallization [12]. Fe_2O_3, CaO, K_2O and MgO versus SiO_2 were negatively correlated and indicate a separation of ferromagnesian minerals during crystallization (Figure 4).

Various models were used to determine the ancestry of the migmatite gneiss. Awo migmatite gneiss on the Na_2O/Al_2O_3 vs K_2O/Al_2O_3 plot was used to discriminate between igneous and sedimentary/metasedimentary rocks [14]. Approximately 90 % of the plots fell within sedimentary/metasedimentary field (Figure 5). Similarly, the K_2O vs Na_2O plot [8] showed an overwhelming 90 % of the values plotting within eugeosynclinal sandstones field (Figure 5). Furthermore, in the TiO_2 vs SiO_2 diagram [16], the plot fell within sedimentary field which suggests that the protolith of the migmatite gneiss has been grossly affected by crustal contamination (Figure 5).

Trace and Rare Earth Elements Geochemistry

Trace element concentrations of the paleosome and neosome are presented in Table 1.The concentrations of Large Ion Lithophile Elements (LILE) such as Ba, Rb and Sr for paleosomes and neosomes are enriched, but the mean values are slightly higher in paleosome than neosome (Table 1). The concentrations of High Field Strength Elements (HFSE) like Ta, Nb and Hf are generally depleted; neosomes are more depleted in HFSE than paleosomes. However Zr is moderately enriched compared to other HFSE (Table 1). For trace elements, high content of Ba with mean values of 737 × 10^{-6} and 562 × 10^{-6} for paleosome and neosome respectively (Table 1) are conspicuously discernible which indicates its concentration in felsic minerals. This attests to granitic origin of the rock samples. The assertion is further corroborated by moderate amount of Rb (179 × 10^{-6} and 127 × 10^{-6}) and Zr (238 × 10^{-6} and 242 × 10^{-6}) for paleosomes and neosomes respectively which are concentrated in rocks of acidic or intermediate composition. The LILE such as Ba, Rb and Sr generally exhibit positive anomaly, while HFSE such as Ta, Nb, Hf and Zr display weak anomaly (Figure 6).

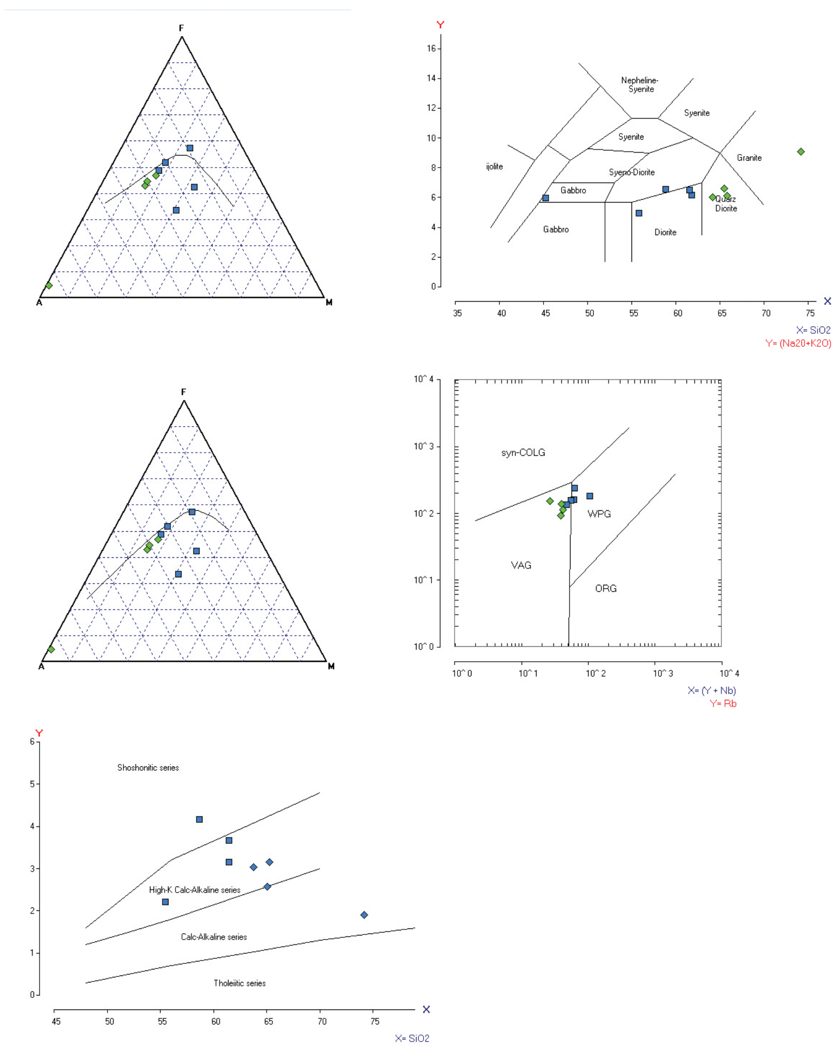

Figure 3: *Top left - AFM diagrams (after Irvine and Baragar [10]); middle left – (after Kuno [9]); top right - Plot of Na_2O K_2O versus SiO_2 (after Cox et al [8]); middle right - K_2O versus SiO_2 plot (after Peccerillo and Taylor [13]); bottom - Rb versus Y + Nb tectonic discrimination diagram (after Pearce et al [17]).*

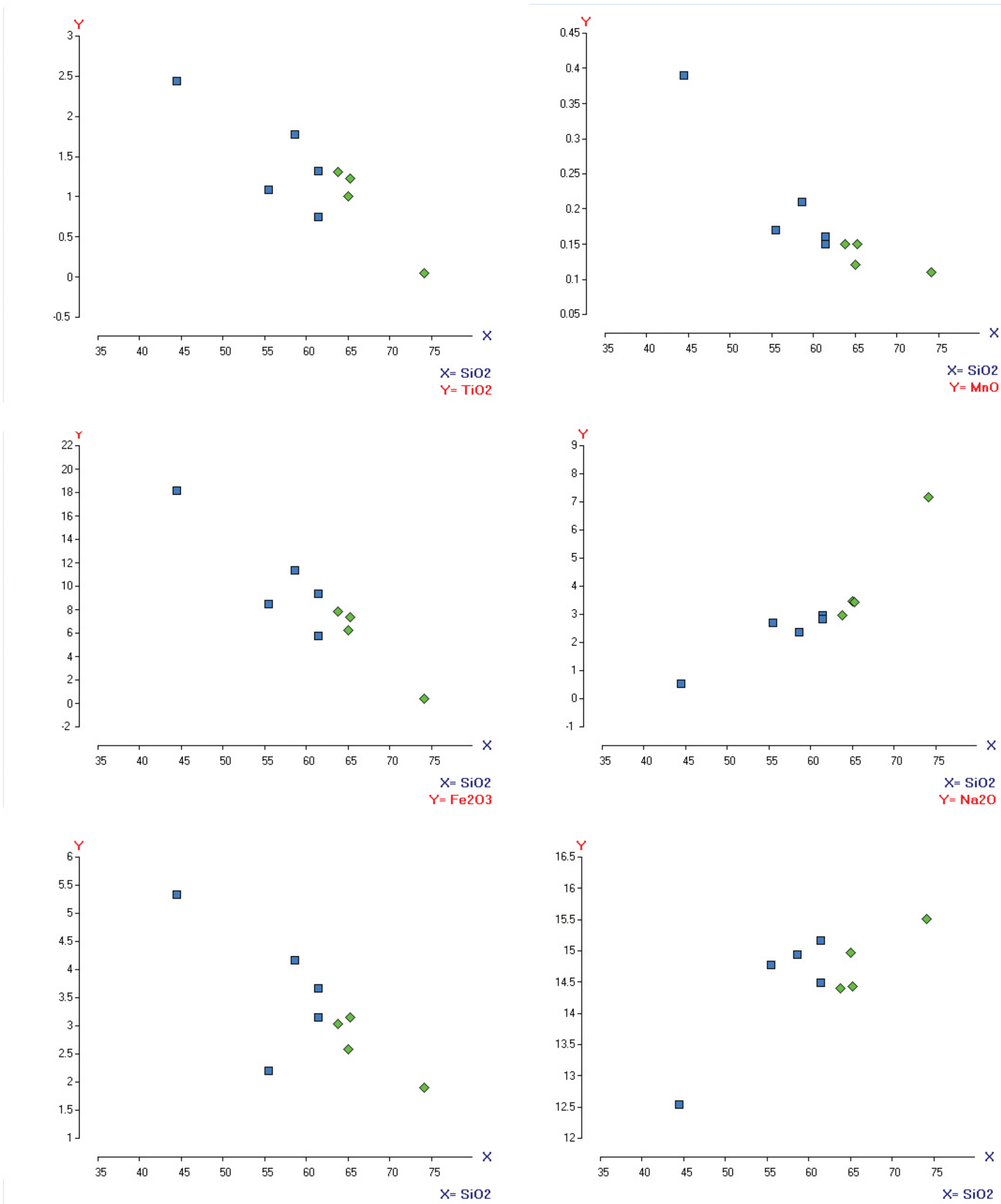

Figure 4: *Harker's variation plot of SiO_2 versus other major elements*

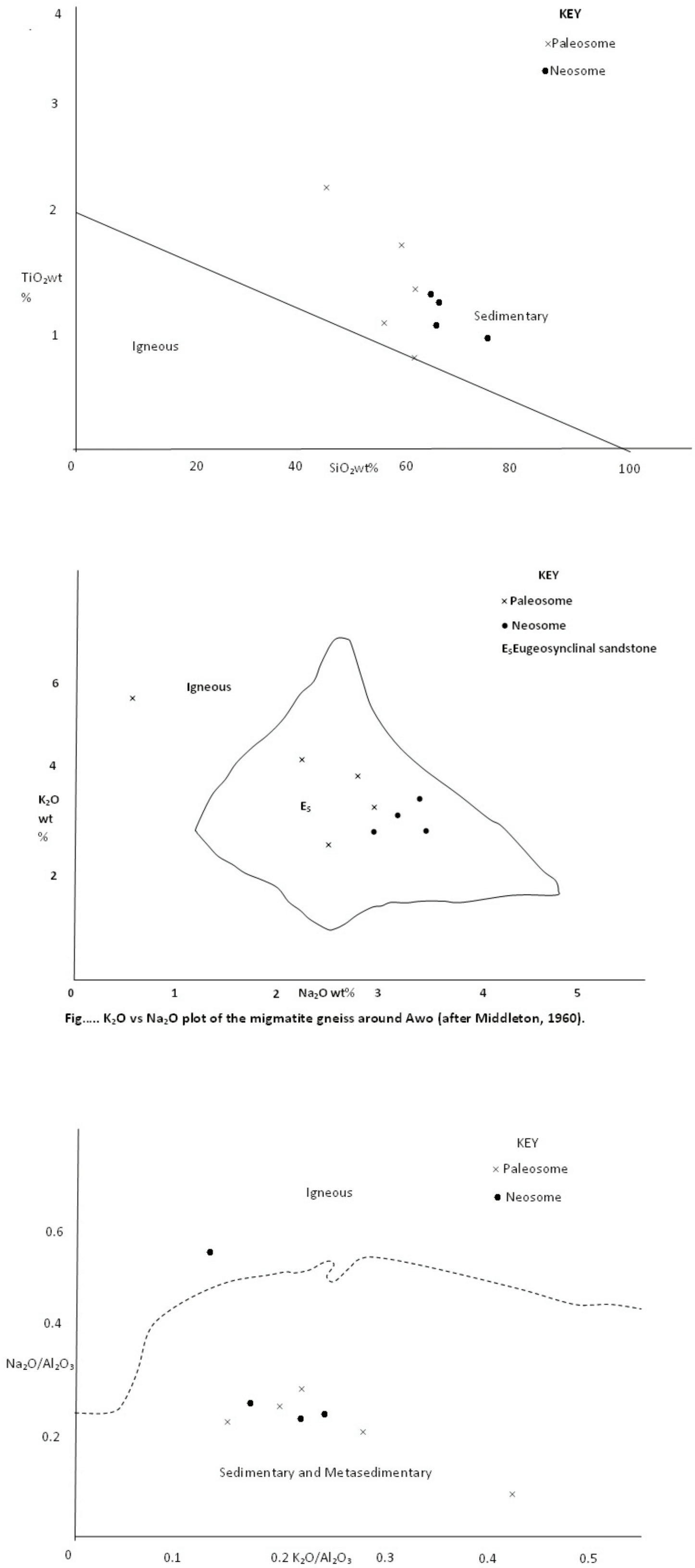

Figure 5: *Top - TiO_2 versus SiO_2 plot (after Tarney[16]); middle - K_2O vs Na_2O plot (after Middlemost[15]); bottom - Na_2O/Al_2O_3 versus K_2O/Al_2O_3 diagram (after Garrels and Mackenzie[14]).*

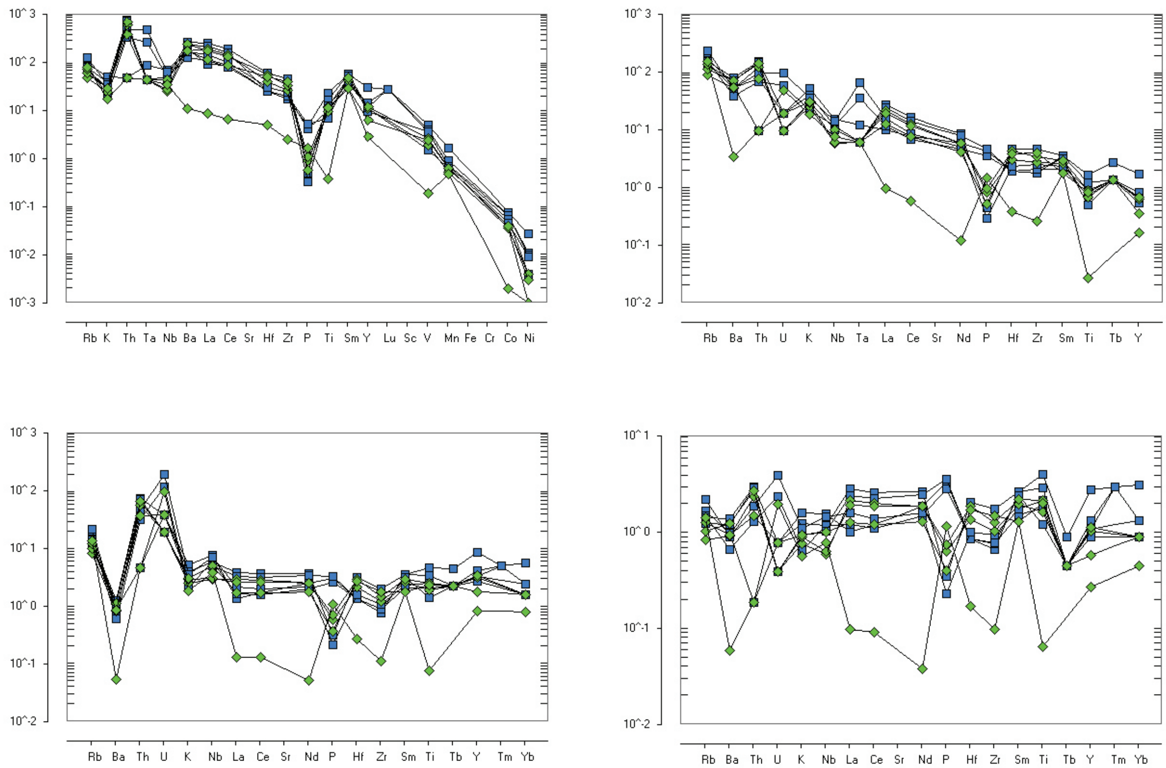

Figure 6: *Left - Mantle normalized pattern of trace elements for Paleosome and neosome (after Wood et al[18]); right – Chondrite normalized pattern of rare earth elements for paleosomes and neosomes after Haskin et al[19]).*

The enrichment in LILE and depletion in HFSE reflect geotectonic setting from which the rocks originated. The setting suggests the rocks to evolve in a process of subduction. REE concentrations of the paleosomes and neosomes as presented in Table 1 reveal strong positive anomaly for LREE such as La, Ce, Pr and Nd while HREE like Ho, Er, Tm, Yb, and Lu show weak anomaly. Source materials of the migmatite gneiss can be inferred from trace and rare earth element patterns [12]. The moderately enriched LREE and weakly negative Eu anomaly possibly suggest the melt to have been derived from rocks of intermediate composition like diorite and quartz diorite (Figures 5 and 6).

Conclusion

The study area occurs within metamorphic terrane of the south western basement complex of Nigeria. Formation of different rock types around the area is probably connected to post-collisional events that influenced the structural and textural features of the various geological units. The available geochemical data from the study area suggest the paleosomes and neosomes to be mostly of sedimentary parentage with minor input from igneous protolith (Figure 5). The paleosome and neosome bear compositional similarities. However, minor petrological differences exist between each component. The differences are associated with the composition of their sources and crustal contamination during the transportation of the melted materials. The migmatite gneiss is derived from rocks of dioritic composition belonging to calc-alkaline series. Negative correlation between SiO_2 and major elements like Fe_2O_3, CaO, K_2O and MgO indicate a pronounced effect of fractional crystallization during the formation of the dioritic rocks. Large Ion Lithophile Elements (LILE) such as Ba, Rb and Sr generally exhibit positive anomaly while High Field Strength Elements (HFSE) notably Ta, Nb, Hf and Zr display negative anomaly. The REE geochemistry revealed strong positive anomaly for LREE (La, Ce, Pr and Nd) while HREE (Ho, Er, Tm, Yb and Lu) are weakly anomalous. Evidence from geochemical data coupled with patterns of major, trace elements and rare earth elements revealed that the paleosomes and neosomes have common magmatic and geotectonic source.

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Data preparation for groundwater modelling – Ljubljansko polje aquifer system

Priprava podatkov za modeliranje podzemne vode – vodonosni sistem Ljubljansko polje

Janja Vrzel[1, 2, *], Nives Ogrinc[2, 3], Goran Vižintin[4]
[1]Ecological Engineering Institute, Ljubljanska 9, 2000 Maribor, Slovenia
[2]International Postgraduate School Jožef Stefan, Jamova 39, 1000 Ljubljana, Slovenia
[3]Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia
[4]University of Ljubljana, Faculty of Natural Sciences and Engineering, Aškerčeva 12, 1000 Ljubljana, Slovenia
*Corresponding author. E-mail: janja.vrzel@iei.si

Abstract

The paper presents data preparation for groundwater modelling of Ljubljansko polje aquifer system in central part of Slovenia. Data preparation is part of the conceptualisation, which is the first step for developing a regional steady state model. This model will provide a framework for the development of transient groundwater flow model for the whole Ljubljansko polje aquifer system. The FEFLOW software is used for the visualization of the groundwater flow model of the Ljubljansko polje aquifer system and its geometry is based on the geological composition and hydrological characteristics of the studied area. Already known fact that too precise model geometry leads to the instability of the model was proved in ours study case, therefore many deliberate and rational decisions should be made during the conceptualisation. The model will extend our knowledge about interactions between surface and groundwater.

Key words: FEFLOW, GIS, modelling, Ljubljansko polje aquifer system

Izvleček

V prispevku je opisana priprava podatkov za modeliranje vodonosnega sistema Ljubljansko polje, ki se nahaja v osrednji Sloveniji. Priprava podatkov je del konceptualizacije obravnavanega območja – prvega koraka v pripravi regionalnega stacionarnega modela. Le-ta pa bo pozneje nadgrajen v nestacionarni hidrodinamski model vodonosnega sistema Ljubljansko polje. Model pripravljamo v računalniškem programu FEFLOW, definicija njegove geometrije pa temelji na geološki sestavi in hidroloških lastnostih vodonosnika. Potrdili smo že znano dejstvo, da preveč natančna geometrija modela povzroča njegovo nestabilnost pri umerjanju, zato je potrebno med konceptualizacije sprejeti dobro premišljene odločitve, s katerimi se model poenostavi do takšne mere, da še lahko pričakujemo zadovoljive rezultate. Nastajajoč model bo razširil naše znanje o interakciji med površinsko in podzemno vodo.

Ključne besede: FEFLOW, GIS, modeliranje, vodonosni sistem Ljubljansko polje

Introduction

Hydrological cycle is one of the most important cycles for people and their environment, therefore a lot of attention, efforts and money were directed to control its processes through the history. Special attention should be paid to groundwater research, where it is important to know its sources, infiltration areas, its dynamics and vulnerability to possible contamination from industrial and agricultural activities, and to assure its sustainable development for future generations. Nowadays, new technologies involving different models enable us to better understand rather complex processes of the hydrologic cycle [1]. The model is defined as a simplified representation of a complex natural system with three different types of applications: (1) predictive, used as a framework for prediction of future conditions, (2) interpretative, used for studying system dynamics or organizing data, and (3) generic, used to analyse the hypothetical hydrogeologic systems [2].

A regional steady state model for the whole Ljubljansko polje aquifer system is under preparation, which is the main drinking water source for Slovenian capital city Ljubljana and its surroundings. The aquifer has also economic importance, since this aquifer is also an invaluable water resource for the Union brewery (Pivovarna Union, d. d.) located within a highly urbanized and industrialized area near the centre of Ljubljana. The groundwater model will be extended into a transient transport model describing the transport of stable isotopes of O and H and ^{3}H activity. The transport of dissolved species in groundwater systems facilitate to assess potential hazards to the public, when contaminants are used as transport material. The vulnerability of aquifer to environmentally harmful substances was observed in previous investigations: higher concentrations of herbicide diklobenil were detected in drinking water in 2001 due to maintenance of cemeteries; and high concentrations of atrazine could still be detected in drinking water in 2003 due to intensive agriculture [3, 4]. Few models of groundwater flow in Ljubljansko polje aquifer system were already developed in the past [5–7].

The aim of our work is to upgrade the existing models of Ljubljansko polje system with finite elements numerical model able to represent Sava river with higher accuracy than any other numerical model build until now. Numerical modelling of a physical system requires very well understanding of the system behaviours. The present work is motivated by the collection and processing of huge required data and the necessity to generate a complete DTM (Digital Terrain Model) of the entire computational domain, including the wetted region of the Sava river channel. The reason for it is in the great influence of the Sava on the elevation of the water table in the Ljubljansko polje aquifer system with intergranular porosity promoting the exchange between groundwater and Sava through the stream bed. Because of the high resolution of the Sava's bed geometry treatment in the groundwater model more stable model is expect during the calibration.

Background

At the Ljubljansko polje aquifer system (Figure 1) extensive investigation has been conducted in the last fifty years [8–10], therefore many geological and hydrological data are available for the formulation of a good conceptual model. Mathematical model simulates a natural system indirectly using a set of governing differential equations that describe physical processes occurring in the system, and numerical methods yield approximate solutions to the governing equation through the discretization of space and time [2, 11]. Many software were written to solve the governing equations for the different spatial, geological and hydrological conditions, which are based on two numerical techniques usually: the finite difference method (FDM), e.g. MODFLOW, and finite element method (FEM), e.g. FEFLOW. The FDM approximates differential equations by a differential approach, while FEM approximates differential equations by an integral approach [12]. The FEM is more appropriate choice when a subject of a research is a calculation of a precise water table elevation. On the other hand, it is better to use FDM when a calculation of a precise groundwater flux is performed. In our study the finite element flow simulation system FEFLOW® v6.1 from MIKE Powered by Danish Hydraulic Institute (DHI) was used, which enables to use stable isotopes as conservative transport materials. FEFLOW is a software package for three dimensional (3D) visualization of groundwater flow, mass transfer and heat transport in porous media. [14] 3D FEM for fluid flow and solute transport was developed by Huyakorn and Wadssworth in 1985 [13], while it is based on the equations for conservation of mass, Darcy's law for the anisotropic medium and the time-dependent species transport equation [14, 15]. The FEFLOW has the following advantages: (1) an ability to treat irregular shapes of a complex model boundary; (2) to refine the density of the mesh around features (e.g. wells, rivers, border, etc); (3) to simulate a groundwater age and transport of stable O and H isotopes [14].

Numerical models are used in parallel with development of powerful and affordable computer systems. In our case a 64-bit workstation under Windows 7 with CPU INTEL Core i7 and graphics ATI FirePro W7000 was used as a platform. The coefficients of the governing equations are the parameters that described the properties, boundaries, and stress of the system [11]. The choice of parameters is known as parameterisation, which is generally the most time-consuming procedure during modelling. The following data were obtained from different institutions/companies: (1) the counter map of the hardpan depth from VO-KA; (2) depths of piezometric groundwater table and groundwater abstractions from 48 and 35 wells, respectively from the VO-KA and Pivovarna Union, d. d, brewery; (3) isotopic analyses from the Jožef Stefan Institute. The ArcMap and AutoCAD Map were used for data processing before using FEFLOW. All three software FEFLOW, ArcMap and AutoCAD Map are fully integrated allowing quite easy transfer of the data between them. ArcMap and AutoCAD Map are geographic information systems (GISs), which are used for the management, analysis, and display of geographic information. GIS supports several views for working with geographic information: (1) the geodatabase view, (2) the geovisualization view, (3) the geoprocessing view [15]. Further, a coordinate system is extremely important when we are dealing with geographic information. It is recommended to define it already in the GIS. Our model is prepared in D48/GK coordinate system. However, the replacement of the current coordinate system (D48/GK) with the European Spatial Reference System (ESRS) is in progress in Slovenia. Its horizontal direction is defined with the European Terrestrial Reference System (ETRS89/TM) [16]. Therefore, an extremely caution is required, while using GIS data since they are archived in different coordinate systems.

The direction of groundwater flow within the Ljubljansko polje aquifer system is toward southeast in general. However, groundwater mining has a large influence on the hydrodynamic in the aquifer [17]. Ljubljansko polje aquifer system recharges mainly through infiltration of precipitation and river water. A smaller proportion of groundwater is recharged by lateral underground inflow [17, 18] in the area where the hardpan is deep enough at Ljubljansko barje in south and Kamniško-Mengeško polje in the north [18]. However, the underground inflow is still not very well known therefore a study about it should be made in the future. Small water recharge from surrounding hills is present as well.

The Sava river is one of the most important sources of groundwater in Ljubljansko polje aquifer system, although it does not recharge the aquifer along its entire length. The Sava river water inflows into the aquifer system between Tacen and Šentjakob [19], while the groundwater recharges the Sava downstream from Šentjakob. It is important to highlight that there are some locations where the Sava's bed lies on the hardpan, therefore no river-groundwater interactions are present. An important loss of groundwater is also water supply. There are four pumping stations in Ljubljansko polje: Kleče, Jarški prod, Hrastje and Šentvid. The largest is in Kleče, where 55 % of drinking water was pumped in 2003 [20].

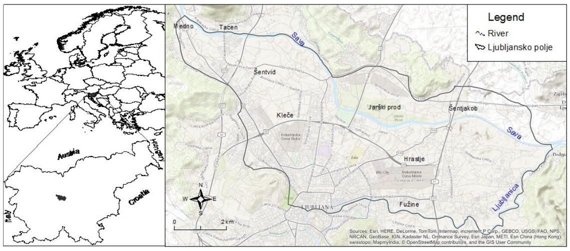

Figure 1: *Map of Ljubljansko polje.*

Information about geological composition of Ljubljansko polje was taken from previous studies and approximately 115 drilling reports from the Javno podjetje Vodovod-Kanalizacija, d. o. o., (VO-KA) and Pivovarna Union, d. d. Different lithological terms in drilling reports were used in the last 70 years therefore it was first necessary to unify them. Golden Software Strater was used for this purpose. According to all lithological information, the aquifer was divided into five modelled layers presented in Table 1. The aquifer is composed of Holocene and Pleistocene fluvial sediments, while its basement is composed of impermeable rocks (a hardpan). The geometry of the hardpan is diverse, its outcrops are in Šentjakob, Črnuče and Tacen. On the other hand, it is located quite deep, even more than 100 m, in the central part of the aquifer.

Three topographic data types, obtained from different institutions/companies, were used for generation the model surface: (1) Digital elevation model (DEM) from The Surveying and Mapping Authority of the Republic of Slovenia; (2) LiDAR data for Sava floodplain from Holding Slovenske elektrarne, d. o. o., (HSE, d. o. o.); and (3) 126 Sava's cross-sections from the City Municipality of Ljubljana (MOL). The precise surface generation of the aquifer is a demanding task and thus presented in the second part of the article.

Precise surface generation for modelling

The most appropriate GIS data for FEFLOW were prepared in the SHP or DAT files. The model geometry: polygon of the border, lines of the left and right banks of the Sava river, and points of wells and piezometers was constructed using SHP files. The outcrops of the hardpan, the Ljubljanica and Kamniška Bistrica rivers were the main criteria when the border of the study area was defined. The lines were extrapolated from TIN file with the following procedure.

Designing a grid is one of the critical steps in groundwater modelling. Although fine grids provide more accurate solutions, the grid should be generated wisely since the duration of calculation depends on number of finite elements. Therefore, it is reasonably to use fine grids where accurate solutions are expected and coarse girds where details are not important [12].

The aquifer domain was discretised by Triangle Mesh Generator, into 96 129 mesh elements per slice or 480 645 mesh element in total. Triangle is an extremely fast meshing tool for complex meshes. It has been developed by Jonathan Richard Shewchuk [21]. The mesh in floodplain domain was refined after the discretization. The reason is higher aquifer vulnerability to pollution at that area. The mesh structure for the Sava river bed has been refined until the mesh was small enough and consequently appropriate for interpolation of the river cross-sections data. The mesh is succinct around pumping wells and piezometers as well, since pumping wells have a great influence on the aquifer and the known elevation of the hydraulic head is important for the model calibration. Figure 2 shows the full map extent of the Ljubljansko

Table 1: *Lithological composition of modelled layers (ML)*

<table>
<tr><th>No. ML</th><th>Lithology</th><th>Epoch</th></tr>
<tr><td>1</td><td>Gravel, sand, gravel with sand and silt</td><td>Holocene</td></tr>
<tr><td>2</td><td>Conglomerate, clay, conglomerate with lens and clay</td><td rowspan="4">Pleistocene</td></tr>
<tr><td>3</td><td>Gravel with clay, sand with clay, gravel with narrow lines of conglomerate, gravel with sand and silt</td></tr>
<tr><td>4</td><td>Conglomerate is predominate</td></tr>
<tr><td>5</td><td>Gravel with sand and silt</td></tr>
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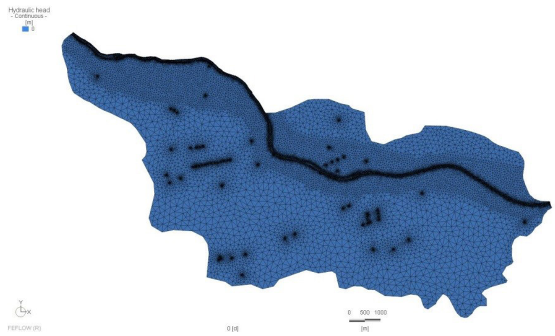

Figure 2: *Two-dimensional view of the Ljubljansko polje model domain with a finite element mesh.*

polje with aquifer discretization using a finite element mesh. The model domain is greater than 70.85 km^2 and it is bounded approximately by the latitudes 46.12° N and 46.08° N and the longitudes 14.43° E and 14.64° E.

DEM, Light Detection and Ranging (LiDAR) and the river cross sections were needed for interpolation of a surface, which were obtained as bunch of XYZ, LAS and KOO files, respectively. A XYZ file stores x, y, and z coordinates as floating-point values, where each row represents a distinct point record. A LAS file is an industry-standard binary format for storing airborne LiDAR data [22]. A KOO file is used for storing coordinates in national coordinate system, this is Gauss-Kruger coordinate system in Slovenia. These ASCII files were transformed into SHP files. The transformation of the XYZ and the KOO files is easy, while transformation of LAS files is more demanding. The LAS files were transformed indirectly into the SHP file through Terrain and Raster files. The ArcCatalog is needed for creating the Terrain file and 3D Analysis Tools in ArcMap for transformation Terrain file into the raster file with its anxious resolution.

Once the data were imported into the FEFLOW, the surface interpolation was provided using the following steps: (1) interpolation of the full model surface by DEM data (25 m × 25 m); (2) interpolation of the floodplain by LiDAR data (10 m × 10 m); and (3) interpolation of the river bed. AKIMA linear interpolation was used in the first and second steps, while Neighbourhood Relationship interpolation method was used in the third step. Some important properties in Parameter Association should be defined before using Neighbourhood Relationship interpolation method: (1) under Default link selection the line among which the interpolation will be done should be chosen, (2) the Snap distance should be at least similar to the largest distance between cross-sections. The distances between the Sava cross-sections range from approximately 20 m to 690 m along the flow path, thus the Snap distance 690 m was used in our case. To find the border between wet and dry region of the river bed is demanding and time-consuming process. For this purpose the 3D Analysis Tool was used for conversion of the Terrain file into TIN file (Triangle Irregular Network). Figure 3 shows the result of the river bed topography interpolation in FEFLOW.

Further, nodes for single interpolation should be chosen carefully. To make it easier the SHP files (polygons of the floodplain and the wetted region of the river bed) were made, which enable fast selection of mesh items by map polygon. The Data Management Tool in ArcMap was used, which further enables a fast conversion of lines into a polygon.

The counter map of the hardpan defined by hydrogeologists, was reconstructed using: (1) coordinates of later drilled wells that reached the hardpan, and (2) extrapolated outcrops of

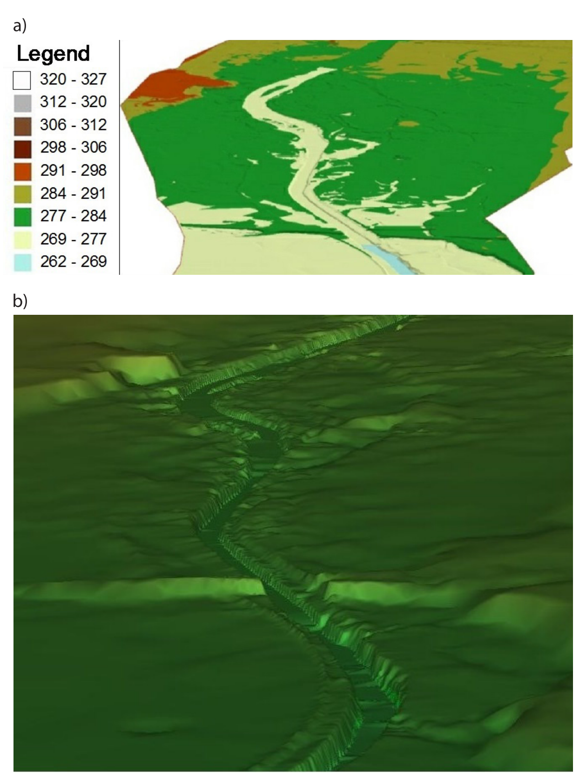

Figure 3: *The Sava river bed terrain a) and in the model b).*

the hardpan around Ljubljansko polje from the digitalized geological map. Few interpretations of new datasets were made and finally the most reasonable geometry of the hardpan was selected.

Conclusion

The conceptual model of Ljubljansko polje aquifer system was constructed, which will be progressed into the regional groundwater flow model. The main advantage of conceptual model is the construction of very high resolution of model domain geometry, especially the Sava river topography, which was constructed with river cross-sections data. The hardpan is the basement of the five model layers. The existing counter hardpan map was updated according to later drilling reports and digitalized geological map.

However, during a conceptualisation it is necessarily to accept the trade-off among realism, generality and precision [23]. The simplification of a natural system is another great problem for beginners, who do not understand the philosophy of modelling yet – less is more [2]. Extremely high resolution of our model geometry causes instability of the model as well. Therefore, the model geometry had to be reconstructed.

When the model geometry was constructed the initial and boundary conditions were defined. In the next step the calibration of the steady state model of groundwater flow will be performed.

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Analyisis of shallow tunnels construction in swelling grounds

Analiza gradnje plitvih predorov v nabrekalnih hribinah

Jakob Likar[1, *], Andrej Likar[2], Jože Žarn[1], Tina Marolt Čebašek[1]
[1]University of Ljubljana, Faculty of Natural Sciences and Engineering, Aškerčeva 12, 1000 Ljubljana, Slovenia
[2]Geoportal, d. o. o., Tehnološki park 21, 1000 Ljubljana, Slovenia
*Corresponding author. E-mail: jakob.likar@ntf.uni-lj.si

Abstract

Swelling pressures of the rock as a result of chemical and physical processes which are present during construction and operation of tunnels and have the influence on loads and deformations of primary and inner concrete lining. Deep geomechanical analysis of swelling indicates that in practice very often conservative way of calculating load capacity of primary as well as inner lining were used with a goal to keep long-term stability of the tunnel. Particular emphasis was placed on the physical and chemical assessment of the time dependent development of deformation. In the present paper the practical case of tunnel construction in specific swelling clay ground »Sivica« is analyzed. Based on 2D and 3D geostatic analyses, a rigid primary lining was chosen as a final design, because the depth of the tunnel is only about 30 m below the surface. The geotechnical parameters of hoist ground »Sivica« are a result of laboratory and »in situ« tests, which were conducted according to technical standards. During a construction and after it the geotechnical measurements were conducted. The measurement results confirm the correct technical decision in the design stage.

Key words: Road tunnel, support elements, Finite Element Method, primary shotcrete lining, geotechnical measurements

Izvleček

Nabrekalni tlaki v hribinah so rezultat kemijskih in fizikalnih procesov, ki med gradnjo in obratovanjem predorov vplivajo na obtežbe in deformacije, ki se razvijajo tako v primarni kot tudi notranji betonski oblogi. Poglobljene geomehanske analize nabrekalnih pojavov v hribinah so pogosto osnova za konzervativne načine izračuna potrebne nosilnosti primarne in tudi notranje obloge predora z namenom, da se zagotovi dolgoročna stabilnost podzemnega objekta. Posebna pozornost analiz je namenjena fizikalnim in kemijskim procesom v hribinah z nabrekalnim potencialom v odvisnosti od časovno odvisnih deformacij. V tem prispevku je podan praktičen primer gradnje cestnega predora v glinasti hribini »Sivica«, ki ima specifične nabrekalne lastnosti. Končna tehnična rešitev gradnje na osnovi rezultatov geostatičnih analiz 2D in 3D je temeljila na uporabi toge primarne obloge, ker je globina predora le okrog 30 m pod površino terena. Geotehnični parametri »Sivice« so bili določeni z upoštevanjem laboratorijskih in terenskih raziskav, ki so bile izvedene skladno z veljavnimi standardi. Med gradnjo in po njej so bile izvajane geotehnične meritve, katerih rezultati so omogočili primerjavo z izračunanimi parametri in posledično potrditev ustreznosti projektnih rešitev.

Ključne besede: cestni predor, metoda končnih elementov, primarna obloga iz brizganega betona, geotehnične meritve

Introduction

Understanding the basic theory of chemical and physical processes in swelling ground is fundamental condition for successful technical solution of tunnel construction in such circumstances. When tunneling takes place in swelling ground such as anhydrite or swelling clay minerals, i.e. montmorillonite, whole process of construction, including underground water presence and designed technology, needs to be analyzed. This is very important, because in the past in more cases of tunneling in such grounds, after deep analysis were carried out, clear shown the influence of unusable technology which caused and activated swelling potential of present ground layers (Figure 1). It is known that chemical reaction of anhydrite ($CaSO_4$) in the gypsum ($CaS0_4 \cdot 2H_20$) results in the increase of volume up to 61 %. The similar can apply in the shale formations with swelling potential where physic-chemical reaction depends on stress relief and reduction of the chloride concentration by water adsorption (osmotic swelling). The chloride ion diffusion is assumed to be the mechanism for the reduction of the chloride concentration.

Research activities of swelling processes in ground

Numerous calculation methods have been presented in the past to simulate the swelling behavior and the resulting structural response [1–9]. Very important laboratory tests on swelling rocks were done by Barla [10], where swelling gouge from weakness zone in tunnel were investigated.

High sophisticated constitutive laws have been developed to account for the phenomenon of swelling in terms of continuum mechanical models, i.e. [12–15]. Several PhD theses were done on the topic of swelling processes in rocks [10, 16, 17], in which authors were explained fundamentals of physical and chemical base of the such ground behavior. More attention is paid on experimental investigation which was done by [18]. He had shown the compression and swelling behavior of the Callovo-Oxfordian argillite. Two series of oedometric tests were carried out, first one showed that the argillite exhibits a swelling behavior even when fully saturated under stresses higher than the in-situ stress, and the second series of tests showed that the swelling capacity appeared to increase with compression. In both cases, swelling was related either to pre-existing cracks due to sample coring, storage, drying, wetting and trimming or to cracks induced during compression. In this regard, compression was suspected to occur by local pore collapse that created micro-cracks that afterwards swelled when hydrated. Indeed, sample compressed to a higher pressure exhibited higher swelling potential.

A high quality investigation of swelling phenomena was carried out [19] which focused on repair works done in old railway tunnel in Switzerland. Long-term laboratory tests showed that the swelling behaviour occurred in stages and bands of precipitated gypsum were found in samples analysed by mineralogical test after test completion [20]. The swelling processes require water and this could be facilitated by spalling type fractures, brittle failure behaviour with associated extensional fracture development as a potentially controlling mechanism in creating a water conductive zone beneath the tunnel invert. Such brittle fractures were observed during tunnel construction in anhydrite by [21, 22]. Therefore, gypsum crystal growth is most likely to occur where water has access

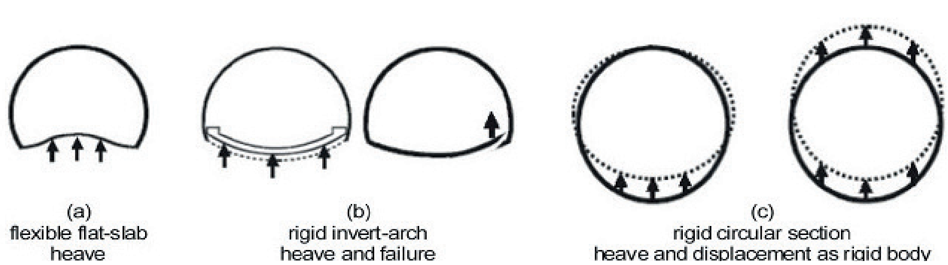


Figure 1: *Typical events associated with swelling in tunnels according to [11].*

and the state of stress is favourable for stress fracturing. On the low confinement side of the spalling limit, water has access through fractured ground and the rock mass is essentially free swelling until the support provides sufficient pressure to prevent further swelling.
One of the important investigation of swelling phenomena was relating to the goal of the presented investigations and that is to describe the phenomenon of self-sealing quantitatively (Figure 2, 3) and to establish a model, by means of which it is possible to take the self-sealing phenomenon into account when designing tunnels in swelling rock [23, 24].
It is expected, that due to the new models a more effective and economic design of tunnels in swelling rock will be possible. Swelling pressures, which had been identified in some old railway tunnels that were built in the 19th and in the early years of the 20th century, manifested in many cases, particularly in the floor inverts. In some cases it was necessary to carry out rehabilitation even twice, because the invert had shallow arch which hadn't enough

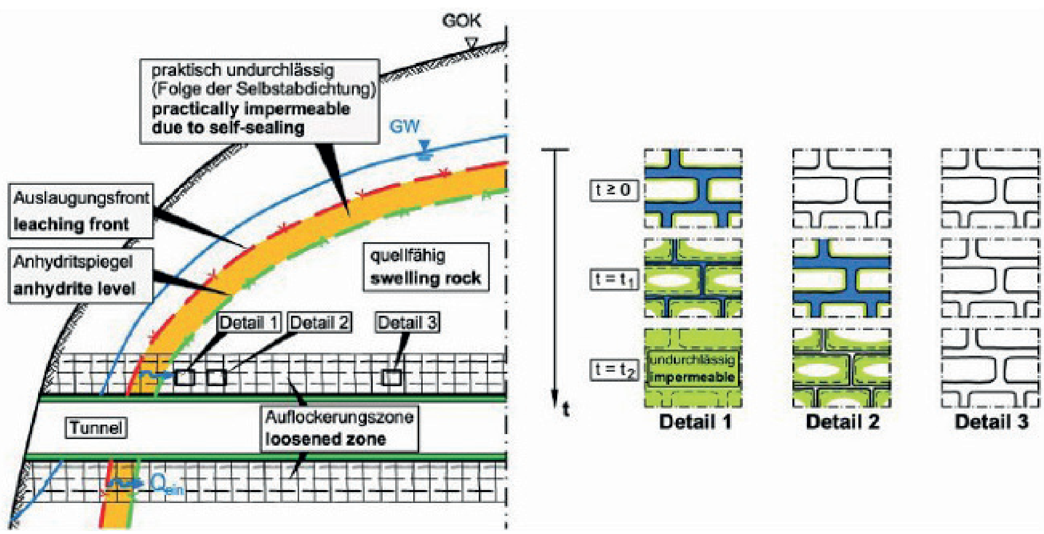


Figure 2: *Mechanisms of self-sealing in SBR [23].*

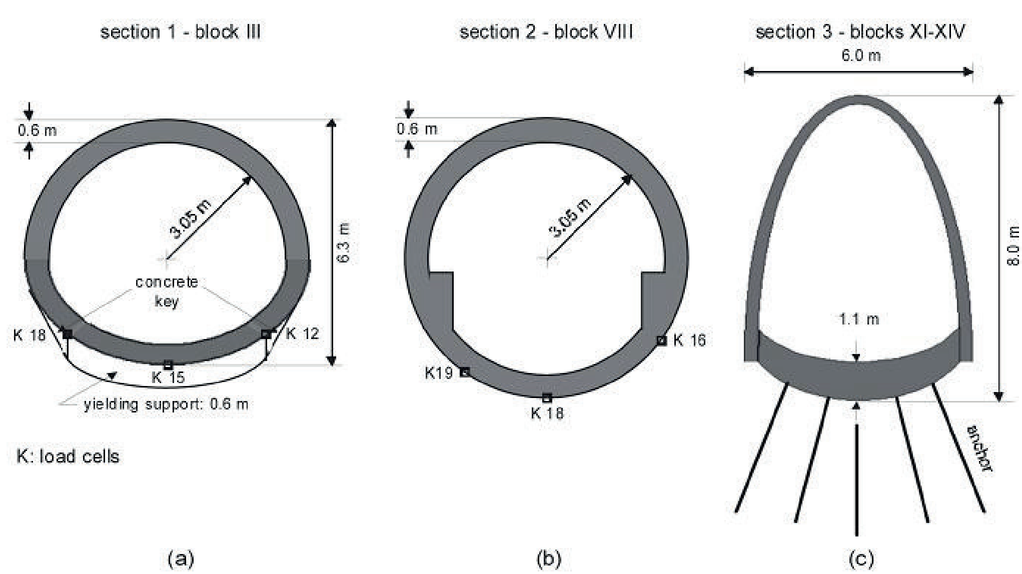


Figure 3: *Characteristics of tests sections in test gallery U1 of Freudenstein tunnel modified [25].*

static resistance of the support ring (Wagenburgtunnel, built in 1957) [26]. From several analyzed cases it can be summarized that the process of swelling is usually intensely present in the floor and in the sides of the underground facility, which represents lower static capacity of the structure.

Special case of tunnel construction in swelling rocks was Engelbergtunnel tunnel, which was built in 1990 [26]. The primary lining has been damaged at the beginning of construction at the connection point between the tunnel side the tunnel invert. At the beginning the original basic design was based on dry rock conditions during construction. Furthermore, in the upper design stage it was planned inner lining of reinforced concrete in the goal to excluding the effect of swelling pressure of the surrounding rock. During the construction phase, the design concept was significantly revised since instead of 30 cm thick shotcrete lining in the invert, 1.5 m thick concrete lining was installed, additionally anchored in the foundation ground. This way sufficient static resistance to swelling pressures was provided. Above anchored and reinforced invert high deformable layer called »Knautschzone« was constructed to prevent possible damages on the inner lining. And finally, the inner lining in invert was installed with a thickness of 3 m, as shown in Figure 4.

In the design procedure is important question when in case of construction of the underground facility the increment of the volume change will be prevented enough with the installation of rigid support system in the goal to reduced deformation in acceptable limit. That requirement in the conclusion still need adequate primary lining with sufficient load bearing capacity to ensure stability during the construction. It should be noted that the time evolution of swelling pressures depends on the amount of water in contact with swelling ground and stiffness properties of the primary lining. This takes into account the principle of long-term stability of the facility with the primary lining, which consists of a standard shotcrete lining, steel arches, steel wire mesh and rock bolts or anchors. A typical example of the combination of swelling and squeezing rocks can be found in Karavanke road tunnel connecting Slovenia and Austria, which was built in the second half of the 1980s and put in operation in 1991. In fact is that deformations, which in some sections had started to develop immediately after completion of construction or even already in the time of construction did not stabilize. The continuous time developed deformations called for the implementation of the rehabilitation of certain sections. Measurements which were carried out in the last years showed that the deformation process after refurbishment not stopped in some sections. Due to difficulties in identifying key parameters for such swelling laws the engineering approach predicting the swelling pressure used back-calculation of data monitored during construction of the tunnel in similar ground conditions. The last investigations in the Karavanke tunnel have shown that installation of a deformable layer in the invert between surroundings rocks and refurbished primary lining can be right technical solution for time stable tunnel structure.

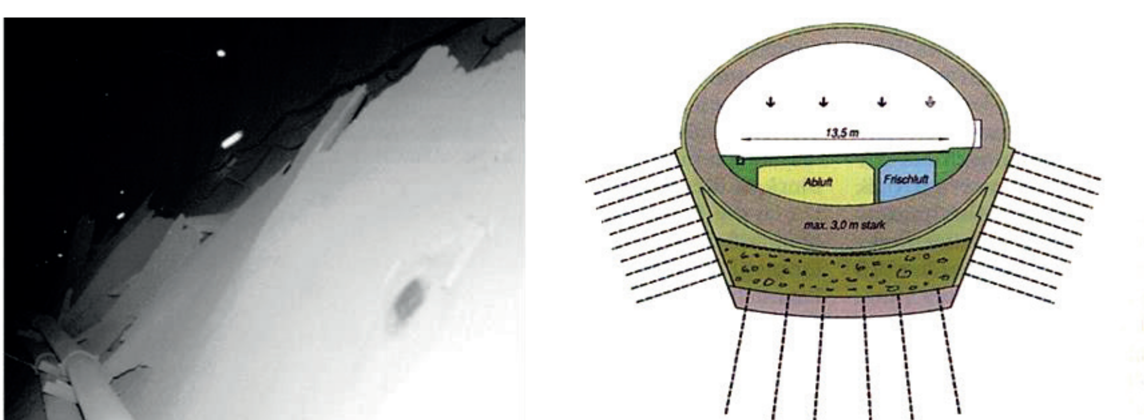


Figure 4: *Construction the Engelbergtunnel* [23].

Basic principles of support system design in swelling ground

The primary mode of support system planning is based on the principle of ensuring a balance between swelling capacity of ground and reacting support pressure. It is exposed to the volume increase that occurs after the excavation step. The relationship swelling ground - support system has important influence on the location of the equilibrium system, as shown in the Figure 5. It should be noted that the release of ground strain is a result of mobilization bearing capacity of the ground and at the same time swelling forces are generated when water or air moisture find the contact with ground surface at the excavation round in the tunnel. Quick and effective prevention of water access indirectly reduces formation of higher swelling pressures relating to formation efficient activation of the self-protection ground layer around tunnel wall. Exactly that self-protective effect has a unique role on reaching equilibrium between the supports system and surrounding ground.

Swelling phenomena aplication in the tunnel Ljubno design

The presented case of the shallow tunnel Ljubno with maximum overburden of about 30 m was built in the ground with swelling potential in the northern part of motorway section A2 Karavanke (Austria) – Obrežje (Croatia), and has shown specific circumstances relating to geotechnical conditions assessment.

The new Tunnel Ljubno was built as the twine road tunnel including reconstruction of the old tunnel tube which is now a part of new motorway (Figure 6). The old tunnel tube was constructed in the 60s of the past century without invert (Figure 6). In more than 40 years that the tunnel was in operation damages such as lifting of the pavement similar as shown in Figure 1–a) occurred. Reconstruction of the old tunnel tube included extension of the current clearance profile according to the standard that requires two lanes with a width of 3.75 m, one intervention lane with a width of 3.20 m and two intervention corridors with a width of 0.8 m which is the same as in the new tunnel which was built 40 m away. The amount of excavated material in the profile is approximately 86 m^2 per running meter of the tunnel.

Results of geological and geotechnical investigation

In order to design construction and reconstruction of tunnel tubes extensive field and laboratory investigations and explorations

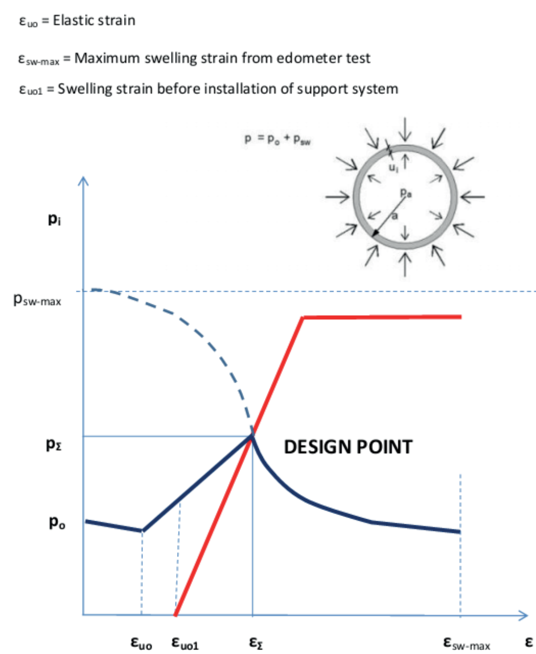


Figure 5: *Basic principle of tunnel support design in swelling ground.*

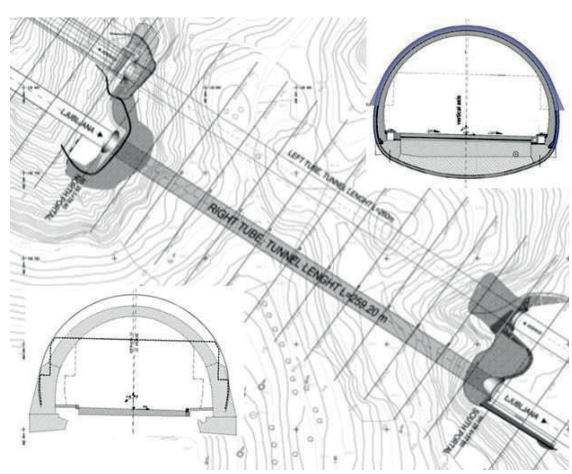


Figure 6: *Location of the new and old tunnel tube with maximum overburden of about* 30 m *and clearance profiles of the old tunnel before reconstruction and after it.*

were carried out to determine geological and geotechnical characteristic of ground materials present in the tunnel area. All investigations and geostatic analysis were carried out before the design of new tunnel tube which was constructed first before the reconstruction of old tunnel tube begun. Special attention was paid to the investigation of hard clay known as »Sivica« in which majority of the excavation works were done. Design of excavation and primary support lining was done in an appropriate way due to extensive amount of information acquired by geological mapping, boreholes drilling, Standard Penetration Tests and Pressuremeter Tests. The prognosis of geological structure is shown on the longitudinal profile in Figure 7. Distance between tunnel tubes is shown in the Figure 8.

The laboratory tests included measurements of moisture content, UCS, Triaxial Shear Tests and particularly attention was paid to the measurements of swelling potential and deformability of »Sivica«. It was found that in a dry environment »Sivica« has solid strength properties, while contact with water causes the relatively high presence of swelling potential. A large number

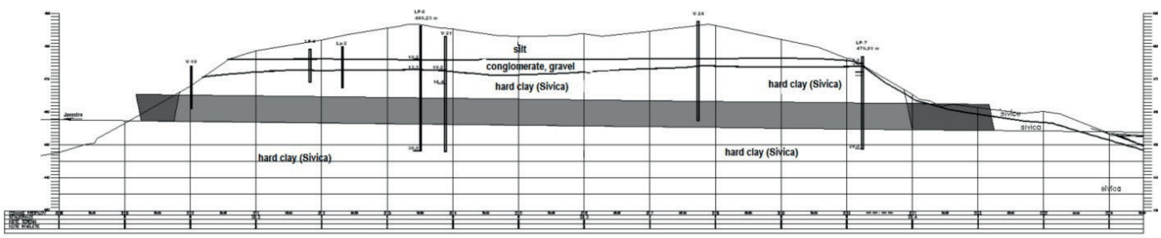


Figure 7: *Longitudinal geological profile of the new tunnel tube.*

Table 1: *Basic geotechnical parameters of the existing ground layers*

Type of ground	Moisture w/%	Unit weight γ/ (kN/m^3)	Youg Modulus E/MPa	Poisson ratio ν	Tensile strenght σ_t/MPa	Unconfined compresive strenght σ_c/MPa	Angle of internal friction φ/°	Cohesion c/MPa
Silty clay	25.0	20.0	5.0	0.4	/	0.001	25.0	0.0
Conglomerat	/	25.0	4 000.0	0.2	/	/	40.0	0.5
»Sivica«	7.0	24.0	200.0	0.3	0.5	5.0	31.0	0.136
Weathered »Sivica«	/	20.0	4.0	0.4	/	/	23.0	0.0

Table 2: *Laboratory determined sweling pressure at prevented strains and swelling strains in the unloading stress conditions*

Depth below the ground (m) (»Sivica«)	Primary vertical ground pressure σ_v/MPa	Swelling pressure p_{sw}/MPa at total prevented strains	Swelling strain ε_{sw}/% at water presece at total first unloading/second unloading conditions
25.0	0.600	0.250	2.0/3.5
20.0	0.480	0.350	2.0/4.0
16.0	0.385	1.45	1.8 /2.0
33.0	0.800	≥ 1.5	1.3/4.0

of laboratory tests to describe rock properties including swelling had been performed. The results were represented in Table 1 and Table 2.
One of the most important investigations was XRD Analysis which was carried out with the goal to determine the mineralogical content of the »Sivica« sediment samples. The diffraction patterns were identified with the data from X'Pert HighScore Plus software ICDD database. The compact gray clay samples were analysed with handheld XRF analyser NI TON GOLDD+ model XL3t He (50 kV) for major and minor element concentrations. The XRF result represents average of four measurements. Analyses were run with helium purge in the XRF in order to determine the degree of improvement in the signal detection attributable to helium's elimination of scattering by atmospheric gases. The analyser uses a 50 keV miniaturized X-ray tube and can quantify elements from magnesium through uranium. Data for all experiments consisted of counts (of X-ray fluorescence) detected per second. Total acquisition times were kept constant at 180 s. Bal variable is balance and incorporates all light elements from H to Na that cannot be detected with this XRF analyser.

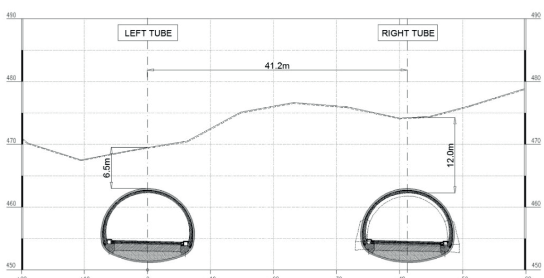


Figure 8: *Vertical cross section through existing (right) and new tunnel tube (left) with low overburden.*

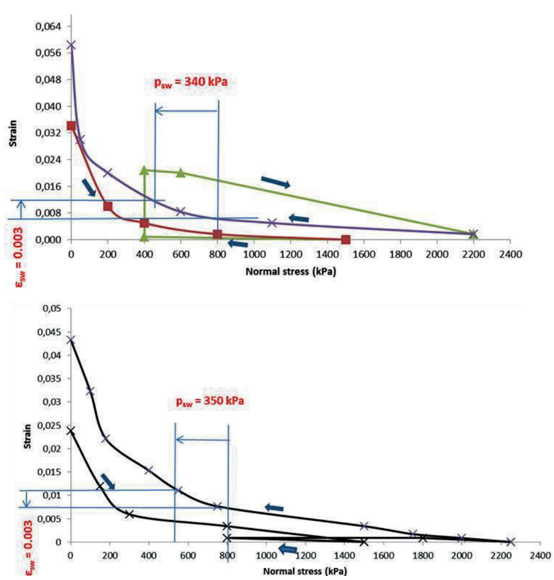


Figure 9: *Laboratory test results of swelling potential of the dark grey hart clay »Sivica« on the sample from the depth* 33.0–33.3 m *below the ground surface which is close to tunnel tubes locations.*

Based on given results as shown on Figure 10 the conclusion has shown that fresh clay sample does not contain any swelling minerals. The clinochlore (chlorite) in the clay sample does not change volume upon solvation with ethylene glycol, but only with the addition of water. When the chlorite mineral in the clay is altered by surface weathering, the alteration in the slate appears to be relatively rapid and complete. Direct surface exposure of the clay leads to the apparent irreversible dehydration of the surface layer of the clay. Weathering procedure is the manner in which chlorite ordinary alters when subjected to an atmospheric environment. It seems that alteration of chlorite leads to formation of mixed-layer chlorite-vermiculite and possibly to montmorillonite (Mg-saponite) which are well known swelling clay minerals.
From the results revealed the presence of swelling potential (Figure 9) and investigation based on XRF analyser (Figure 10), it cannot clear demonstrate the unique possibilities of activation swelling process during construction or reconstruction the tunnel tubes. Taking into account all results of swelling potential analysis, back geotechnical analysis of stability the old tunnel tube (Figure 5) and considerations in the mentioned scientific founding published in adequate journals in the deeper geotechnical design analysis used swelling pressure p_{sw} = 1 200 kPa.

Designed solution for tunnel construction and reconstruction

Due to the expected behaviour of »Sivica« the design provided technological measures to reduce the danger of water influence on the strength of the intact geological material. Immediately after excavation free surface was protected with shotcrete. Drilling and anchoring techniques without water usage were implemented. The purpose of these measures was to avoid contact between ground and any type of water and thus keep »Sivica« in its natural conditions. The basis for determining the swelling ground - support system relationship is a relation between the reactive support pressure and the tunnel wall deformations, as shown in the Figure 11 which is prepared on the basis of assessment usable swelling pressure including in accounting the stiffness of primary shotcrete lining. For assessment of relevant value of design swelling pressure, the elastic pre-deformations ε_{ui} = 0.4 % and stiffness of shotcrete primary lining k_c = 540 MPa with adequate ε_{sw} = 0.3 % radial strains were used in the equations based on close form solution method. The geostatic primary vertical pressure in the rock and the additional swelling pressure which was obtained from laboratory tests (Table 2) were included in the geostatic calculations.

The reduction of reaction support pressure was achieved by introducing the flexibility of the primary support system. Reserves in the capacity of proposed support system were established with a safety factor against the collapse. That was applied during the calculation of internal forces and bending moments from the results of 3D geostatic analyses which are described in the next subsection. Determination of the size of the damaged zone around the tunnel lining in the old tunnel tube was determined based on the examination of drilling cores, which have been acquired in the research stage of design.

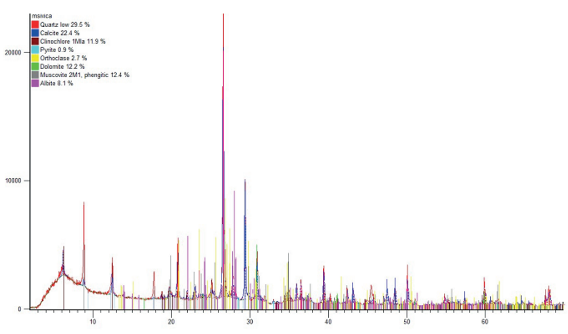


Figure 10: *Result of XRF analysis.*

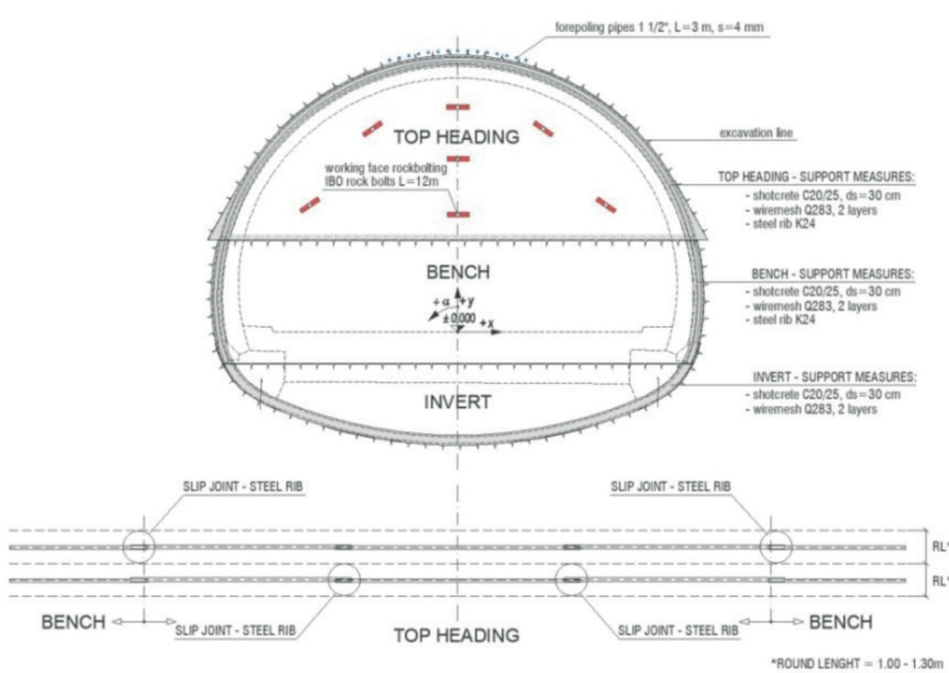


Figure 11: *Designed support measures for essential length of tunnel.*

This ranged from 0.5 m to the on the tunnel roof and around 1.0 m on the tunnel sides and in the floor without invert. During the reconstruction of the old tunnel tubes (Figure 13) the damaged layer around the old tunnel was removed, which is favourable for the establishment of long-term geostatic stability the tunnel system (Figure 12).

Based on the analysis of different theoretical approaches and practical cases of tunnel construction in swelling grounds including the geometrical data and thickness of ground layers cover, the rigid support system was applied. To follow this goal, the standard supporting elements have been considered in the design such as steel arches K24 and sprayed cement concrete thickness between 30 cm and 35 cm with two layers of wire meshes and rock bolts if required (Figure 11). The whole length of the tunnel tubes was scheduled with invert built from shotcrete with the same thickness. Rock classification was made according to Austrian standards OENORM B 2203.

Geostatic analysis of tunnels support measures

To verify the support measures designed as primary lining, extensive 2D and 3D numeric analyses, using Phase2D and MIDAS GTS computers codes, were done. The comparison between load cases without and with considering additional pressures caused by swelling (340 kPa) were carried out for two different design solutions. The swelling pressure was simulated with

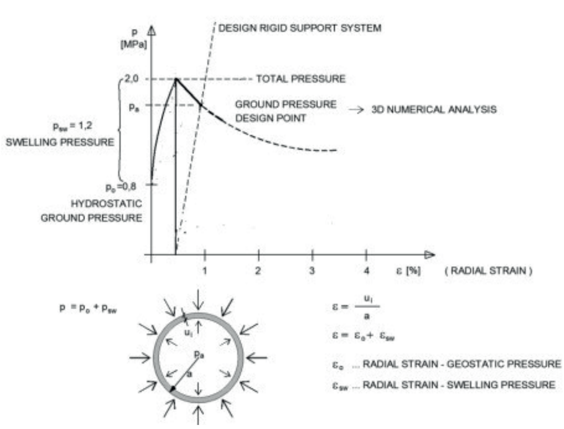


Figure 12: *Reactive support pressure versus radial strain in the swelling ground.*

proportionally higher unit weight of ground. In the Table 3 and Table 4 input ground geotechnical data for both numeric analyses are shown. The excavation of the tunnel was divided into a top heading, bench and invert, while on the longitudinal direction the excavation was simulated in progressive steps of 2 m in length.

The support elements in the calculations were planned with reinforced shotcrete lining with two steel meshes. Figures 14 and 15 shows the results of the calculation displacements without and with swelling pressure considered. In the first case the displacement could reach the value of 3.0 cm in the invert and, while in the second case, displacements were below 6.5 cm. The values of displacement for both calculations are shown in the Table 5. From the same figures the area of influence of tunnel excavation is in the worst case stretched up to 15 m left and right of the planed axis of the new tunnel, which means that the new tunnel tube excavation on the existing tunnel tube practically hasn't effect on stress-strain changes. The same can be concluded from the Figures 16 and 17, where the calculated Strength Factor (SF) is shown. If the values and distribution of main stresses Sigma 1 and Sigma 3, FS and total displacements around tunnel tubes are compared with each other, it is evident that the main concentration are present in the invert area.

This is mostly related to shallow depth of the tunnel locations and stiff static resistivity of primary linings incorporated in the low bearing capacity of surrounding ground.

3D FEM analysis were carried out in the similar way as 2D calculations. The first numerical simulation was done when the excavation procedure of the new tunnel tube was analyzed. Calculated total diplacement which are shown in Figure 18 has the maximum value approx. 8.5 cm in the invert and the minimum value approx. 3.0 cm on the crown. In the next short presentations of calculations results we can find that higher stresses and strains in the primary lining existed in the roof and invert parts of tunnels tubes (Figure 19 and 20). That are comparable with results of 2D analysis which were shown in Figure 14 to 17.

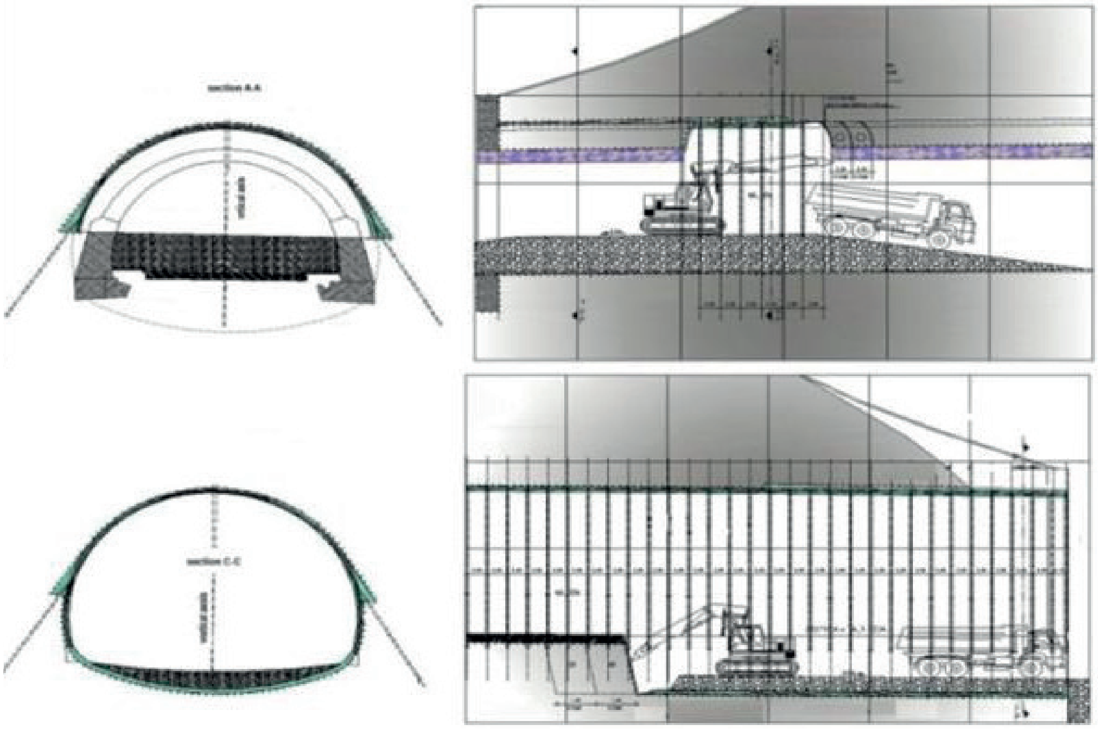


Figure 13: *Designed reconstruction procedure for old tunnel tube.*

Table 3: *Input geotechnical ground data for the analysis*

Type of ground	Unit weight γ/(kN/m^3)	Young Modulus E/MPa	Poisson ratio ν	Cohesion c/kPa	Angle of internal friction φ/°
Silt	20	5	0.4	1.0	25
Conglomerat	25	4 000	0.2	500.0	40
Sivica	24	200	0.3	136.0	31

Table 4: *Mechanical parameters of support elements*

Support element	Unit weight γ/(kN/m^3)	Young Modulus E/MPa	Poisson ratio ν	Thick of primary lining (m)	Wire mesh Q189 (pcs.)
Shotcrete (fresh)	25	3 000	0.30	0.35	2
Shotcrete (final)	25	15 000	0.25	0.35	2

Table 5: *Calculated displacements in the invert and side walls*

Object	Calculated maximum displacements (cm)			
	without swelling		with swelling	
	invert	side wall	invert	side wall
New tunnel tube	3.0	1.1	6.2	2.3
Reconstructed tunnel tube	1.1	0.7	1.4	1.0

The results of 3D simulations of the excavation and primary support installation for new and reshaped tunnel tube with respect to the swelling pressure of the surrounding rock are calculated depending on the depth and characteristics of »Sivica« and the size of the tunnel tubes. For both tunnel tubes calculated total displacements are between 2 cm and 6 cm at the roof and invert (Figure 21).

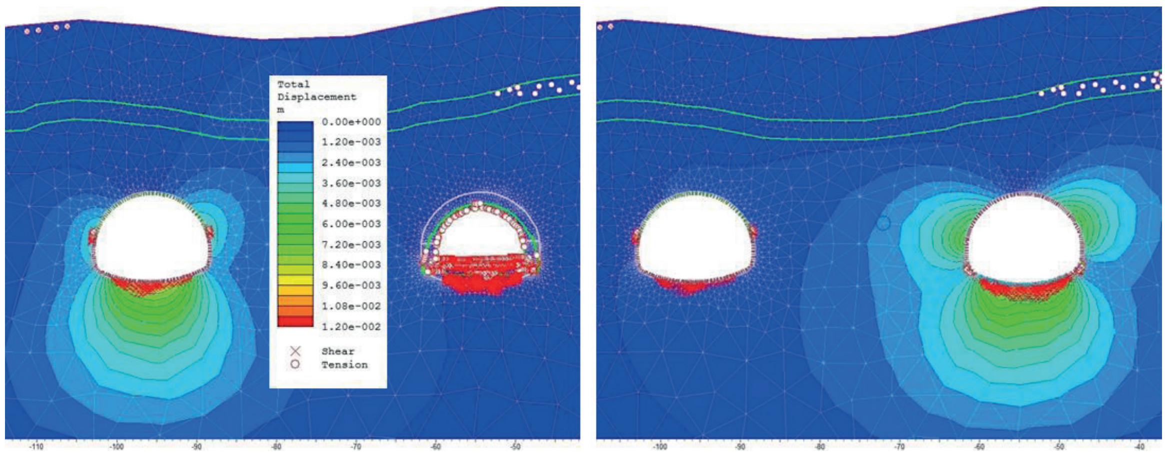


Figure 14: *Calculated displacements in the new and reconstructed tunnel tube without taking into account designed swelling pressure.*

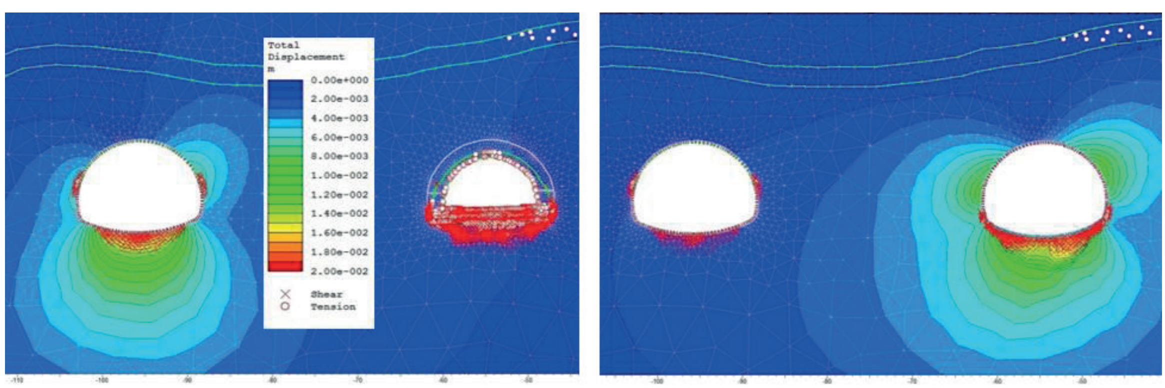


Figure 15: *Calculated displacements in the new and reconstructed tunnel tube with taking into account designed swelling pressure.*

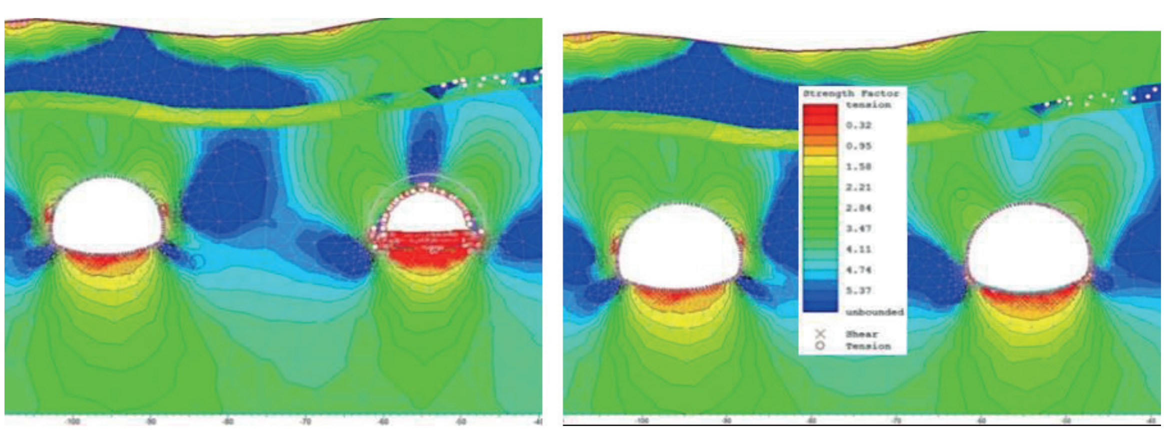


Figure 16: *Calculated Strength Factor (SF) in the ground for the new and reconstructed tunnel tube without taking into account designed swelling pressure.*

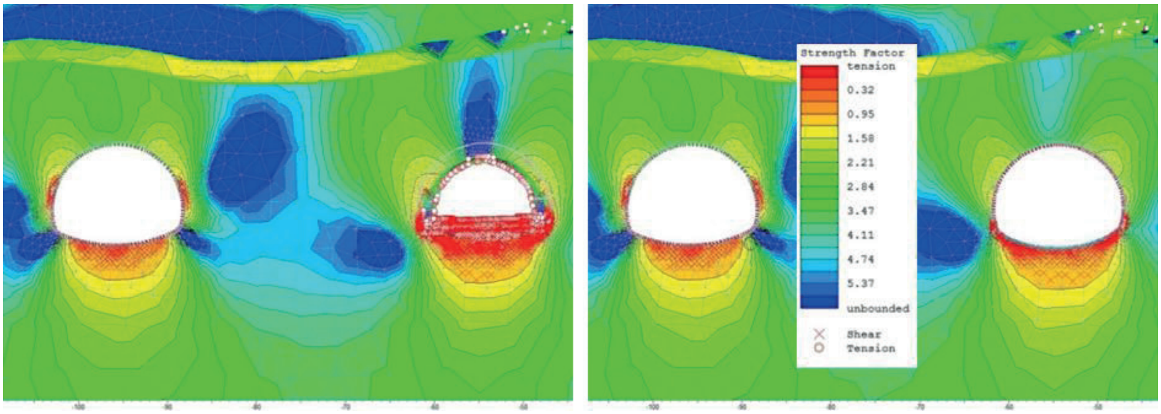


Figure 17: *Calculated Strength Factor (SF) in the ground for the new and reconstructed tunnel tube with taking into account designed swelling pressure.*

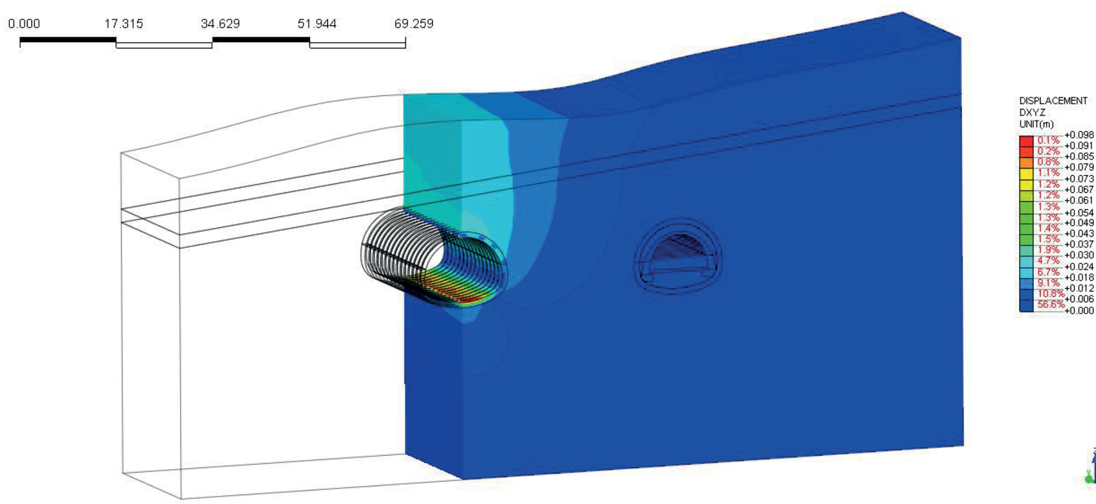


Figure 18: *Total displacements after excavation and support of the new tunnel (left tube direction toward Ljubljana).*

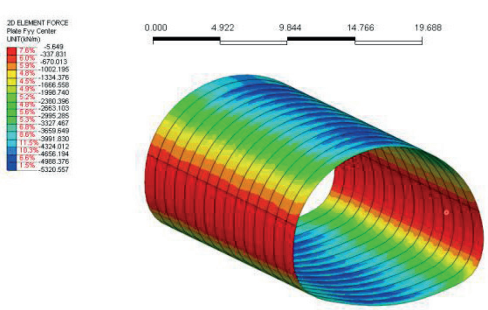


Figure 19: *Tangential axial forces in primary lining – new tunnel (left tube).*

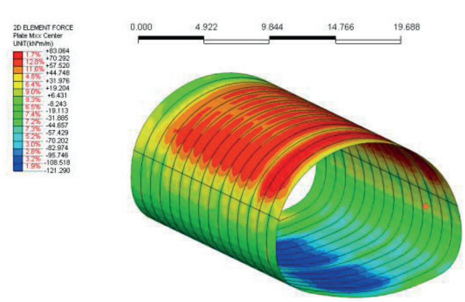


Figure 20: *Bending moments in primary lining – left tube.*

The maximum axial forces in the primary lining were found in the both sides where the calculated values are around –5 000 kN. While the smallest values of calculation results are shown in the roof and in the invert of tunnel tubes which amount to around –300 kN. It is worth noting, as their value is very small and is close to the tension zone, which is which is compensated by a double reinforcement wire mesh, so that provides sufficient safety against

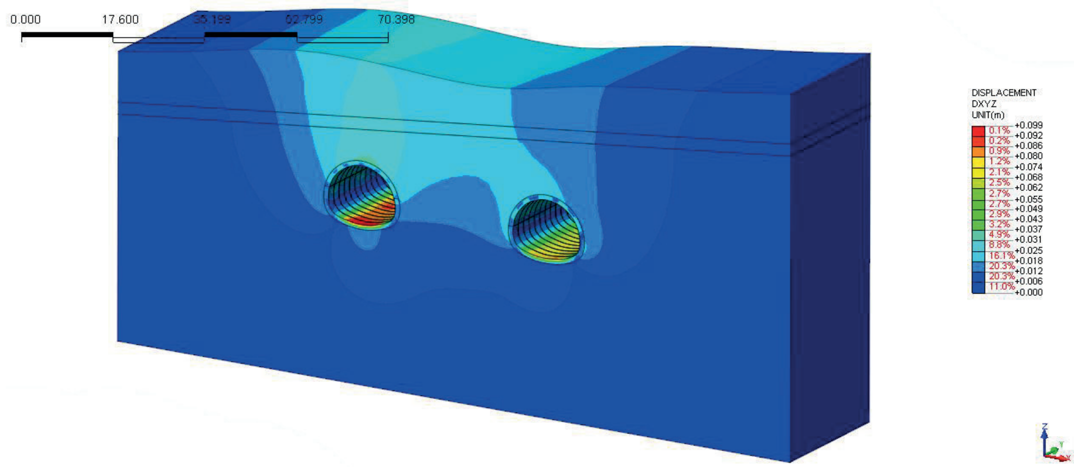


Figure 21: *Total displacements after excavation and support of the right tube (direction toward Ljubljana).*

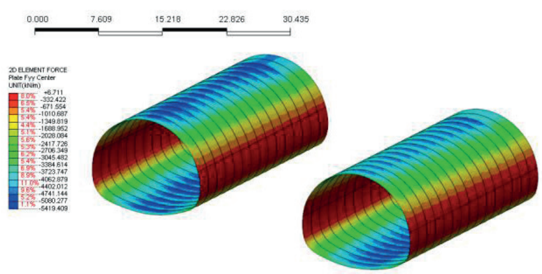


Figure 22: *Tangential axial forces in primary lining – left and right tube after excavation and support of the old one tunnel (right tube – direction toward Ljubljana).*

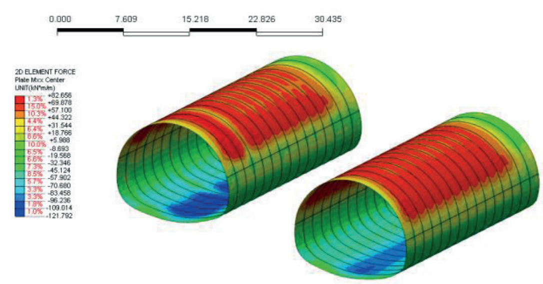


Figure 23: *Bending moments in primary lining – left and right tube after excavation and support of the right tube.*

the development of tensile cracks. Particular attention was dedicated to the construction of joint primary lining in contact between top heading and bench with invert. The results are shown in Figure 22. Analysis of the bending moments in the primary support shows that in the ceiling value regardless of the format of a positive in ground vault but negative. Their value ranges from about +82 kN m/m to about –122 kN m/m, which is not a problem for the provision of required stability (Figure 23).

Some distinctive features of the construction

A relatively short length of the tunnel was not suited for performing excavation with several phases going on simultaneously. Therefore, the excavation of the concrete invert was made first, followed by making a bench and top heading which were constructed together. Since the northern portal was not accessible, the whole excavation was made from the southern portal running towards the northern portal, where the breakthrough was made directly to the surface, meaning that no previous protective measures were necessary on the northern portal.

Figure 24 shows the breakthrough of the top heading in the inaccessible area. The last few metres of the top heading were built in the side gallery, with the cross section profile of approx. one third of the cross section of the top heading. This method of excavation reduced the risk of overbreak during the breakthrough. The breakthrough, as well as the excavation of northern portal and excavation of the remaining top heading of the tunnel, were made successively.

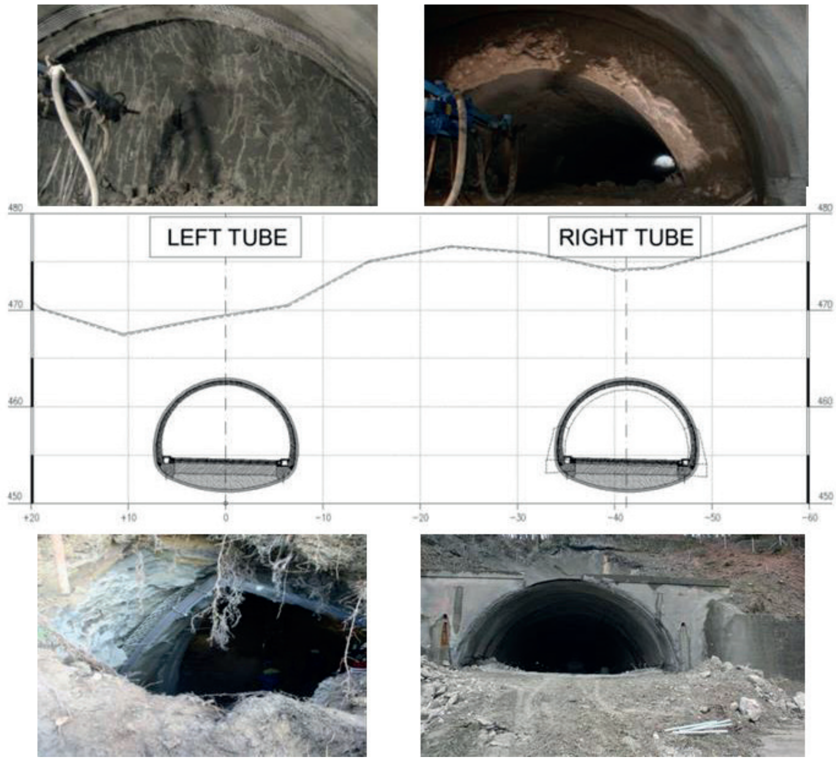


Figure 24: *Excavation face and breakthrough at the Nord portal of the new tunnel tube and reconstruction of the old tunnel.*

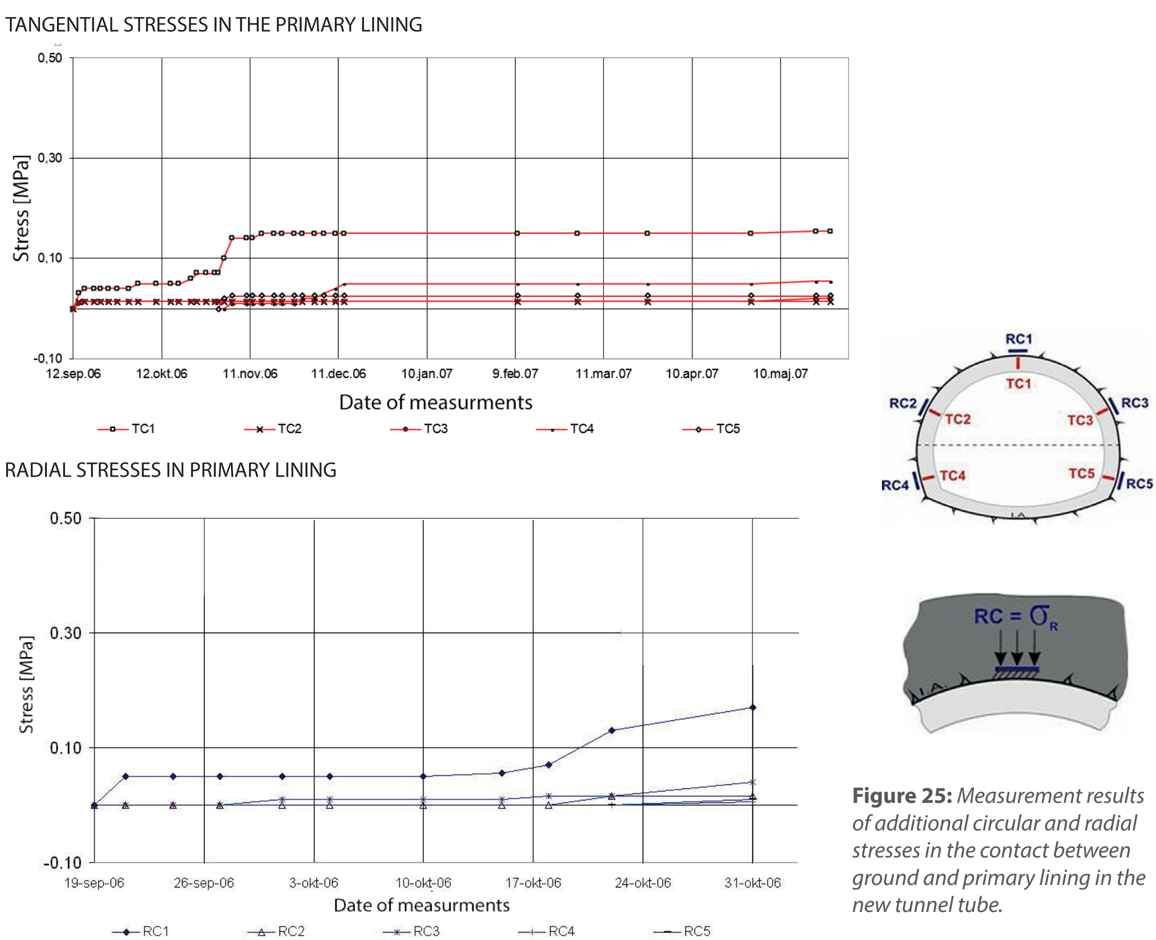


Figure 25: *Measurement results of additional circular and radial stresses in the contact between ground and primary lining in the new tunnel tube.*

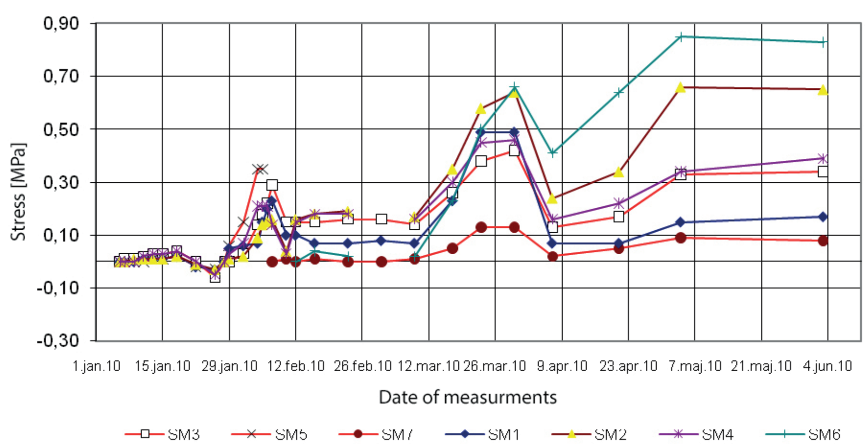
Gelogical observations and geotechnical measurement during construction and in operation

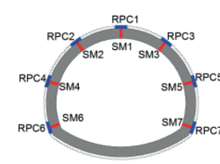
The results of monitoring measurements in pressure cells (and extensometers), which were installed during the construction of the new tunnel tube in the same geological geotechnical conditions did not show additional increases in circular (tangential) and radial stress (Figure 25 and 26) as a result of influence of the reconstruction of old tunnel.

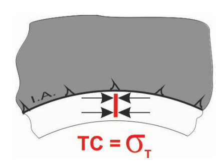
In future the swelling potential will not produce additional stresses on the inner lining, because the primary lining has a sufficient loading capacity. The process which explains swelling pressure increase in examined ground shows that the closure of cracks depends of ground water isolation.

This is consistent with the results of extensive research of various swelling rock types [25, 26], which have rheological properties similar to hard clay (Sivica). It has been proven that naturally developed swelling pressures are much lower or minimum than those which are obtained from laboratory investigations. The determination of meaningful swelling pressure to be applied to the tunnel lining based on laboratory tests is largely depending on the scale effect, the stiffness ratio of the tunnel lining and surrounding ground and the in-situ stress and water conditions. Hence, swelling load conditions are difficult to predict in the reality. The displacements measured during the excavation were smaller than expected, i.e. less than 3 cm. This is probably due to more favourable geological and geotechnical conditions and high level of technological discipline of contractor. Measurements of displacements over time proved that the process slowed down and practically stopped one week after the excavation, with-

TANGENTIAL STRESSES IN THE PRIMARY LINING







RADIAL STRESSES IN PRIMARY LINING

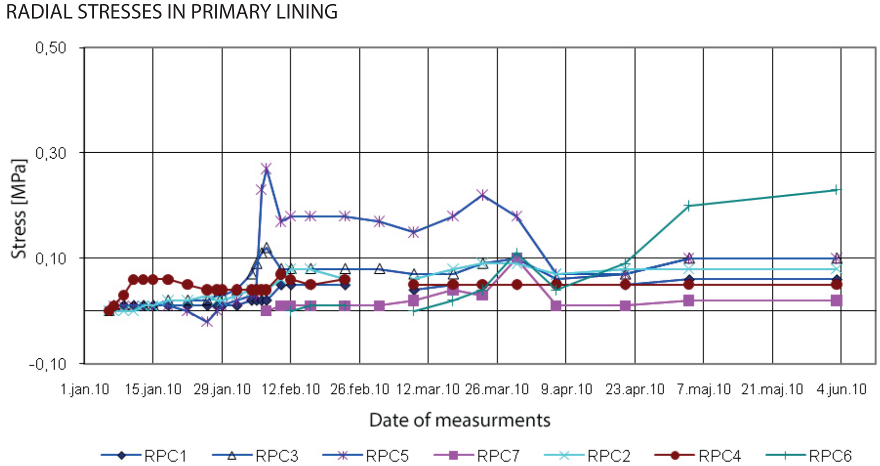


Figure 26:
Measurement results of additional circular and radial stresses in the contact between ground and primary lining in the reconstructed tunnel tube.

out any significant deviations. The excavation of the bench was followed by the excavation of the concrete invert and building of the foundations and concrete invert, at a suitable distance of about 30 m to 40 m.

During the excavation of the new tunnel tube, displacements of the lining in the adjacent existing tunnel tube have been monitored. Only minimal displacements have been noticed, mainly caused by vibrations and due to precise measurements and inaccessibility of the measuring points. The results of measurements have shown that the construction of the new tunnel tube has no impact on the existing tunnel.

Conclusions

In recent decades many studies were conducted relating to investigation of the construction of tunnels in the swelling rocks. The main goal of these investigations was determination the effects of chemical and physical processes on the swelling pressure development with time.

The essential distinction in the design of tunnels in the swelling grounds is depth i.e. primary stress state in grounds layer and other geological and geomechanical properties of geological materials.

Different approaches to research, interpretation of their results and suggesting methods of tunnel construction in these types of grounds are a good basis for the construction method decision for each case separately.

Substantial progress in understanding the development of swelling pressure is taken into account self- closure effect. This is important for the proper selection of construction technologies which should be at the time of construction imposed to strict control.

Successfully design and build a new tunnel tube and reconstruction of an old tunnel tube of the road tunnel Ljubno in the dark gray clay »Sivica« with swelling potential, is an example of good engineering practice in the construction of shallow tunnels in swelling rocks.

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Professional paper

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Geological setting, compositional features and economic evaluation of marble deposits around Alaguntan, southwestern Nigeria

Geološka lega, značilnosti sestave in gospodarska ocena nahajališč marmorja v okolici Alaguntana v jugozahodni Nigeriji

Olugbenga Okunlola[1,*] and Hafsat Muritala[1]
[1]University of Ibadan, Department of Geology, Nigeria
*Corresponding author. E-mail: gbengaokunlola@yahoo.co.uk

Abstract

Marble, occurring up to 5 000 m long and up to 30 m thick lenses within gneisses and other metasediments in Alaguntan area, southwest Nigeria, have been studied with the aim of investigating their compositional and industrial characteristics .
From X-ray Diffraction studies, the marble is composed dominantly of dolomite (95.67 %) with minor amount (up to 1.95 %) of calcite, tremolite, quartz, and actinolite. Chemical analytical results using Inductive Coupled Plasma Mass Spectrometry (ICPMS) confirm the mineralogical dolomitic nature with Ca^{++} /Mg^{++} (1 : 1.39) and average $CaMg(CO_3)_2$ content of 95.69 %.
Physical and mechanical tests reveal that the marble samples have effective porosity between 0.51 % and 0.76 %, hardness according to Mohs's scale is 3.0, compressive strength is between 87.53 MPa and 92.72 MPa, confirming their suitability for construction purposes. Further chemical and agronomic tests show the milled marble samples are useful in soil acidity neutralizations and in metallurgy for production of refractory lime and chemicals, manufacture for production of chemicals.

Key words: Nigeria, marble, composition, industrial use, deposits

Izvleček

Marmor, ki ga najdemo v lečah, dolgih do 5 000 m in debelih do 30 m v gnajsih in drugih metasedimentnih kamninah na območju Alaguntana v jugozahodni Nigeriji, smo preučevali za oceno značilnosti njegove sestave in industrijske uporabnosti.
Preiskava z rentgensko difrakcijo pokaže, da sestoji marmor pretežno iz dolomita (95,67 %) z majhno količino (do 1,95 %) kalcita, tremolita, kremena in aktinolita. Rezultati kemične analize z induktivno vezano plazemsko masno spektrometrijo (ICPMS) potrjujejo mineraloško ugotovljeno dolomitno naravo kamnine z razmerjem Ca^{++}/Mg^{++} 1 : 1,39 in povprečno vsebnostjo $CaMg(CO_3)_2$ 95,69 %.
Fizikalni in mehanični preizkusi kažejo v vzorcih marmorja efektivno poroznost med 0,51 % in 0,76 %, trdoto 3,0 po Mohsovi lestvici in stisljivo trdnost med 87,53 MPa in 92,72 MPa, kar potrjuje njihovo primernost za uporabo v gradbeništvu. Nadaljnje kemične in pedološke preiskave pričajo o uporabnosti mletega marmorja za nevtralizacijo kislosti tal, v metalurgiji za proizvodnjo ognjevzdržnih snovi in za proizvodnjo kemikalij.

Ključne besede: Nigerija, marmor, sestava, industrijska uporabnost, nahajališča

Introduction

Marble deposits globally, have attracted reasonable economic interest and have been classified under six main general areas of applications based on application in industry namely: metallurgical, chemical, environmental, constructional, and agricultural [1, 2].
Metamorphosed carbonate deposits (marbles) in Nigeria generally are found within the eastern margin of the Nigerian Schist belts. (Figure 1) The Schist belts occupy generally N-S trending troughs infolded into the migmatite-gneiss-complex and are best developed in western half of the country [2, 3]. Recently, we have identified some metamorphosed carbonate deposits (marble) in Alaguntan area in the southwest of Nigeria. The deposits are being studied to unravel the geologic setting, mineralogical variation and chemical quality with a view to find the potential industrial application of the marble. Marble occurs as lensoidal body similar to other prominent marble deposits in the eastern margins of the Nigerian Schist belt around Igarra, Kwakuti, Ubo, Igbetti, Osara, Jakura and Burum[4].

Materials and methods

Field sampling and sample preparation

About 25 fresh representative rock chips of white and grey marble samples and the selected representative host rocks were collected from

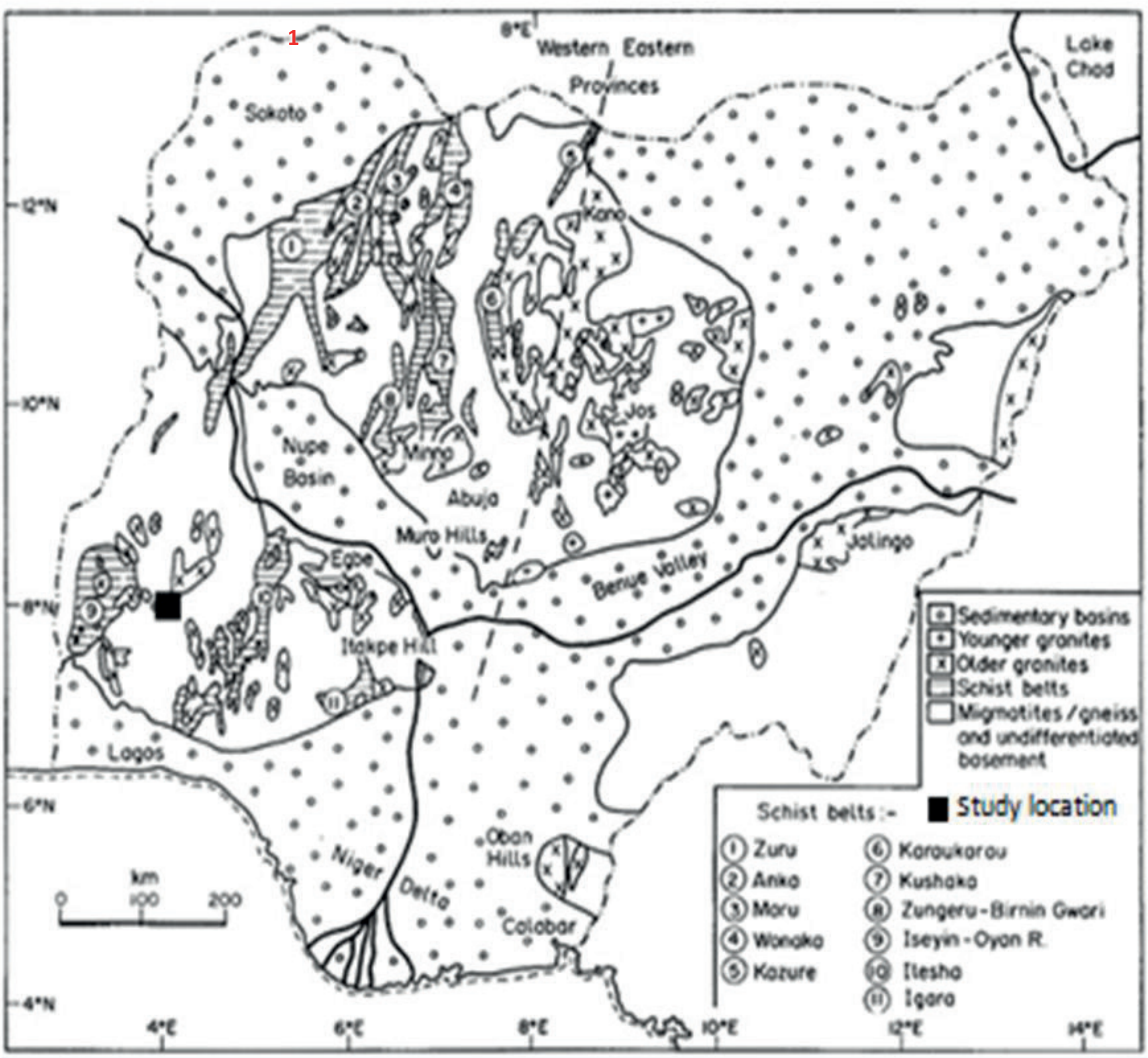

Figure 1: *Geological map of Nigeria showing the Schist belts (after Turner 1983).*

different portion of the mapped area around Alaguntan. For sample preparation, 100 g from each of the representative marble sample were pulverised below 100 µm for the mineralogical, chemical and agronomical studies.

Thin sections of representative samples of associated host rocks were studied microscopically. Mineralogical analyses were also carried out using X-ray diffraction (XRD) and chemical analyses by Inductive Coupled Plasma Mass Spectrometry (ICPMS) analytical techniques. Both analyses were carried out in Acme Analytical Laboratories Vancouver, Canada. The XRD was done using Siemens D500 diffractometer.

Effective porosity and bulk density were determined by immersing an oven dried sample with the mass about 200 g in water for 24 h, till it attains a constant mass. This was re-dried after removal and weight again. The fraction increase in mass relative to the original mass of sample was determined. The ratio of the original sample mass and water volume change was calculated as the Bulk density.

Loss on ignition was determined by heating the weighted samples in a furnace and the temperature set at 1 000 °C and fired for an hour. After an hour, the furnace was switched off for 30 min, after which the samples were packed from the furnace into a dessicator, covered to air tight and then allowed to cool in the dessicator for an hour, another measurement was taken to get the mass loss. All the physical and geotechnical tests on the marbles were carried out in the Department of Geology, Federal University of Technology, Akure, Nigeria.

Agronomical characteristics/parameters determination was done at the Institute of Agricultural Research and Training, Ibadan, by mixing 50 g of acidic soil samples of pH (5.9) collected within the University of Ibadan, Ibadan, premises with 20 g of 90-mesh Alaguntan marble samples and 50 ml of distilled water added for a period of 8 weeks. Major and minor soil nutrient were determined using Atomic Absorption Spectrometry (AAS) and Flame Photometry. Organic matter content, Cation Exchange Capacity, Conductivity, Base saturation were further assessed. The tests were carried out at the soil laboratory, Department of Agronomy, University of Ibadan.

Results and Discussion

Geological setting

The Alaguntan marbles and associated gneisses are part of the Precambrian basement rocks of Nigeria, which is situated in the pre-drift mobile belt that separate West Africa and Congo Cratons [5]**.** On the basis of structural, lithostratigraphic and geochemical data, and available geochronology data, the Precambrian basement complex of Nigeria have indicated polycyclic nature with multi orogenic events. The rocks of Nigeria have been regionally classified into three major groups namely: Migmatite Gneiss Complex, Metasedimentary and Metavolcanic rocks (Schist belts), and Pan African Granitoids / Older Granites [2] (Figure 1).

The schist belts show distinctive petrological, structural and metallogenic features. The schist belt is dominated by low grade metasediments, remnants of reworked supracrustal cover during the Pan African Orogeny. The schists belt in the southwest include those of the Iseyin, Igara, Egbe-Isanlu, Ife-Ilesha areas [2, 5, 6,]. The centrally located ones include the Lokoja-Jakura, and Toto-Gadabuike belts [4, 7, 8]). Some of the belts have also been identified in the southeastern parts of the country though not shown in Figure 1 [9, 10].

In the area of study, outcropping rocks include: Hornblende biotite gneiss, Granite gneiss, Quartzite, Calc silicate gneiss, Marble and Quartz veins (Figure 2). The marble outcrops are positioned within the granite gneiss (Figure 2).

Hornblende biotite Gneiss is the most common rock type mapped, it covers the northern and northeastern parts of the studied area. The extensive outcrops occur as low lying unit, well foliated with preferred orientation of the platy biotite and prismatic hornblende. Thin section studies show the samples are made up of quartz (20 %), biotite 17 %, plagioclase 30 %, hornblende 20 %, and minor amount of muscovite 3 %.

The Granite gneisses occupy the southern and southwestern part of the studied area. It is found as low lying outcrops at Aloba not far away to Alaguntan village. It is medium grained in texture with irregular bands rich in biotite and hornblende and are found to alternate with thicker bands richer in felsic minerals. The mineral assemblages includes: quartz 40 %, biotite 20 %, microcline 17 %, plagioclase feldspar 10 %, and muscovite 10 %.

Quartzite outcrops occur sub parallel to the calc-silicate rock and marble bodies. They occur as elongated lensoidal bodies up to 30 m thick and about 1.5 km long parallel to the calc-silicate rock with a displacement along shear zones between the marble bodies. The contact with the marble is tectonic and is marked by the development of silicified mylonites. Mineral composition is dominantly quartz with accessory muscovite mica

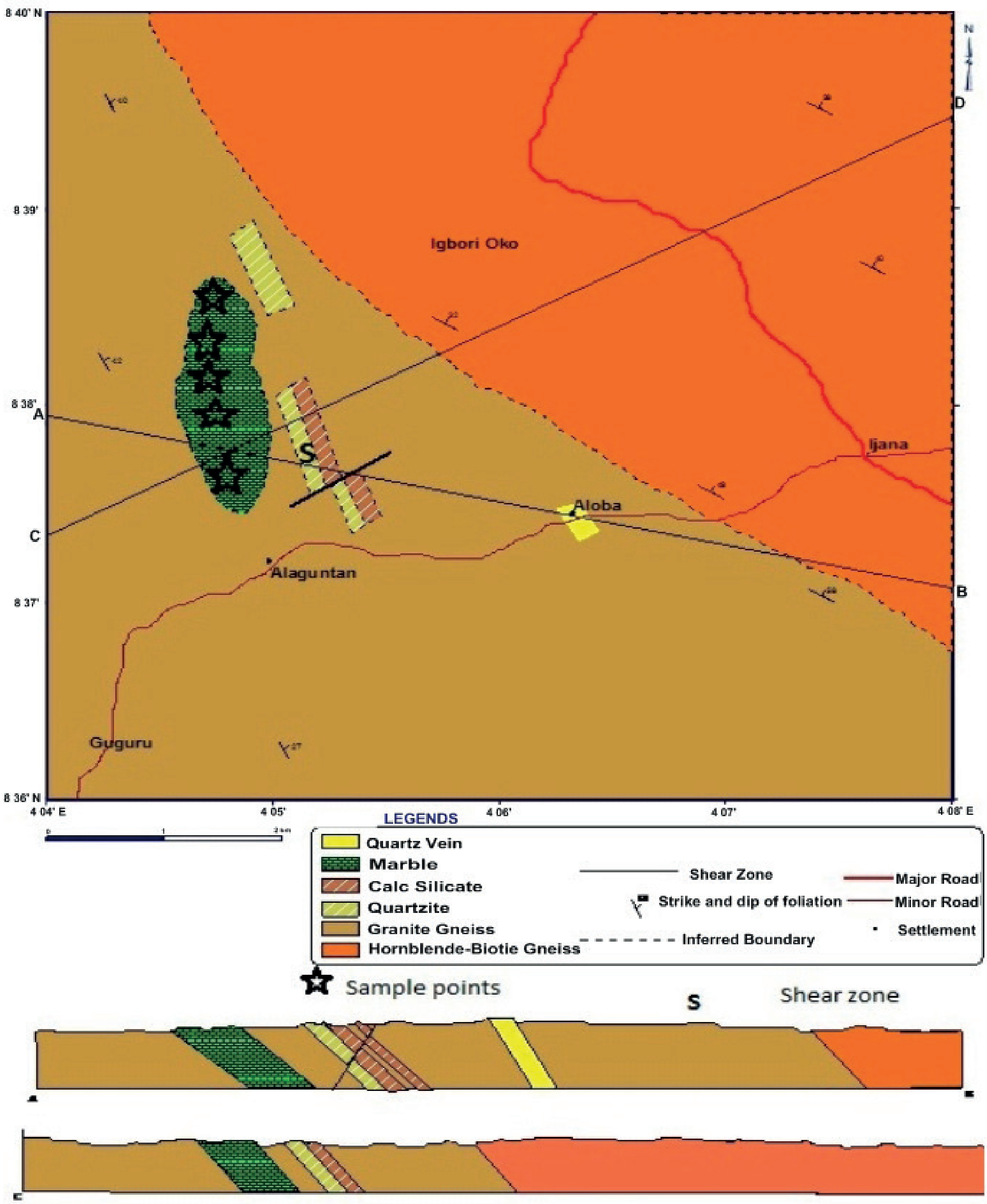

Figure 2: *Geological map of Alaguntan area.*

Calc-silicate gneiss occurs parallel to the marble bodies and quartzite.They are Dark grey in colour, medium grained and foliated.
Mineralogical constituent from XRD indicates it is composed mainly of dolomite (50 %), tremolite (26 %), quartz (2 %), calcite (10 %) with minor amounts of magnesian spinel and graphite 2 % (Figures 3, 4, Table 1).
The marble occurs in the western part of the study area. It occurs as lensoid bodies up to 2 000 m along the strike, 500 m wide and it crops out about 500 m wide around Alaguntan village. Color varieties ranges from pure white found at the southern part (Figure 5) and light to grey colour which occurs in the northern part of the occurrence. The colour variation may be due to the presence of tremolite and the magnesian spinel in places. The grain sizes vary from fine grain to medium grained (1–2 mm). From XRD analysis, the marble is dominantly dolomite (95.4 %) with minor amount (below 3 %) of quartz, calcite and tremolite, while magnesian spinel, as trace mineral is less than 1 % (Table 1).
The association of marble with 'S' type granitoids and gneisses of metasediments (greywacke) origin suggests that the gneisses were reworked from ancient sedimentary sequences, as earlier suggested by [11] for the Burum marble in central Nigeria. The location of the marble at the eastern fringe of Iseyin – Oyan belt suggests that they are relict inliers of carbonate rich and epicontinental transgressive, silicic, arenaceous sequences. These were metamorphosed during a later tectono-metamorphic cycle and accompanied by shearing/mylonitisation probably in the Pan African, resulting in the final formation of carbonate sequences.
The mineralogical composition shows that the marble is mainly dolomite (average 95.4 % up to 96.5 %) with minor amount (below 3 %) of calcite, colemanite, tremolite, actinolite, and quartz while the calc silicate associated with the marble contains dolomite (50 %), calcite (2.5 %), tremolite (19 %), quartz (25 %) magnesian spinel (1.8 %) and graphite 1.5 %) (Table 1).
Samples of marble contain average MgO 23.08 % and CaO 32.01 %. Average silica (SiO_2) content is 2.81 %. The average of alkalis: NaO, K_2O and Al_2O_3 are all lower than 0.1 % while Fe_2O_3 content is slightly greater than 0.1 % but not more than 0.4 % (Table 2). TiO_2, $P_2 0_5$ and Cr_2O_5 were not detected in any of the samples. Ti, P and Cr oxides have staining influences (Ofulume, 1993), and the absence in the samples account for relatively high whiteness of the marble. These analytical results are comparable to values for other Precambrian marbles of Nigeria [2, 12, 13] and those for Shapfell, United Kingdom [14] (Tables 3, 4, 5). Trace element Pb, Zn, Ni, As, all have the average values: (3, 14, 3, 3) × 10^{-6} respectively. Sr value though significant at 41 × 10^{-6} is not considered high enough for sample coloration influences [4]. For economic and industrial raw material consideration purposes, these trace elements values are below deleterious levels.
The plot of Molar ratio Mg^{2+}/Ca^{2+} against temperature [15] Figure 6, reveals that the temperature of dolomitising solution in Alaguntan marbles may have been around 70 °C revealing a dolomitisation at shallow depth with low formational pressure. Plot of salinity against molar ratio Mg^{2+}/Ca^{2+} also show salinity of formation water at 20 000 × 10^{-6} (Figure 7). This is much higher than fresh water average of 1 000 × 10^{-6}, but less than average sea water (35 000 × 10^{-6}) suggesting dolomitisation was facilitated by mixture of sea and fresh water. This agrees with the earlier suggestion of [15] that dolomitisation can occur at admixtures of 30–40 % sea water and 60–70 % fresh water.
Carbon and Oxygen isotope content determination of 4 marble samples carried out at the act labs in Ontario, Canada reveal that $\delta^{13}C$ values range from –0.8–3.9 ‰ while $\delta^{18}0$ range from 0.8 ‰ to –8.2 ‰. These values suggest diagenetic equilibration with meteoric water and it is consistent with the fact that the formation water have dilution of sea by fresh water [16]. These stable isotope values are also consistent with values for Burum marble of the same lithologic position and presumably the same genetic environment [2, 4] and Saxone basin carbonates, Germany [17]. These values are also comparable with values for carbonates that have undergone appreciable diagenesis in the presence of oxidizing organic matter and release of CO_2 [16].

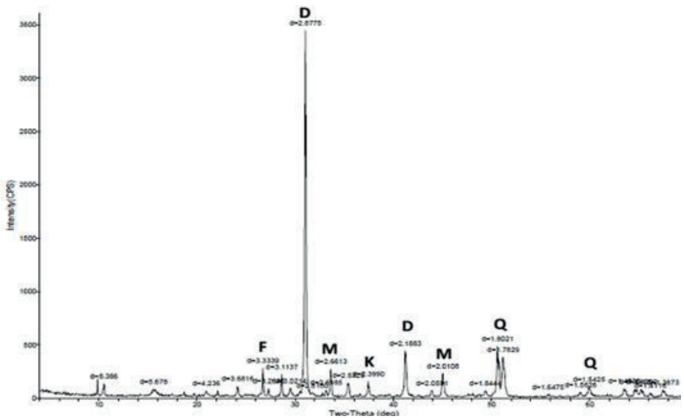

Figure 3: *XRD dIffractometer pattern of Alaguntan marble (Sample 1).*

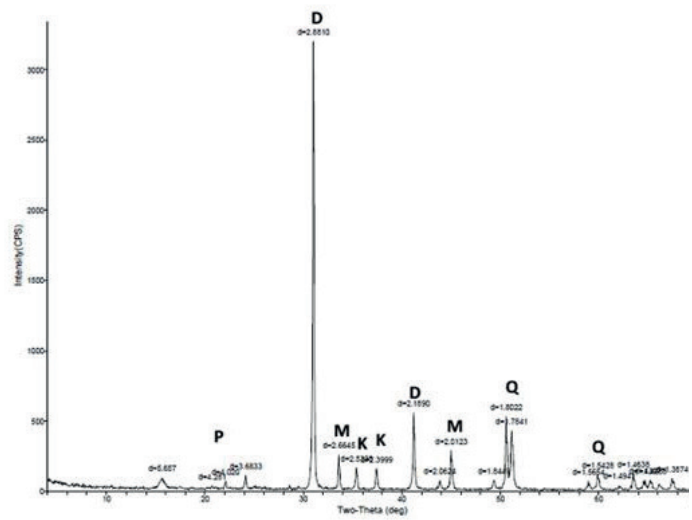

Figure 4: *XRD diffractogram pattern of Alaguntan marble (Sample 2).*

Table 1: *Mineralogical composition of Alaguntan marble from XRD results*

Mineral, w/%	1	2	3
Dolomite	94.24	96.91	95.92
Calcite	1.20	–	–
Quartz	–	0.54	0.35
Colemanite	1.20	2.55	2.59
Tremolite	1.35	–	1.14

Figure 5: *Showing the Alaguntan white marble.*

Marble Usefulness evaluation

Economic and industrial raw material usefulness was carried out in relation to such industries as agriculture (agronomic), metallurgy, construction, chemicals and environmental, materials (like fillers and extenders).

Construction:

Marble is one of the oldest building materials and is only predated by mud and stone [18]. It is presently widely used in aggregates for soil stabilisation, mansory and as ornamental stones where it is polished into decorative slabs.

General requirements are w(CaO + MgO) content above 95 % and $w(CO_2)$ < 50 %, compressive strength > 20 MPa, tensile strength > 7 MPa [19]. In term of finess, it must leave a residue not more than 5 % of 75 µm. Alaguntan marble meets these specifications and could thus be used as road stabilisers, ornamental

Table 2: *Chemical analytical results of the major oxides of Alaguntan raw marbles samples*

Oxides, w/%	1	2	3	4	5	6	7	8	9	10	Range	Average
SiO_2	1.56	1.58	2.93	5.56	1.89	4.69	2.74	2.52	1.51	3.15	1.51−3.15	2.81
Al_2O_3	0.10	0.05	0.10	0.04	0.07	0.07	0.03	0.13	0.04	0.02	0.03−0.13	0.07
Fe_2O_3	0.13	0.10	0.11	0.21	0.24	0.24	0.19	0.07	0.10	0.16	0.10−0.24	0.15
MgO	23.50	23.50	23.14	22.74	23.15	22.99	22.98	23.25	23.22	22.53	22.37−23.50	23.20
CaO	33.12	32.96	31.83	21.17	31.52	31.52	32.12	32.43	32.36	32.24	30.79−33.12	32.16
Na_2O	0.03	0.04	0.02	0.04	0.01	0.08	0.01	0.02	0.04	0.04	0.01−0.08	0.03
K_2O	0.03	0.02	0.01	0.01	ND	0.02	ND	0.02	0.02	ND	0.01−0.03	0.02
MnO	0.01	0.01	0.04	0.03	0.04	0.03	0.03	ND	0.01	0.04	0.01−0.04	0..03
LOI	41.1	41.1	41.4	39.8	42.5	39.9	41.5	41.2	42.3	35.9	35.9−41.5	41.15
Sum (%)	99.61	99.61	99.60	99.61	99.61	99.60	99.60	99.62	99.61	99.59	99.60−99.62	99.61

Table 3: *Chemical analytical results of the trace element of Alaguntan raw marble samples*

Trace element ($\times 10^{-6}$)	1	2	3	4	5	6	7	8	9	10	Range	Average
Ba	10	5	3	2	3	4	3	3	5	3	2–10	4.1
Sr	40.5	40.4	34.9	48.5	41.7	50.1	54.6	28.2	30.1	42.6	28.2–54.6	41.26
U	0.2	0.2	0.4	0.4	0.3	0.4	0.6	0.4	0.2	0.3	0.2–0.6	0.34
Zr	1.3	1.9	1.6	0.6	1.2	1.3	1.3	1.1	1.1	0.5	0.5–1.9	1.19
Y	0.5	0.5	0.6	0.4	0.7	0.5	0.5	0.2	0.2	0.3	0.2–0.7	0.44
La	0.3	0.4	0.8	0.5	0.8	0.5	0.3	0.2	0.8	0.3	0.2–0.8	0.49
Ce	0.6	0.5	1.4	0.6	1.0	1.0	0.6	0.5	0.6	0.3	0.4–1.0	0.71
Pr	0.09	0.05	0.12	0.06	0.10	0.07	0.04	0.04	0.03	0.02	0.03–0.12	0.06
Pb	1.6	2.0	5.7	3.5	4.6	3.7	3.2	2.5	2.9	5.5	1.6–5.7	3.41
Zn	2	3	6	29	7	19	40	5	7	21	2–40	13.9
Ni	2.0	2.3	5.0	2.5	3.5	3.4	3.0	1.9	2.2	2.3	1.9–5.9	2.81

Table 4: *Average chemical analytical results of Alaguntan marble and some marble deposit and lime products in Nigeria and the world.*

Oxides $w/\%$	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
$Si0_2$	2.81	0.49	Tr	3.81	3.51	0.43	1.45	3.47	1.18	1.94	3.5
Al_20_3	0.07	0.02	0.02	0.16	0.03	0.06	0.02	1.00	0.08	0.21	0.11
Fe_20_3	0.15	0.06	0.06	0.15	0.05	0.02	0.05	0.21	0.07	0.12	0.04
Mn0	0.03	0.03	0.03	0.01	0.03	0.03	0.03	N. a.	0.03	0.01	N. a.
Mg0	**23.20**	**20.70**	**26.85**	**20.75**	**33.25**	**0.58**	**0.85**	**2.23**	**1.75**	**2.20**	**2.18**
Ca0	**32.16**	**28.94**	**38.29**	**31.03**	**59.17**	**54.17**	**95.35**	**51.29**	**53.64**	**52.5**	**51.69**
Na_20	0.03	0.01	0.01	0.05	N. a.	0.03	0.03	N. a.	0.01	0.02	0.92
K_20	0.02	0.01	0.01	0.12	N. a.	0.06	0.03	N. a.	0.02	0.17	0.26
$Ti0_2$	ND	ND	ND	0.17	0.03	0.01	0.03	N. a.	N. a.	0.06	N. a.
P_20_5	ND			0.03				0.03		0.05	1.63
LOI	41.15		34.73	43.56		43.81	2.12	41.53		41.6	41.97
Total	99.61			99.88		99.87				99.16	

1. Alaguntan marble | 2. Igbetti marble (Emofurieta et al, 1995) | 3. Igbetti lime (Emofurieta et al, 1995) | 4. Burum marble (Elueze and Okunlola, 2003) | 5. Burum lime (Elueze and Okunlola, 2003) | 6 . Jakura marble (Elueze and Okunlola, 2003) | 7. Jakura lime (Elueze and Okunlola, 2003) | 8. Ukpilla marble (GSN Report No 1192) | 9. Ososo marble (Emofurieta, 1995) | 10. Shapfell marble (Dowrie et al, 1982) | 11. South Korean marble (DPR) | ND Not detected | Tr Traces

Table 5: *Chemical analytical results of the calc silicate gneiss*

Oxides, $w/\%$	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**CaO**	**NaO**	**K_2O**	**TiO_2**	**MnO**	**P_2O_5**	**LOI**	**Sum**
	10.34	0.03	0.16	22.27	30.79	0.02	0.01	ND	0.04	0.02	35.9	99.64
Element ($\times 10^{-6}$)	Ba	Sr	U	Zr	Y	La	Ce	Pr	Pb	Zn	Ni	As
	6	30.9	0.2	0.1	0.2	0.3	0.4	0.04	5.5	4	2.3	3.0

Table 6: *Physical properties of the Alaguntan raw marble samples*

Effective porosity	$n = 10$ 0.51–0.76	$n = 10$ 0.64
Hardness (Mohs scale)	3.0	3.0
Bulk density g/cm^3	2.65–2.67	2.66
Specific gravity	2.85–2.86	2.86
Compressive strength (MPa)	87.53–92.72	90.12
Shear strength (MPa)	13.62–15.10	14.36
pH	8.4–8.6	8.5

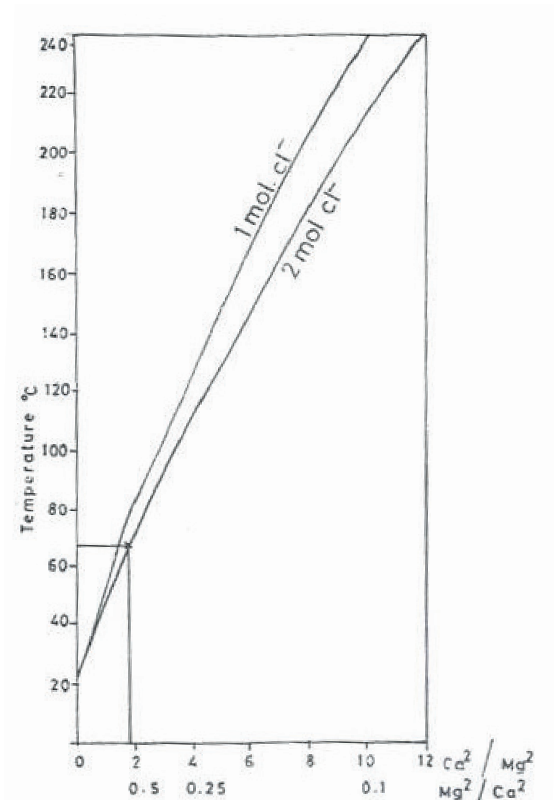

Figure 6: *Molar ratio of calcium and magnesium required for dolomitisation of calcite as a function of temperature (Modified after Hardie [15]).*

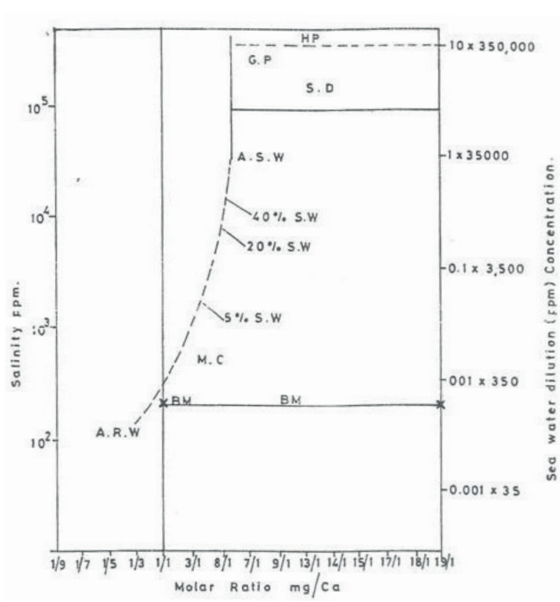

Figure 7: *Relationship between total salinity, Mg/Ca ratio and origin of dolomite. (After [15]). Alaguntan Marble plots at* 200 ppm *salinity (0.008 × 300 dilution of sea water).*

stones and building blocks considering the values of the compressive strength, (90.12 MPa) and shear strength of 14.36 MPa (Table 6, 7).

Agricultural (soil acidity neutralizer):

Results of agronomic tests (Table 8) have shown that the addition of the pulverised (below xμm) marble samples to an acid soil samples at intervals for 8 weeks reduced the soil acidity (Table 8) pH of interstitial water rose from 5.9 to 7.5 after 8 weeks. Organic matter content also increased to 12.31 from 11.70, base saturation show slight increase, while the available nutrient of N, P, K, Na, Ca, Mg, Fe, Mn, Zn, Cu, all show relative increases in their values from the original sample values.

Alaguntan marble thus has the potential of being useful in ameliorating soil acidity.

Metallurgy:

Raw marble and their lime products have been found to be very useful in the metallurgy industry. The largest application is for fluxing steel [19, 20]. Requirement for metallurgical lime include (Ca,Mg)O, or $w(CaO)$ > 50 %, high reactivity, low $w(SiO_2)$ (1–1.5 %), and low $w(SO_3)$ (0.05–1 %). Also, $(Ca,Mg)CO_3$ or $w(CaCO_3)$ > 95 %.

Alaguntan marble meets these specifications and therefore is useful as steel fluxes. Another metallurgical application of lime is production of refractory lime. This is used for lining open hearths. The requirements are similar to those of fluxes except for the less stringent SiO_2 requirement (2–4 %). Alaguntan marble can thus also be useful for production of refractory lime as seen from the chemical analytical results.

Chemicals production manufacture:

Among the largest uses of raw marble and their lime products is the production of sodium compounds such as sodium carbonate, sodium hydrogen carbonate, and sodium hydroxide by the Solvay (or ammonium soda) process. The basic requirement is a total carbonate $w(CaCO_3 + MgCO_3)$ content greater than 70 % or lime/dolomite (CaO,/CaMgO content of > 80 %. Alaguntan deposit also meet these requirements. In the manufacture of calcium carbide, an important source of acetylene, quicklime is

Table 7: *Physical properties of Alaguntan marble compared with other marble samples*

	1	2	3	4	5	6	7	8	9	10
Effective porosity	0.69	0.65	0.68	0.62		0.68	0.65	0.67	n. a.	0.64
Hardness (Mohs scale)	3.0	3.0	3.0	3.0	3.0	3.0	n. a.	3.0	n. a.	3.0
Bulk density	2.76	2.65	2.67	2.65	2.65		2.65		2.61	2.66
Specific gravity	2.73	2.70	2.70	2.71	2.73	2.68	2.71	2.73	2.75	2.86
Compression strength	90.48	95.52	92.83	n. a.	90.81	n. a.	90.5	88.2	n. a.	90.12
Tensile strength	3.87	3.92	3.81	n. a.	3.21	n. a.	6.5	4.52	n. a.	n. a.
pH	8.38	8.5	8.3	8.1	8.35	n. a.	8.11	8.5	8.6	8.6
Oil absorption (ml/100)	n. a.	18.0	18.0	19.20	18.40	18.71	n. a.	20.15	n. a.	n. a.
Colour	n. a.	82.0	83.0	80.0	80.0	92.8	n. a.	91.7	n. a.	n. a.

1. Igbetti | 2. Jakura | 3. Burum | 4. Shapfell | 5. Cheetor | 6. British whiting | 7. Muro marble | 8. Indiana marble | 9. Ososo marble | 10. Alaguntan marble
Source 1–9: (Elueze and Okunlola, 2003)

Table 8: *Agronomical properties of Alaguntan marble*

Treatment	pH	Organic matter g/kg	CEC	Base saturation %	N g/kg	P mg/kg	K ←	Na cmol/kg	Ca	Mg →	Fe	Mn mg/kg	Zn mg/kg	Cu
OS	5.9	11.70	4.64	95.69	1.21	3.38	0.77	1.31	1.40	0.96	116.00	140.00	6.50	2.35
SA	5.9	11.70	4.64	95.69	1.21	3.38	0.77	1.31	1.40	0.96	116.00	140.00	6.50	2.35
A1	7.3	12.10	5.81	95.70	1.27	3.79	0.83	1.53	2.16	1.04	117.50	142.0	6.93	2.41
A2	7.5	12.31	6.88	95.74	1.34	3.86	0.98	1.71	2.36	1.53	119.00	144.00	6.94	2.41

OS = Original soil sample | SA = Soil + Alaguntan marble | A1 = Soil + Alaguntan marble after 4 weeks | A2 = Soil + Alaguntan marble after 8 weeks | CEC = Cation Exchange Capacity

mixed with coke and heated in electric furnaces to 2 000 °C. Molten carbide is removed from the furnaces and crushed upon solidifying. It is then ground for use. High calcium lime (w(CaO) = 90 %) / low w(P) (< 0.02 %) and w(Mg) < 0.5 % are required. Marble samples from the study area do not meet this requirement because of higher than acceptable MgO content. Also, in the production of cement, the major requirement are w(MgO) < 3 %, lime saturation factor (L. S. F.) 66–102 %, and hydraulic modulus (H. M.) 1.7–2.0 %. The marble deposit is not suitable because of too high w(MgO) content of 23.20 %.

Environmental:
Crushed and milled marble and their lime products have found application for environmental purposes [1]. This can be used for waste water treatment and water softening. Lime reduces bicarbonate hardness. The requirement include w(CaO) > 65 %, high alkalinity which makes it free from acid insolubles and toxic heavy metals like Cd, Pb, Ag, Zn and Cr thereby having pH > 10, w(MgO) < 2 %, $w(SiO_2)$ < 0.01 and absence of Co. Alaguntan marble has high w(MgO) and $w(SiO_2)$ > 0.01, therefore cannot be used as a calcite lime but meets the specification for dolime manufacture.

Table 9: *Summary of usefulness potentials and specification for Alaguntan marble.*

Industry	General requirements	Suitability
1. Metallurgy		
a. Fluxes in steel	(Ca, Mg)CO_3 or $w(CaCO_3)$ > 95 % $w(SiO_2)$ = (1–1.5) % $w(SiO_3)$ = (0.05–1) %	Alaguntan marble is suitable because of its high silica content.
b. Refractory lime	Same as in fluxes but SiO_2 allowed 2–4 %	Alaguntan marble is suitable.
2. Construction	Compressive strength > 20 MPa Shear strength > 7 % (ASTM, 1976)	The deposit is suitable.
3. Chemicals		
a. Sodium compounds	CaO, (Ca,Mg) w(O) > 70 % w(CaO) > 90 %, w(P) < 0.02 %	The deposits is suitable.
b. Calcium carbide	w(Mg) < 0,5 % w(SiO) < 1.2 %	Not suitable due to high magnesium content.
c. Pesticides	$w(Fe_20_3)$ < 0.5 % $w(CaCO_3)$ > 90 %	Suitable.
d. Bleaches	w(CaO) > 80 %, $w(SiO_2)$ < 2 %	Not suitable due to high magnesium content.
4. Agriculture		
a. Soil liming	pH > 8, $w(SO_3)$ = 2 %	Agronomical test carried out revealed its suitability.

Fillers and extenders:

Mineral filler are inert materials incorporated into different compounds to accomplish a variety of final result such as modification of physical characteristics, colour, opacity hardness, impact strength, surface texture, viscosity, heat conductivity, reduction in cost of production and many other applications. Extender pigment is necessary in all types of coating in paint industry. This keeps the relatively more expensive pigment material volume to a minimum without affecting paint performance. For suitability for paint, requirement is $w(CaCO_3)$ > 95 %, $w(MgCO_3)$ = 2 %, $w(SiO_2)$ = 0.5 %, $w(Fe_2O_3)$ = 0.05 %, $w(Al_2O_3)$ = 0.30 % while for rubber is $w(CaCO_3)$ > 95 %, CaO, free CO_2, w(MgO) = 0.02 %, Fe_2O_3, Al_2O_3, SiO_2 must be in traces only. Alaguntan marble does not meet the above purposes because it has higher $MgCO_3$ content.

Conclusions

The Alaguntan lensoidal marble body which occur for about 2.5 km along the strike within granite gneiss, subparallel to quartzite and calc silicates in Alaguntan village, southwestern, Nigeria, is of the dolomitic mineral composition with Mg/Ca 0.72). The SiO_2 content is low compared to similar marble bodies in Nigeria and elsewhere. K_2O, Na_2O, MnO_2, Al_2O_3 are all low, Fe_2O_3 marginally high while TiO_2 is undetectable like some other marble deposit. Physical and mechanical test for the raw marble samples such as effective porosity, specific gravity, compressive and tensile strength in combination with chemical composition revealed their suitability as raw material in metallurgical, construction, chemical and agricultural industries, Table 9.

Recommendations

The study has been able to unravel the geological setting, compositional features and usefulness of the marble. Appropriate drilling programme should be designed and carried should be applied in order to quantify the reserve. Also, further work should be done on the calcined product of the marble.

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- Poljudni članki, ki povzemajo znanstvene in strokovne dogodke zavzemajo do dve (2) strani.

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Vsi prispevki bodo predloženi v recenzijo. Recenzent oceni primernost prispevka za objavo in lahko predlaga kot pogoj za objavo dopolnilo k prispevku. Recenzenta izbere uredništvo med strokovnjaki, ki so dejavni na sorodnih področjih, kot jih obravnava prispevek. Avtorji morajo predlagati tri recenzente. Pravico imajo predlagati ime recenzenta, za katerega ne želijo, da bi recenziral njihov prispevek. Uredništvo si pridržuje pravico, da izbere druge recenzente. Recenzent ostane anonimen. Prispevki bodo tudi tehnično ocenjeni in avtorji so dolžni popraviti pomanjkljivosti. Končno odločitev za objavo da glavni urednik.

Oblika prispevka

Prispevek lahko posredujte preko e-pošte ter na USB-mediju ali CD-ju.
Predloga za pisanje članka se nahaja na spletni strani: **www.rmz-mg.com**.
Besedilo naj bo podano v urejevalniku besedil Word. Digitalni zapis naj bo povsem enostaven, brez zapletenega oblikovanja, deljenja besed, podčrtavanja. Avtor naj označi le krepko in kurzivno poudarjanje.

Zgradba prispevka

Naslov

Naslov članka naj bo natančen in informativen in naj ne presega 100 znakov. Avtor naj navede tudi skrajšan naslov članka. Naslov članka je podan v angleškem in slovenskem jeziku.

Information on the Authors

Information on the authors should include the first and last name of the authors, the address of the institution and the e-mail address of the leading author.

Abstract

The abstract presenting the purpose of the article and the main results and conclusions should contain no more than 180 words. It should be written in Slovene and English.

Key words

A list of up to 5 key words (3 to 5) that will be useful for indexing or searching. They should be written in Slovene and English.

Introduction

Materials and methods

Results and discussion

Conclusions

Acknowledgements

References

The sources should be cited in the same order as they appear in the article. They should be numbered with numbers in square brackets. Sources should be cited according to the SIST ISO 690:1996 standards.

Monograph:
[1] Trček, B. (2001): *Solute transport monitoring in the unsaturated zone of the karst aquifer by natural tracers*. Ph. D. Thesis. Ljubljana: University of Ljubljana 2001; 125 p.

Journal article:
[2] Higashitani, K., Iseri, H., Okuhara, K., Hatade, S. (1995): Magnetic Effects on Zeta Potential and Diffusivity of Nonmagnetic Particles. *Journal of Colloid and Interface Science*, 172, pp. 383–388.

Electronic source:
CASREACT – Chemical reactions database [online]. Chemical Abstracts Service, 2000, renewed 2/15/2000 [cited 2/25/2000]. Available on: <http://www.cas.org/casreact.html>.

Podatki o avtorjih

Podatki o avtorjih naj vsebujejo imena in priimke avtorjev, naslov pripadajoče inštitucije ter elektronski naslov vodilnega avtorja.

Izvleček

Izvleček namena članka ter ključnih rezultatov z ugotovitvami naj obsega največ 180 besed. Izvleček je podan v angleškem in slovenskem jeziku.

Ključne besede

Seznam največ 5 ključnih besed (3–5) za pomoč pri indeksiranju ali iskanju. Ključne besede so podane v angleškem in slovenskem jeziku.

Uvod

Materiali in metode

Rezultati in razprava

Sklepi

Zahvala

Viri

Uporabljane literaturne vire navajajte po vrstnem redu, kot se pojavljajo v prispevku. Označite jih s številkami v oglatem oklepaju. Literatura naj se navaja v skladu s standardom SIST ISO 690:1996.

Monografija:
[1] Trček, B. (2001): *Solute transport monitoring in the unsaturated zone of the karst aquifer by natural tracers*. doktorska disertacija. Ljubljana: Univerza v Ljubljani 2001; 125 str.

Članek v reviji:
[2] Higashitani, K., Iseri, H., Okuhara, K., Hatade, S. (1995): Magnetic Effects on Zeta Potential and Diffusivity of Nonmagnetic Particles. *Journal of Colloid and Interface Science*, 172, str. 383–388.

Spletna stran:
CASREACT – Chemical reactions database [online]. Chemical Abstracts Service, 2000, obnovljeno 15. 2. 2000 [citirano 25. 2. 2000]. Dostopno na svetovnem spletu: <http://www.cas.org/casreact.html>.

Scientific articles, review papers, preliminary notes and professional papers are published in English. Only professional papers will exceptionally be published in Slovene.

Annexes

Annexes are images, spreadsheets, tables, and mathematical and chemical formulas.
Annexes should be included in the text at the appropriate place, and they should also be submitted as a separate document, i.e. separated from the text in the article.
Annexes should be originals, made in an electronic form (Microsoft Excel, Adobe Illustrator, Inkscape, AutoCad, etc.) and in .eps, .tif or .jpg format with a resolution of at least 300 dpi.
The width of the annex should be at least 152 mm. They should be named the same as in the article (Figure 1, Table 1).
The text in the annexes should be written in typeface Arial Regular (6 pt).
The title of the image (also schemes, charts and graphs) should be indicated in the description of the image.
When formatting spreadsheets and tables in text editors, tabs, and not spaces, should be used to separate columns. Each formula should have its number written in round brackets on its right side.
References of the annexes in the text should be as follows: "Figure 1…" and not "as shown below:". This is due to the fact that for technical reasons the annex cannot always be placed at the exact specific place in the article.

Manuscript Submission

Contributions should be sent to the following e-mail address: rmz-mg@ntf.uni-lj.si.

In case of submission on CD or USB flash drive, contributions can be sent by registered mail to the address of the editorial board:
RMZ – Materials and Geoenvironment, Aškerčeva 12, 1000 Ljubljana, Slovenia.

The contributions can also be handed in at the reception of the Faculty of Natural Sciences and Engineering (ground floor), Aškerčeva 12, 1000 Ljubljana, Slovenia with the heading "for RMZ – M&G".

Znanstveni, pregledni in strokovni članki ter predhodne objave se objavijo v angleškem jeziku. Izjemoma se strokovni članek objavi v slovenskem jeziku.

Priloge

K prilogam prištevamo slikovno gradivo, preglednice in tabele ter matematične in kemijske formule.
Priloge naj bodo vključene v besedilu, kjer se jim odredi okvirno mesto. Hkrati jih je potrebno priložiti tudi kot samostojno datoteko, ločeno od besedila v članku.
Priloge morajo biti izvirne, narejene v računalniški obliki (Microsoft Excel, Adobe Illustrator, Inkscape, AutoCad ...) in shranjene kot .eps, .tif ali .jpg v ločljivosti vsaj 300 dpi. Širina priloge naj bo najmanj 152 mm. Datoteke je potrebno poimenovati, tako kot so poimenovane v besedilu (Slika 1, Preglednica 1).
Za besedilo v prilogi naj bo uporabljena pisava Arial navadna različica (6 pt).
Naslov slikovnega gradiva, sem prištevamo tudi sheme, grafikone in diagrame, naj bo podan v opisu slike.
Pri urejevanju preglednic/tabel, v urejevalniku besedila, se za ločevanje stolpcev uporabijo tabulatorji in ne presledki.
Vsaka formula naj ima zaporedno številko zapisano v okroglem oklepaju na desni strani.
V besedilu se je potrebno sklicevati na prilogo na način: „Slika 1 ...", in ne „... kot je spodaj prikazano:" saj zaradi tehničnih razlogov priloge ni vedno mogoče postaviti na točno določeno mesto v članku.

Oddaja članka

Prispevke lahko pošljete po elektronski pošti na naslov rmz-mg@ntf.uni-lj.si.

V primeru oddaje prispevka na CD- ali USB-mediju le-te pošljite priporočeno na naslov uredništva:
RMZ – Materials and Geoenvironment, Aškerčeva 12, 1000 Ljubljana, Slovenija

ali jih oddajte na:
recepciji Naravoslovnotehniške fakultete (pritličje), Aškerčeva 12, 1000 Ljubljana, Slovenija s pripisom „za RMZ – M&G".

The electronic medium should clearly be marked with the name of the leading author, the beginning of the title and the date of the submission to the Editorial Office of RMZ – M&G.

Information on RMZ – M&G
— Editor-in-Chief
  Assoc. Prof. Dr. Peter Fajfar
  Telephone: +386 1 200 04 51
  E-mail address: peter.fajfar@omm.ntf.uni-lj.si

— Secretary
  Ines Langerholc, Bachelor in Business Administration
  Telephone: +386 1 470 46 08
  E-mail address: ines.langerholc@omm.ntf.uni-lj.si

These instructions are valid from July 2013.

Elektronski mediji morajo biti jasno označeni z imenom vsaj prvega avtorja, začetkom naslova in datumom izročitve uredništvu RMZ – M&G.

Informacije o RMZ – M&G
— urednik
  izr. prof. dr. Peter Fajfar
  Telefon: +386 1 200 04 51
  E-poštni naslov: peter.fajfar@omm.ntf.uni-lj.si

— tajnica
  Ines Langerholc, dipl. poslov. adm.
  Telefon: +386 1 470 46 08
  E-poštni naslov: ines.langerholc@omm.ntf.uni-lj.si

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Slovenčeva 93
SI 1000 Ljubljana
tel.: +386 (1) 560 36 00
fax: +386 (1) 534 16 80
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