THE DEVELOPMENT AND ANALYSIS OF 3D GEOLOGICAL/GEOMECHANICAL MODELS FOR THE KOZJAK PUMPED-STORAGE HYDROELECTRIC POWER PLANT

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Abstract

In order to specify the geological and geotechnical conditions for the construction of the Kozjak pumped-storage hydroelectric power plant (HPP), the site area has undergone considerable geological, geophysical and geomechanical investigations. Due to the complexity of the geotechnical constructions and the size of the investigated site a novel approach was proposed, where the results of the investigation were used to develop 3D geological/geomechanical models. The models were created with the integration of all the available results and data into typical geomechanical units that were subsequently given spatial dimensions. Through an analysis of the models the relationships between the different units were better understood and the critical areas were quickly identified and verified. In this paper the models for the accumulation reservoir and the engine room are presented. The overview of the executed investigations and the results are given together with a discussion on the scope and the number of executed investigations from the standpoint of the 3D geological/geomechanical model's creation.

Keywords

Geological and geomechanical investigations, 3D geological and geomechanical models, Kozjak HPP

1 INTRODUCTION

First, some basic technical information about Kozjak HPP is presented, so that the size and the complexity of the proposed construction can be better understood. This is followed by a description of the type and the number of investigations for the accumulation reservoir and the engine room. The information about the general geological setting for the wider area of the investigated site is followed by a description of the 3D-model development for the accumulation reservoir and the engine room. An example of the use of the 3D models for detecting the critical areas of the reservoir and the engine room is shown. A discussion on the scope and the number of executed investigations from the standpoint of a 3D geological/geomechanical model development is also presented. Finally, the conclusions are presented.

2 KOZJAK HPP- BASIC TECHNICAL DATA

The future Kozjak pumped-storage hydroelectric power plant (HPP) is to be built on the left bank of the River Drava, near the Fala hydroelectric power plant, some 20 km away from Maribor in the northeast part of Slovenia. The general location of the proposed power plant is shown in Figure 1 (see next page).

The pumped-storage power plant is composed of three key facilities: the accumulation reservoir, the pipeline and the engine room. The turbine of the power plant will be located at the bottom of a 85-m-deep engine-room shaft at approximately 200 metres above mean sea level. The shaft will be located in the field, in close proximity to the accumulation reservoir of Fala HPP, so that the water from there can be used to fill up the reservoir of Kozjak HPP. The accumulation the reservoir of Kozjak HPP will be located 995 meters above mean sea level, on top of the hill named Kolarjev vrh. The reservoir will have an area of approximately 300,000 m^2 (880 m x 350 m) and will hold approximately 3 million cubic metres of water. It will be protected by a 25-m-high embankment. The engine room and the reservoir will be connected by a 2.4-kilometre-long pipeline that will run from 85 to 300 metres below the surface and will

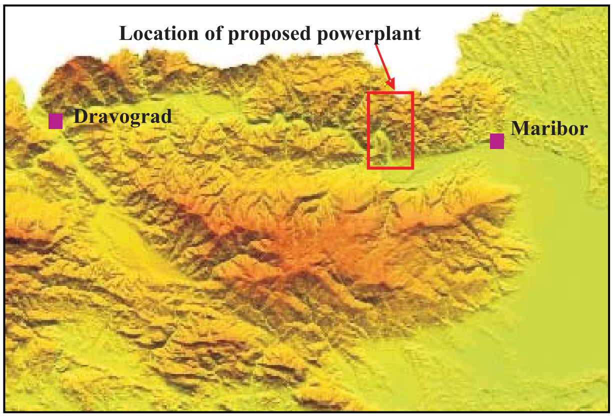

Figure 1. Ge neral loca tion of the proposed power plant.

have a diameter from 3.6 to 4 meters. The characteristic longitudinal cross-section of Kozjak HPP is shown in Figure 2.

3 OVERVIEW OF THE EXECUTED INVESTIGATIONS

3.1 INTRODUCTION

The idea of constructing Kozjak HPP is more than 30 years old, and preliminary investigations were carried out by [1] and revised by [2]. Since then the quality of the investigation techniques and, especially, the requirements in accordance with the standards and design approaches have changed. Therefore, new investigations were necessary. From November 2006 to November 2008, geological, geophysical and geomechanical investigations were carried out at the location of Kozjak HPP. The purpose of these investigations was to identify the geotechnical conditions for the construction of all three facilities: the engine-room shaft, the accumulation reservoir and the underground pipeline. The investigations for the pipeline are not presented in this paper. Based on their different operational purposes, design requirements and sizes, the number of investigations and the geotechnical considerations were somewhat different for each facility. Some of the investigations, however, were carried out for Kozjak HPP as a whole, and these will be presented first, followed by the investigations carried out for each reservoir and engine room.

3.2 INVESTIGATIONS CARRIED OUT FOR THE GENERAL AREA OF KOZJAK HPP

In order to obtain information on the tectonic and lithological, engineering geological and hydro-geological characteristics at the different facilities, general investigations of the wider area were carried out. These general investigations included the following.

Morphotectonic analysis

The morphotectonic analysis of the digital model of relief (DMR) was carried out in order to determine the most common azimuths of the lineaments present. An area of 10x10 km with a point density of 12.5x12.5 m was studied. The results showed the occurrence of four distinct families of possible structural lineaments in the region. The recognized directions and traces served as the input information, used and verified in structural-geological and engineering geological mapping as possible fault lines.

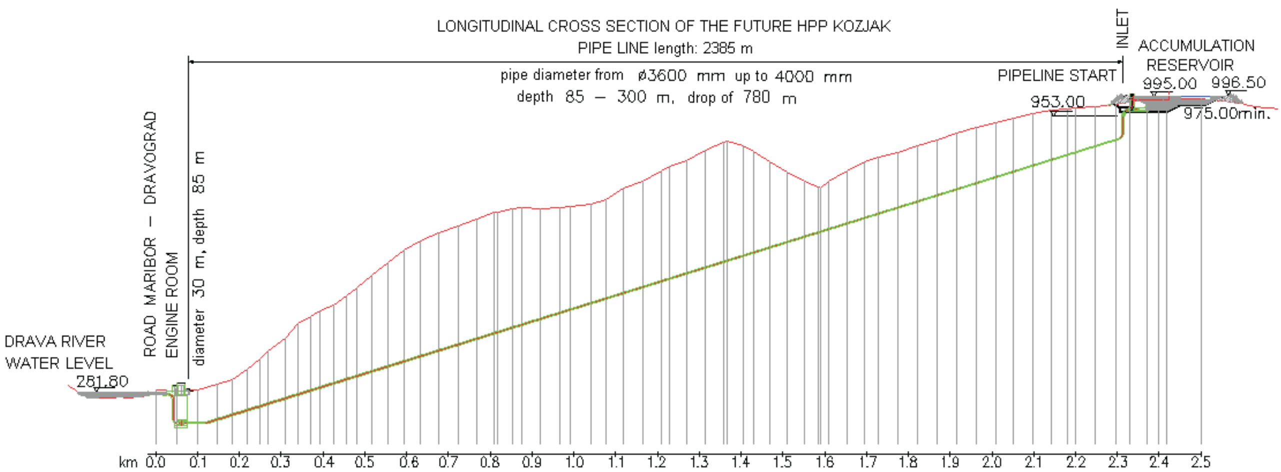

Figure 2. Longitudinal cross-section of Kozjak HPP.

Structural geological, engineering geological and hydrogeological mapping

An area of 12 km^2 around the Kozjak HPP was mapped in detail on a topographical scale of 1:5000. The reviews of results from a previous mapping were carried out and the results from Mioć et al. [3] and Masič et al. [1] were used. Due to the considerable topographic diversity and the thickness of the vegetation cover, the method of profiling and outcrop tracking was used. The mapping consisted of the lithological and engineering geological identifications of the rocks and soils. In addition, the structural characteristics of the rocks, such as the strike and dip of the foliation and lineation, the orientation of the joints, the orientation of the mesoscopic folds, and the orientation and presence of the tectonically disturbed fault zones, were logged. For the purpose of the faults' kinematic analysis, the slips on the fault zones were measured as well. During the engineering geological mapping, the thickness of the soil cover was measured where possible and the GSI at the outcrops was determined. The hydrogeological mapping consisted of field observations, the logging of springs and other sources of water discharges.

3.3 INVESTIGATIONS CARRIED OUT FOR THE RESERVOIR BASIN

The accumulation reservoir is to be located at the top of the hill and protected by a 25-m-high earth-filled embankment. The embankment will be constructed with local material obtained from the excavation of the basin bowl, so detailed investigations of the local material quality were necessary. An earthquake sensibility and stability assessment was one of most important tasks, due to the position of the accumulation basin and the height of the embankment. The investigations were carried out according to those requirements and they included the following.

Structural drilling and excavation pits

In the area of the accumulation reservoir 16 structural boreholes with a total length of 353 m were drilled. Intact quality samples were required, so diamond-bit crowns with double core barrels and bentonite rinse were used. The lengths of the individual boreholes varied from 15 to 28 m, and they were all placed at the toe or beneath the crown of the proposed embankment. In addition to boreholes, four pits up to a depth of 5 m were excavated: two beneath the crown of the proposed embankment and two inside the basin area.

Geological logging, in-situ measurements and geophysical investigations

The obtained cores and excavation pits were photographed and logged in detail in terms of the lithology, the foliation dip, the discontinuities dip, the spacing, the filling and the roughness of the joints, the RQD, etc. At each metre of core several measurements of the uniaxial compressive strength were carried out using a Schmidt hammer. The rock-classifications indexes GSI and RMR were determined for each metre of the borehole. In the excavation pits a penetrometer was used to measure the undrained shear strength of the soils. From the boreholes and the excavation pits the soil and rock samples were taken for further geomechanical, petrologic and mineralogical laboratory investigations.

A total of 42 pressiometric measurements were carried out in the 16 boreholes using an OYO rock elastometer. Each investigation contained three measurements with three load/unload loops in the selected 3.5-m-long section. The values of the pressiometric elasticity loading and unloading modules were obtained from those measurements. The hydraulic conductivity of the soils and rocks was obtained from 16 slug tests. They were carried out in 12 boreholes and on average each test lasted for 10 hours.

The purpose of the geophysical investigations in the area of the accumulation was to obtain information about the tectonic setting, the dynamic elastic properties and to define the design of the earthquake-acceleration parameters. The following investigations were carried out: six 240-m-long seismic refraction profiles (measurements of both the p and s waves), a micro-tremor with 32 triaxial point setting and a full spectral analysis in all three directions as well as down-hole measurements in 11 boreholes (measurements of the p and s waves).

Laboratory investigations

From the boreholes and the excavation pits a total of 180 samples of soils and rocks were taken. In the geomechanical laboratory the following investigations were carried out: the granularity, the natural and dry volume weight natural moisture, the atterberg limits, the investigation of the strength of the rocks (point load tests, uniaxial compression test, triaxial shearing tests, direct shearing tests along discontinuities) and the soil (direct shear test), the investigation of the rocks' elastic properties (E-ν) and the edometric tests on the soils. In addition, special investigations for the usage of local material for the embankments were carried out. This included water-adsorption tests, methyl-blue tests, suction tests, a mineralogy investigation, frost-sensibility tests, crushing sensibility tests, etc.

3.4 INVESTIGATIONS CARRIED OUT FOR THE ENGINE-ROOM SHAFT

The engine room will be constructed in an 85-m-deep and 30-m-wide circular shaft, and at the bottom of the shaft a junction with an underground pipeline is designed. For an excavation pit of these dimensions, the stability of the excavation has to be a major concern. The engine room is located 80 metres below the water level of the Fala HPP accumulation basin, on one side, and at the foot of the 800-m-high slopes on the other side. Under such a setting the underground water inflows under pressure had to be taken into consideration and investigated. The following investigations were carried out.

Structural and rotary-percussion drilling

Around the outer perimeter of the engine-room shaft, three structural boreholes, each 110-m-deep, were drilled. One rotary-percussion borehole at the centre of the excavation with no core recovery to a depth of 90 m was also drilled. This borehole was used for geophysical and hydro-geological investigations.

Geological logging, in-situ measurements and geophysical investigations

For the geological logging the same principles were applied as for the reservoir area. In the boreholes, 33 pressiometric investigations and a few short pumping tests were carried out. In addition, the measurements with a multi-parametric mini probe were made: the temperature (T), the pH, and the electric conductivity (η) were measured along the borehole. Along with the pumping tests, Lugeon tests were also carried out in the boreholes. Due to the instability of the borehole walls, some tests could not be completed; however, in total, 25 tests were carried out in three boreholes. Based on the hydro-geological investigations performed in the boreholes, at least two different origins of the water sources were confirmed.

The geophysical investigations were aimed at detecting the faults that could otherwise not be detected due to an alluvium cover. The following methods were used: electrometric profiling of the specific electrical resistance parameters (eight 100-m-long profiles), the electrical resistivity method or misse-a-la-masse (in four boreholes), seismic refraction profiling (two 240-m-long profiles) and seismic tomographic profiling in three directions with the hydrophones located in all four boreholes. Logging with a video camera was also carried out in all four boreholes.

Laboratory investigations

From the boreholes a total of 90 samples of rock were taken for the laboratory investigations, where similar investigations were carried out as for the accumulation reservoir. Petrologic analyses were carried out on 19 specimens prepared from the core samples of the boreholes. The optical effects in the scanning minerals under scanning light enable a qualitative identification of the minerals and their structure. On the basis of their structure and texture, the sequence of the minerals' separation can be determined, and by considering the stability fields of the individual minerals and the observed reactions between them, the environment of their formation and the geological history of the investigated rock can be identified. Microscopic analyses were required for the calibration of the macroscopic observations, the identifications and the descriptions, which were carried out for all the cores.

4 RESULTS

4.1 GENERAL GEOLOGICAL CONDITIONS

The Kozjak HPP will be located in the Kobansko region, which is part of the Central Alpine metamorphic rocks complex. The region has passed the medium-grade of metamorphism, with the rocks having undergone subsequent retrograde metamorphism. The most frequently occurring rock in this territory is mica schist, with transitions into gneiss; in the lower part of the complex the rocks are strongly carbonized and marbles are often present. The accumulation reservoir will be completely located inside the phyllonite block, which is the highest-lying unit. It is built up of strongly altered slates and gneisses. The rocks show extremely strong signs of shear deformations: a mylonithic structure, dense foliation and penetrative shear belts, which are usually heavily weathered, with good cleavage along the foliation. This unit outcrops in the highest parts of the region and has sub-horizontal contact with the underlying unit. The unit represents a sub-horizontal shear zone, which is a maximum of 200 m thick and runs along the main boundary plane between the Pohorje extensional complex and Kozjak [4]. A geological map, which is the result of geological mapping, is shown in Fig. 3. In addition to lithology, the fault systems obtained with mapping and geophysical investigations are also shown in Fig. 3. It is clear that there is a major fault system running along the north-eastern section of the proposed reservoir.

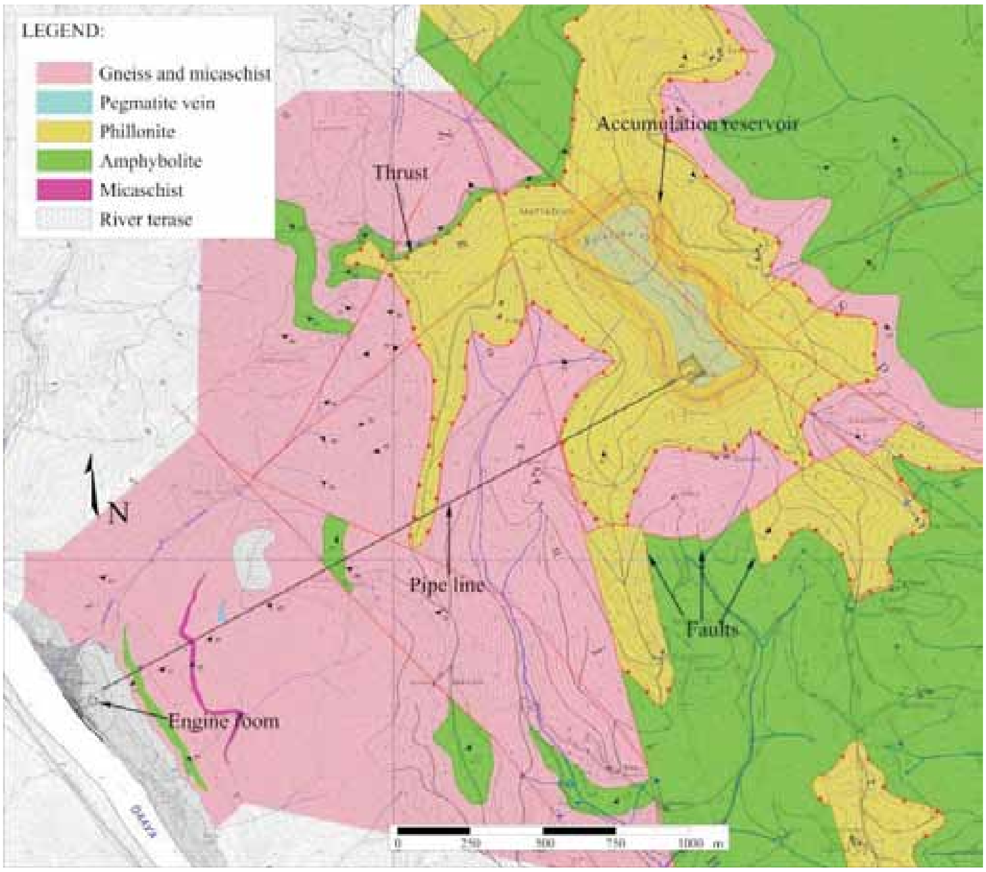

Figure 3. Geological map of the investigated area.

The pipeline is going to be built in a characteristic sequence of metamorphic rocks, which appears through the entire region of Kozjak and the neighboring Pohorje massif. It is predominantly built up of gneisses and subordinately of mica schists. This unit outcrops in the major part of the mapped territory. Inside this unit, lenses and bodies of amphibolites, pegmatite with a mylonithic structure and quartzite appear in the mapped territory. Inlays and lenses can be quickly wedged out laterally. The usual dip of the metamorphic rock strata is in the direction 180-220°, with a strike angle of 20-40°, although the foliation inside these rock strata changes quickly. Only a few major faults are projected to cross the proposed pipeline direction.

The designed engine room is located on the Drava river terrace, where no outcrops were present. Since the surface is covered with quaternary sediments, we obtained the data from the boreholes and geophysical investigations. The terrace is made of up to 10-m-thick gravel deposits that are covered with debris on the hill side of the terrace. Beneath the gravel, metamorphic rocks are found with prevailing marbles, schists and gneisses that are also frequently carbonized. No fault lines are shown in Figure 3 in the area of the engine room due to the scale of the map and the fact that the terrain is covered with alluvium deposits. The tectonic element could not be traced on the surface, but geophysical investigations and boreholes showed the presence of faults that cross the location of the engine room, as will be shown later.

4.2 Development and analysis of a 3D model for the reservoir area

Before the 3D geological/geomechanical model was developed, an analysis of all the available data and results had to be carried out. As was shown in the previous section the reservoir will be built entirely inside the phyllonite complex. The first step in the model development requires that the geological units are interpreted from the standpoint of their engineering and geomechanical properties. Based on the results from in-situ measurements, laboratory results, the mappings of tectonic disturbance and the weathering of cores, the phyllonite was divided into four geomechanical units. In Fig. 4 an example of the core taken from the borehole is shown, where all four typical units are present.

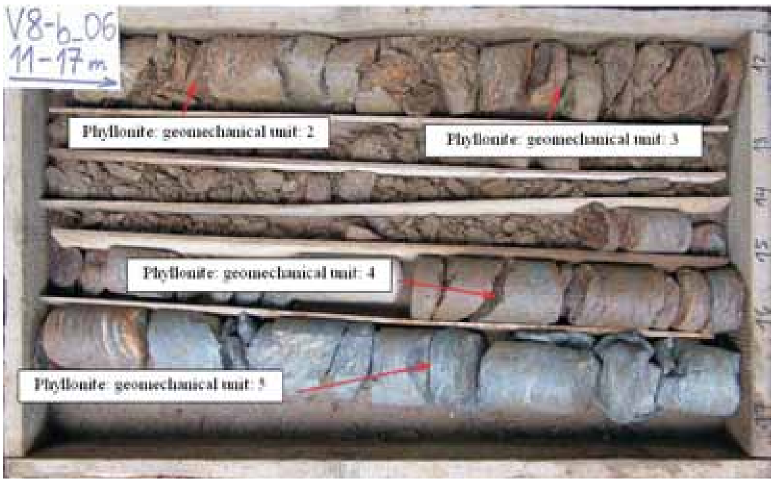

Figure 4. Typical geomechanical units of phyllonite shown in the borehole core.

The first unit (1) or proluvium, which is not shown in Figure 4, represents a surface layer where the phyllonite pieces are still found in the clay matrix, and which is deposited under a layer of humus. The thickness of proluvium changes from 1 m to 4 m and has no engineering significance, since it will be removed. Under the proluvium there is usually a layer of heavily tectonically disturbed and weathered phyllonite (unit 2) with a strong clay content and with only traces of original foliation still present. The thickness of the stratum is highly variable and changes from a few metres up to 20 m in the area of the fault zones. The next unit of phyllonite (unit 3) represents moderately tectonically disturbed phyllonite with distinctive foliation and the original structure still present. The thickness of this unit is variable and is often interchanged with unit 4, which represents a moderately to weakly tectonically disturbed phyllonite with a more distinctive structure. The last unit (unit 5) represents weakly disturbed to undisturbed, unweathered phyllonite, which was only found in the lower part of some boreholes and was identified in other areas by the correlations with geophysical investigations. The ranges of the proposed strength and deformability properties for each unit are summarized in Table 1.

The strength parameters for unit 2 were obtained as a median value with a 95% level of confidence, based on 13 laboratory direct shear tests, and the deformability properties were similarly obtained from a statistical analysis of 17 pressiometer measurements.

For units 3, 4 and 5 the Hoek & Brown strength criterion [5], [6] was applied using RockLab software for a determination of the strength and deformability parameters of the rock mass. The geological strength indexes (GSIs) [7] were taken conservatively for each unit at the lower margins. The uniaxial compressive strength was obtained from laboratory tests. The intact elastic modulus of the rock was obtained from the unloading pressiometeric measurements. They were two to three times higher than the modulus measured in the laboratory. The decision to take pressiometric measurements as

Table 1. Geomechanical parameters for typical units in the area of the reservoir.

Unit	GSI	UCS	Proposed strength parameters		Strength parameters measured in the laboratory		Elastic modulus
		σ_c MPa	c kPa	φ °	c kPa	φ °	E MPa
2	-	0.1-0.4 (0.23)	5.2	32.5	0-17.5	30.5-40.8	32
3	10-20	2.1-9.6 (5)	14-36	30-36	27-33	39-44.3	60-90
4	20-40	8.8-21.2 (14.6)	37-84	44-51	31-47	47-55.6	306-1071
5	30-50	18.8-67.4 (32.3)	92-275	53-56	25-143	41-65.6	3541-13368

an input value was made because the laboratory samples were influenced by foliation and discontinuities, so the values of the intact modulus were affected.

For comparison, the strength parameters obtained from the triaxial tests are presented in Table 1. It is clear that there is generally good agreement between the values determined using the Hoek & Brown strength criterion and the laboratory values for units 4 and 5. For unit 3 the values obtained using the Hoek & Brown strength criterion are lower than the ones obtained in the laboratory. The reason for that could be the conservative approach with the GSI assignment and also due to the tendency towards the better quality samples selection in the laboratory. The same discrepancy for unit 3 was also noted when the deformability parameters were compared.

Based on all the information obtained with the investigations, a 3D geological/geomechanical model was developed using GoCad (Geological Object Computer Aided Design) software. GoCad is a powerful tool used for manipulation, geostatistical analyses, kinematic analyses and the visualization of georeferenced geological, geomechanical and geophysical data. The model is constructed using points, linear elements (wells), curves, planes and volume elements, which in addition to spatial information can also carry other relevant data. The development of the model for the reservoir was carried out in the following steps.

1. The digital model of the terrain was formed from the point elements.
2. The embankment was constructed according to the design requirements with curve elements and planes.
3. The boreholes were inserted into the model as line elements. Each borehole element contained the information (markers) about the position of the boundaries between the different geomechanical units.
4. The geophysical refraction profiles, together with the geophysically interpreted fault planes, were inserted into the model as raster and plane elements.
5. The information obtained from the geological mapping, including the trust line and the fault planes, was inserted into the model and reinterpreted, based on the results from the geophysical investigations.
6. The plane boundaries of the different geomechanical units were interpolated between the boreholes and the fault planes.

An example of a model under development is shown in Fig. 5, with surface, boreholes (containing geomechanical unit markers) and fault planes already inserted.

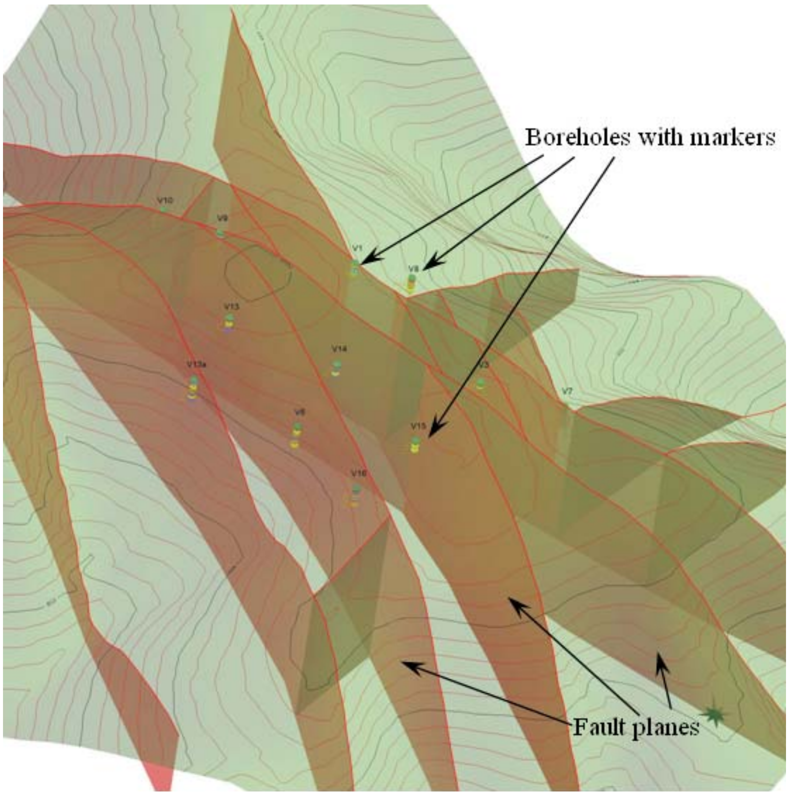

Figure 5. 3D geological/geomechanical model of reservoir under development.

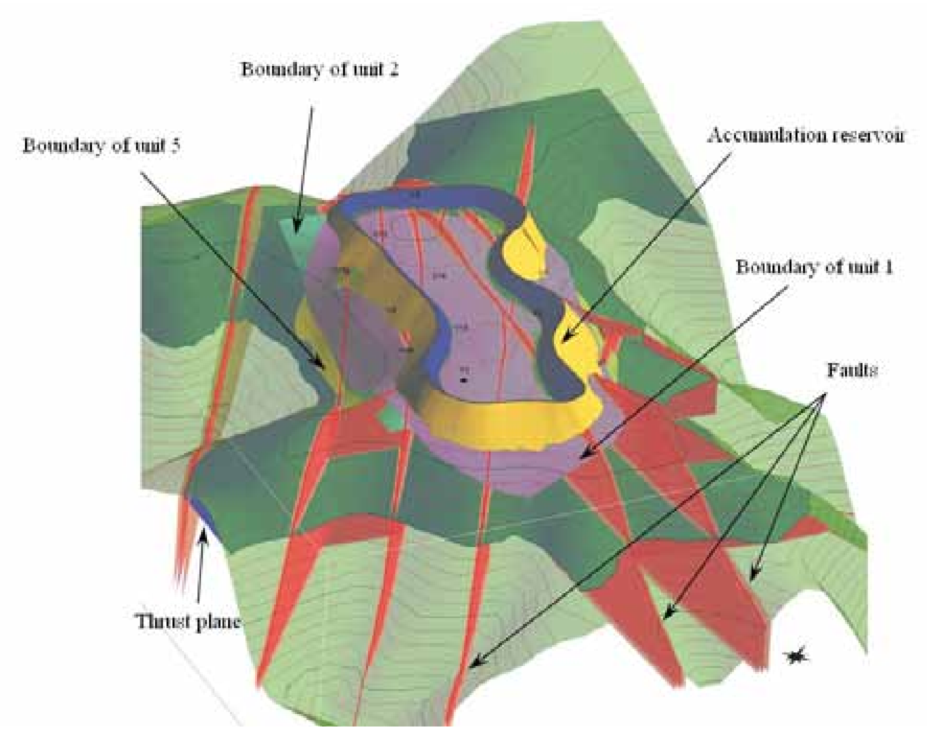

Figure 6. Final 3D geological/geomechanical model of the accumulation reservoir area.

The final 3D geological/geomechanical model of the accumulation area is presented in Figure 6. It includes a thrust plane between the gneiss and phyllonite, as well as the expansions of the planes between the geomechanical units 1, 2, 3 and 5. The geomechanical units 3 and 4 have not been separated due to their irregular interchange in both the vertical and horizontal directions. Thinner segments of the geomechanical unit 2, inside units 3 and 4, have also not been separated. In the area of fault zones, the occurrence of the geomechanical unit 2 was considered up to a depth of 20 m, and the thickness of the fault zone was taken at 10, for smaller, and 20 m, for more prominent, faults. The width of these fault zones was determined on the basis of the geological mapping, the geophysical investigations and the results of drilling and excavations.

The spatial representation of the geomechanical data enabled us to predict the spatial expansion of the geomechanical units in the areas where the investigations were not carried out. It also gave us a better understanding of the relations between the different geomechanical units and their relationship with the proposed design solutions. With the use of the visualization tools in GoCad, we were able to investigate the different areas of the proposed embankment. In Figure 7, a cross-section of the model in the direction SW-NE is shown. It is clear that in this area we have a thick layer of unit 2 so that the embankment is founded completely inside this unit. With further analyses, a similar area was also found in the NW part of the reservoir, as was expected. This area of the reservoir is crossed by a major fault zone that can also be seen in the model and is shown in Figure 6.

With the use of the spatial geological/geomechanical model 2D cross-sections were drawn in most critical areas and analyzed. The results of the analysis carried out showed that the embankment can be built from local material [8], but due to the earthquake stability the slope of the embankment cannot exceed 26°.

4.3 DEVELOPMENT AND ANALYSIS OF A 3D MODEL FOR THE ENGINE ROOM

The geological conditions around the engine room are more diverse in terms of lithology in comparison to the accumulation reservoir. Schists, gneisses are quickly changing with their more carbonized varieties; marbles and pegmatites are sometimes also present. The difference between the different varieties is in the mineral composition that is a consequence of the metamorphoses level and the origin rock. Based on lithology and petrologic investigations, ten different types of metamorphic rocks were identified. In Figure 8 photographs of the cores taken from the two different boreholes at the engine-room area are shown. As can be seen in the left-hand picture, the changes from gneiss to marble and back are seamless.

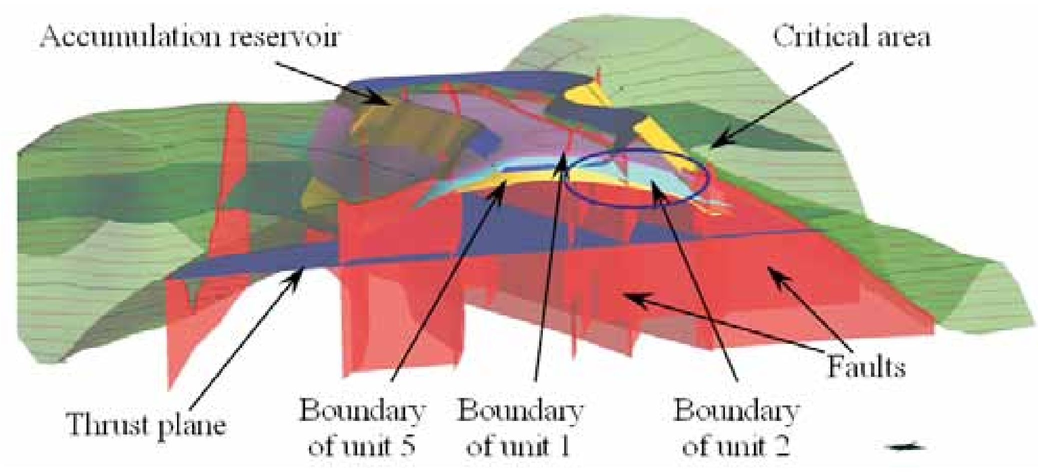

Figure 7. Critical cross-section of the reservoir model.

However, of all ten identified lithological types only a few are relevant due to their predominant occurrence and were according to the lithology, the laboratory results, the geophysical and pressiometric results, divided into four geotechnical units, with all of them shown in Figure 8. The gneisses and schists represent unit A, their carbonized varieties represent unit B, the marbles unit C, and in unit D all three types together with cataklazits are present. They are interchanging at a very fast rate so they cannot be divided into sensible geomechanical units.

Each of these units is further divided into subunits in accordance with the GSI values. The range of the geomechanical properties for each unit summarized in Table 2 was obtained with the Hoek & Brown strength criterion using RockLab. Like with the reservoir area, the GSI values for each unit were taken conservatively at the lower margins. The input parameter for the intact elastic modulus was obtained from the average value of the laboratory measurements and the unloading pressiometric elastic modulus. The uniaxial compressive strength for each unit was determined as an average value of the laboratory measurements and the results obtained with the Schmidt hammer, corrected to the core diameter. For units A and D several different average values were given. For example, in unit A a value of 3 MPa was used for the fault zone and in unit D different values are assigned to rocks with a different degree of disturbance.

The lowest values of the GSIs (values between 5 and 10) and the uniaxial compressive strength were used for a characterization of the fault zones running through the respective unit. The range of the proposed values of the strength and deformability properties for each unit is summarized in Table 2 (on next page).

Figure 8. Most common lithological units in the area of the engine room.

Table 2. Geomechanical parameters for typical units in the area of the engine room.

Unit	GSI	UCS	Proposed strength parameters		Strength parameters measured in the laboratory		Elastic modulus
		σc MPa	*c* kPa	*φ* °	*c* kPa	*φ* °	*E* MPa
A	5-10	3	24	32	-	-	64
	10-20	51.7	62	28	-	-	256-384
	20-30		340	41	-	-	3517
	30-50		280	55	-	-	9381
	50-70		814	51	408	55	30556
	70-80		1952	54	-	-	47971
B	30-50	68	442	53	264	58	7042
	50-70		1074	50	-	-	22937
	70-80		2566	54	-	-	36009
C	50-70	57	1154	49	4274	37.5	62316
	70-80		2198	53	-	-	97831
D	5-10	-	79	20	-	-	64
	10-20	10	226	33	-	-	306
	30-50	35	469	42	-	-	14528

For comparison, the strength parameters obtained from the laboratory are also presented in Table 2. Even though not all the subunits were examined in the triaxial shear apparatus, where the data was available a generally good agreement was found between the values determined by the Hoek & Brown strength criterion and the laboratory values for the representative subunit.

The 3D geological/geomechanical model of the engine-room area was created following the same procedure as for the development of the reservoir model. It was created using the results from boreholes' loggings, inputted as line elements (with markers), seismic tomography profiles (raster images and fault planes) and the results of electric scanning. The model under development is shown in Figure 9 and the final model that includes the fault planes and the boundaries between the different units is shown in Figure 10.

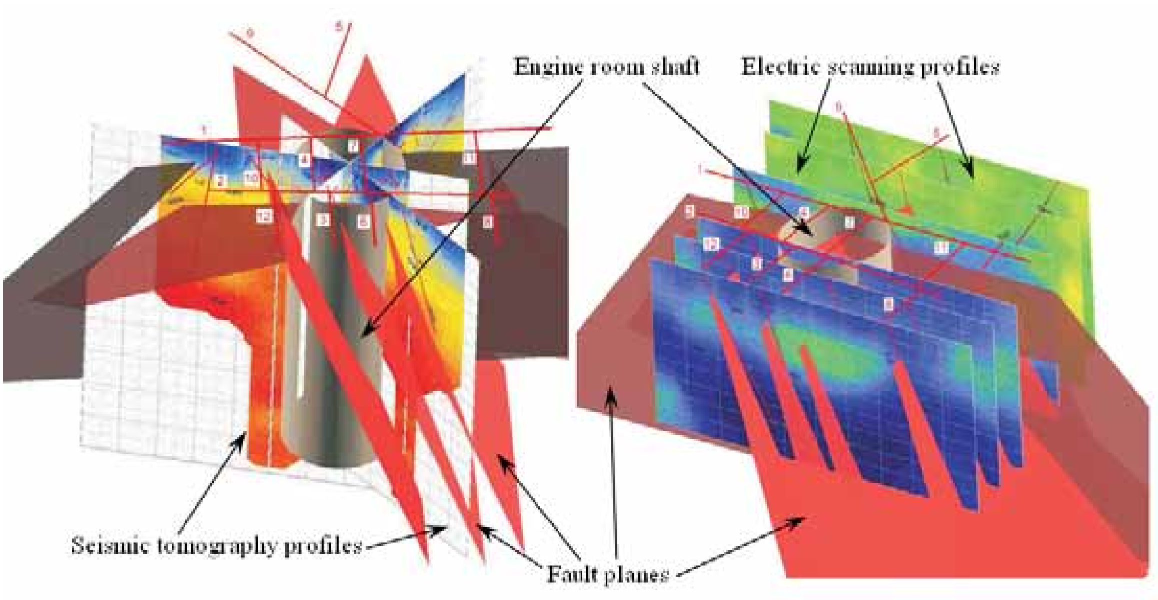

Figure 9. 3D geological/geomechanical model of engine room under development.

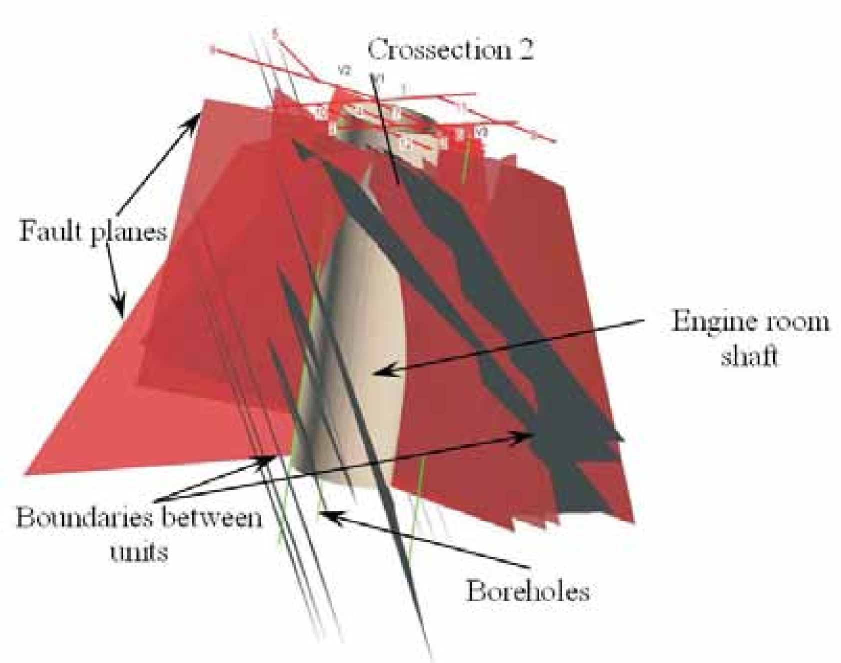

Figure 10. Final 3D geological/geomechanical model of the engine room.

A final model was analyzed in order to access the most critical area and possible failure mechanisms that could endanger the excavation. The most critical cross-section, drawn from the model, is shown in Figure 11a, where a sub-vertical fault can be seen, crossing the engine-room shaft. A spatial analysis revealed that 85% of the entire rock mass around the engine room is composed of rock with a GSI higher than, or equal to, 30, with the unit B being the most dominant unit. The other 15% of the rock mass is found in the faults and fault zones or in the first several metres of weathered rock below the alluvium. Based on the analysis a further simplification of the spatial model was possible and the 3D model for the numerical analysis, shown in Figure 11b, was developed.

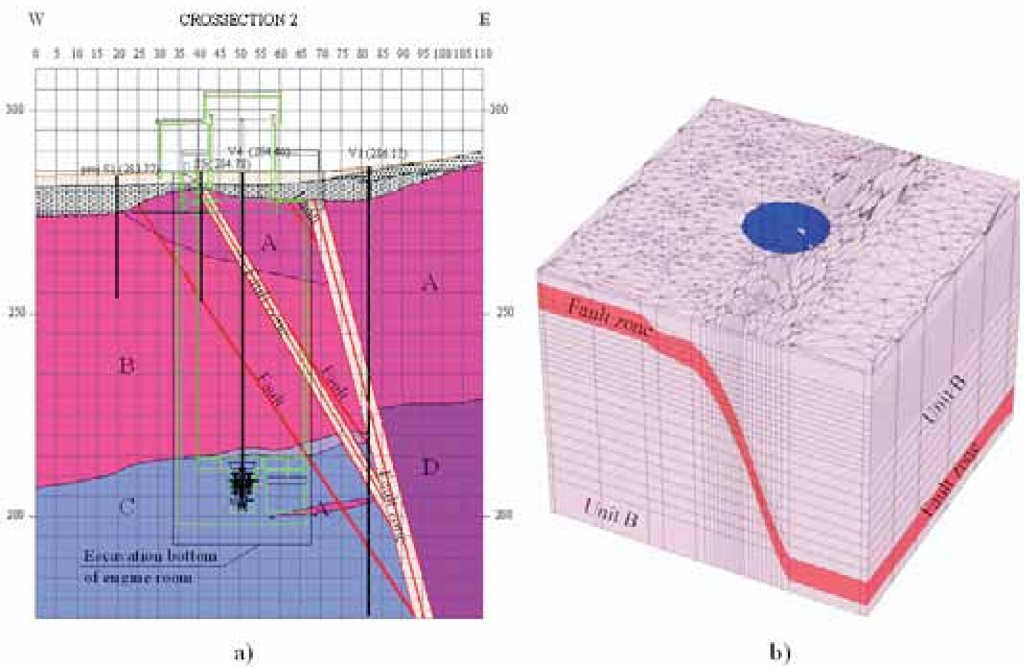

Figure 11. a) Most critical cross-section in the engine-room area, b) 3D numerical model.

A 3D numerical analysis was carried out with the simplified model using the 3D Plaxis Foundation. The geomechanical characteristics used in calculations are shown in bold in Table 2. The excavation to a depth of 85 m in 2.5-m excavation steps, with a primary lining installation and dewatering, was modelled. The results of the analysis showed that if the appropriate support measures (anchors, installation of lining, dewatering and length of the excavation step) are exercised, the engine room can be safely executed. With the use of the 3D geological/geomechanical model an efficient spatial analysis was possible, resulting in simplifications to the numerical analysis.

4.4 DISCUSSION ON THE SCOPE OF THE EXECUTED INVESTIGATIONS

The investigations at Kozjak HPP were carried out in order to obtain the necessary geological and geomechanical characteristics for the safe and economical construction of the reservoir, the pipeline tunnel and the engine room. For the accumulation reservoir an area of 300,000 m^2 was covered with 16 boreholes and 4 excavation pits, amounting to one investigation point per 15,000 m^2. Because all the boreholes were located in pairs at the base and below the crown of the embankment, the distance between the borehole pairs is a more appropriate measure. A 2,500-m-long embankment was covered with a borehole pair at every 300 meters, leaving the interior of the reservoir with an area of 120,000 m^2, covered by only 6 refraction profiles and 4 excavation pits. Due to the relatively uniform geological conditions and the fact that the embankment, which is the dominant geotechnical structure, was sufficiently covered by the investigations, we can conclude that the executed investigations were adequate. In order to obtain more detailed information for the excavation of the interior of the basin, a few more excavation pits, boreholes or refraction profiles, could be executed. But with the help of a 3D model a good estimate was also obtained in this area.

The engine room is relatively small in comparison to the reservoir. An area of 3,600 m^2 was investigated with four deep boreholes and geophysical investigations. In addition to the results from four 40-m boreholes, the refraction seismic profiles from a previous investigation phase were available [1]. From all those investigations, relevant information for the excavation of the engine-room shaft and for the development of the 3D model were obtained. Due to the different origins of the water, the possibility of water inflow through the fault systems has not been fully explained. The already planned investigations that include the drilling of several additional boreholes at different depths and the execution of pumping tests in the boreholes with parallel monitoring and the analysis of water, should give an appropriate answer also to those questions.

5 CONCLUSIONS

In this paper the investigations carried out in the area of the future Kozjak pump-storage hydroelectric power plant were briefly described and discussed. In the area of the reservoir a few more excavation pits or boreholes inside the proposed basin could be carried out, but in general the investigations were adequate. The same can also be stated for the engine-room area, with the exception of the underground water investigations. In general it can be concluded that based on the executed investigations, sufficient data is available in order to access the important geotechnical aspects of the construction of the Kozjak pumped-storage hydroelectric power plant.

The results of all the investigations were synthesized in the form of 3D geological/geomechanical models and 3D models for the reservoir and the engine room were presented. The use of the 3D geological/geomechanical models was very helpful in determining the most critical areas and understanding the mechanisms that can endanger the structure. Those critical sections can then be investigated and a 2D stability analysis or full 3D numerical analysis, as was demonstrated for the engine room, can be executed. Models are also important in areas where we have to make extrapolations of the geological and geomechanical characteristics due to a lack of investigations, as was the case in the interior of the basin. The use of the 3D geological/geomechanical model was shown to be very useful and is probably necessary when complex geotechnical problems are being addressed.

From the geological and geotechnical aspects the main hazards connected with the reservoir are linked with the static and dynamic stability of the embankments in the areas where the phyllonite unit 2 is thick (the subsurface areas and the area of the fault zones). Those problems could be addressed with the reinforcement of the embankment toes with pile walls, on the one hand, or with lowering the height and slopes of the embankments, on the other.

The main hazards connected with the engine room are linked with the possibility of a strong water inflow during the excavation, which has still not been fully investigated. There are also some possibilities of local block instabilities, which could be prevented by the appropriate excavation sequence and temporary support measures (shotcrete, anchors)

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