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Determination of Save Excavation Criteria in Velenje Coal Mine

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Abstract: Ensuring safe conditions for mining coal under water-bearing sands in the Velenje coal mine depends on the designed parameters of hydrogeology, geomechanics and drainage. The purpose of the research is to predict and simulate the hydrostatic pressures above the excavation fields in order to determine the thickness of the insulation layers and the height of the excavation. Coal occurs in the Velenje basin in the form of a slightly concave lens. Directly above the coal seam is an insulating layer of marl or clay. Above the insulating layer are more or less permeable Pliocene sands in which water can accumulate under layer pressure, posing a potential risk of water ingress into underground spaces. In addition to the Pliocene sands, triad layers of different ages and lithology in the bedrock also pose a risk of water intrusion. In order to prevent the intrusion of water into the working areas of underground objects, the criteria for safe mining in the Velenje coal mine under aquifers were established. The scientific research approach to determining the criteria for safe mining enables the safety and determination of excavation heights in coal mining. The following data are required for such a calculation: the water pressure in the first sands, the excavation depth below the surface, the thickness of the insulating layer and the method of excavation or the course of the demolition processes.

Keywords: hydrogeological properties; excavation plate; aquifer; water pressure; Surfer software

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Citation: Vukelić, Ž.; Šporin, J. Determination of Save Excavation Criteria in Velenje Coal Mine. *Minerals* **2024**, *14*, 77. https://doi.org/10.3390/min14010077

Academic Editors: Ivica Ristović and David Cliff

Received: 27 November 2023
Revised: 23 December 2023
Accepted: 5 January 2024
Published: 9 January 2024

1. Introduction

The article aimed to present the problem of safe and economical excavation under aquifers and to show how we proceed with research methods when calculating excavation heights, in the specific case of floor G4/C. The necessary data for calculating the excavation heights were obtained by means of boreholes drilled before excavating the floor and by analyzing the hydrogeological data obtained. In the experimental part, we calculated the hydrogeological properties of the considered area on the floor using the software Surfer v.17 [1].

The geological and hydrogeological properties of the area under consideration, the criteria for safe excavation under aquifers, dewatering systems, types of wells and their construction, the Surfer software, parameters for calculating the permissible excavation height and the design of the hydrogeological properties for further calculation of the excavation height are described.

The height of the excavating front (plate) is decisive for the economic excavation of coal. When determining the excavation height, the aim is to extract as much coal as possible, and at the same time safety criteria must be taken into account so that the roof layers do not break and layered water does not penetrate into the underground mining spaces.

For the safe and economic extraction of coal under aquifers, it is necessary to observe the criteria of safe and optimal mining under aquifers in the mining areas of the Velenje coal mine. In order to calculate the excavation height, the following parameters must be determined: the depth of excavation from the surface, the thickness of the insulating layer, the water pressure in the first sands and the method of excavation (the position of the excavation in the layer in relation to the course of the excavation process). All these data must be determined and included in the criteria for the safe mining of coal under aquifers.

1.1. Geological Characteristics of the Area

The observation area is located in the Savinjska region, more precisely between Velenje and Šoštanj [2]. In geological terms, this area is called the Velenje depression and is of tectonic origin. It was formed in the Pliocene when part of the area between the Karavanke and the eastern extensions of the Savinja Alps subsided. Towards the end of the middle Pliocene, the area began to subside mainly along the Šoštanj fault, which runs in the NW–SE direction. The fault runs from Šoštanj through Velenje to Vojnik. Besides the Šoštanj fault, other neotectonic faults were also activated. As a result, the entire area of the so-called Velenje depression subsided. The subsidence and continuous filling with sediments formed the valley as we know it today, in which, according to its synclinal form, the coal layer was also deposited. The geological situation of the area is shown in Figure 1.

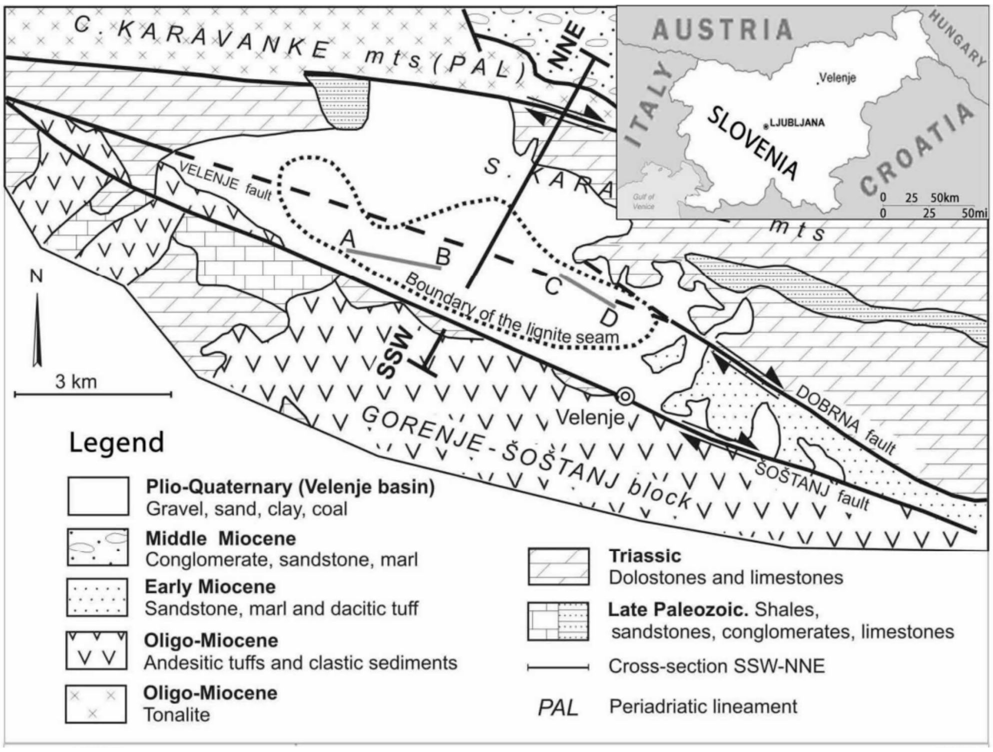

Figure 1. Geological situation of the Velenje depression.

The aforementioned depression is only a part of the somewhat larger Velenje–Dobrna depression. It borders the Triassic margin to the north and the Gorenjska–Šoštanj block to the south. It consists of the Middle Oligocene, Oligomiocene, Miocene and Pliocene deposits. The lower part of the Miocene deposits contains micaceous sandstone, while the upper part contains more sandy marl. Marine deposits can be found in the upper part. The Plio-Quaternary sediments consist of clayey gravel and sandy clay. Coal is found in the underlying Pliocene sediments. The upper part is categorized as Plio-Quaternary and represents the last phase, i.e., the fluvial filling of the Velenje Pliocene lake. Older Pliocene layers are also present in the deeper parts of the depression but do not reach the surface. The alluvium is alluvial in the valleys of the Paka river and larger streams. The material is very heterogeneous. It consists of coarse-grained, medium-grained and fine-grained pebbles, sand and sandy clay.

1.1.1. Pre-Pliocene Bedrock

The Velenje coal basin is of Pliocene and Pleistocene age and was deposited on pre-Pliocene bedrock. It is divided into two parts, which are separated by the strong Velenje fault shown in Figure 2. Oligomiocene deposits occur to the south of this fault. North of the Velenje fault, dolomites from the Lower, Middle and Upper Triassic dominate. Along the northern edge of the Šaleška valley, there are also Carboniferous and Permian conglomerates, sandstones, shale claystones and unconsolidated crystalline limestones. To the east, near Hrastovec, there are freshwater marls and sandstones with brown coal, probably from the Eocene. In the west near Topolšica, a layer of Miocene marls, sandstones and conglomerates about 10 m thick lies above the Triassic layers. The area north of the Velenje fault is tectonically strongly folded and lumpily fissured. Oligo–Miocene strata occur to the south of the Velenje fault.

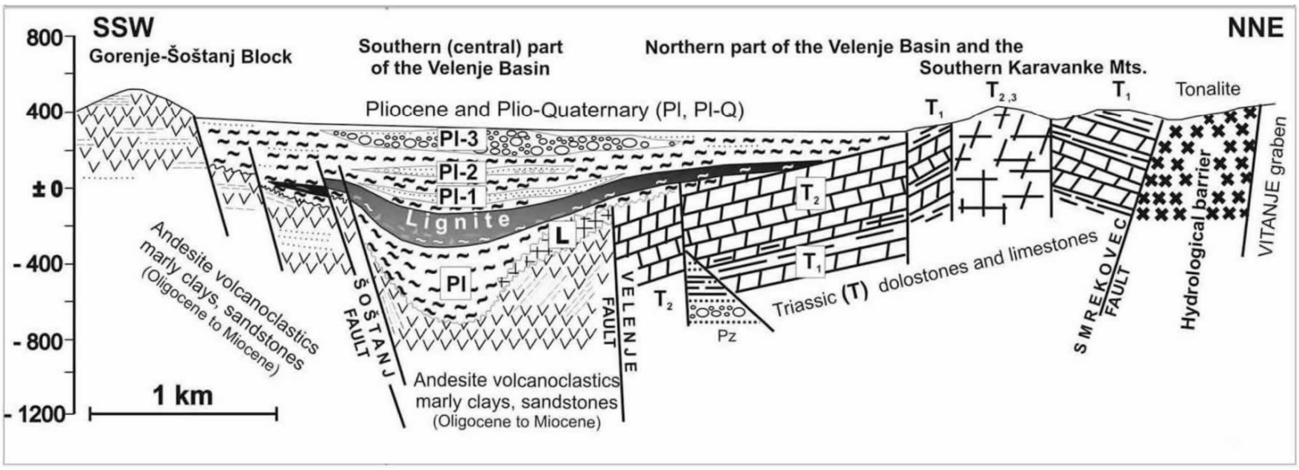

Figure 2. Tectonics of the Velenje depression, direction SW-NE.

1.1.2. Velenje Coal Basin

The depression is filled by the Velenje coal deposit, which dates from the Pliocene and Pleistocene age. This is further subdivided into the overburden, the coal seam and the bedrock. It consists of alternating and interwoven layers of clays, silts, sands, gravels, mudstones, marls and conglomerates. In between lies the Velenje coal seam, which has the shape of a syncline in all sections. The southern edge of the Šoštanj fault is tectonically fractured in some places. The Šoštanj fault runs in a NW–SW direction, and the inclination of the plane is 75° in a N–NW direction. The strength of the material varies depending on its position in the deposit. The sands and gravels originate from marsh and lake rocks, which represent a quiet sedimentary environment. The entire Plio–Pleistocene deposit is more than 1000 m thick and is divided into the bedrock, the coal horizon and the overburden (Figure 2).

1.1.3. Bedrock

The bedrock is the layer below the coal seam. It is bounded by the Šoštanj and Velenje faults. In Figure 2, it is labeled PL (Pliocene) and in the north T (Triad). The palaeo-erosive impact on the pre-Pliocene bedrock was followed by a tectonic phase that led to the formation of thick clastic layers below and finer basal layers above. The sand and gravel grains contained in these layers vary in size, are disorderly mixed and are connected to a silt and clay base. The lower part of the basal layers contains fragments of various surrounding rocks, clayey-silty gravels and sands as well as sandy and gravelly silts. In the higher parts, there are mainly sandy and gravelly silt and clay with intercalations of clayey-silty, quite cohesive sands. The thickness of the basal layers is around 350 to 400 m.

1.1.4. Coal Horizon

The coal horizon begins with the appearance of coal clays and ends with clean coal, which is divided into lower tailings and an upper-quality sections. In the tailings section, coal, tailings coal, coal clay and tailings are exchanged. The tailings are gray clay, light green sandy clay and light green sandy silt. The tailings coal section is up to 50 m thick.

The coal on the eastern side is not of such quality, towards the west it sinks relatively quickly into the depths but becomes thicker and of better quality. The northern periphery is characterized by a relatively steep triadic slope in the eastern part of the Velenje field, along which the overlying layer becomes thinner and rises upwards. The central northern part and the western northern part are characterized by numerous layers of clay and sand embedded in the stratum. Towards the south, they become thinner and disappear. Sand layers also occur in the overburden in this area. Towards the west, in the direction of Topolšica, the coal layer rises, quickly becomes thinner and contains more tailings.

The quality section consists of coal without tailings. In the center of the depression, coal and pre-Pliocene bedrock are separated by a thick stack of bedrock layers, while in the north, where the bedrock contains Triassic dolomites, they are in direct or almost direct contact. South of the Velenje fault, a similar situation exists only next to the Miocene lithotamnic limestone. It is unfavorable for mining if a sand layer occurs between the coal [3,4].

The approximate basic dimensions of the coal seam are 8.3 km long and 1.5 km to 2.5 km wide. The coal seam is closest to the surface at the edges and is deepest in the central part, where it also reaches the maximum thickness of 168 m of quality coal. The Velenje coal seam is one of the thickest individual coal seams in the world [2].

1.1.5. Overburden

After the deposition of coal, the Velenje depression continued to sink, and at the same time, overburden sediments were deposited in this area. The boundary between coal and overburden is sharp. Directly above the coal is a thin layer of marl or marly clay. This is followed by a thick stack of coarse-grained fluvial layers. In the uppermost part, marshy clays occur again, in some places also a thin layer of coal, and even further up there are land sand clays and gravels. The entire lake development can be assigned to the Pliocene, the marsh and land development at the top of the stack to the Lower Pleistocene. In the center of the depression, between the coal and the overlying sand deposits, there is a relatively impermeable clay and silt layer several tens of meters thick. It becomes thinner towards the north so that the coal and the overburden sand are in contact in some places. In the center, the overburden layer is around 450 m thick.

1.2. Hydrogeology Geological Characteristics of the Area

In hydrogeological terms, the Velenje basin is very water-bearing. Hydrogeological problems have existed for many years during coal extraction at the Velenje coal mine. After the first intrusion of water from the triad layers, numerous studies of the aquifers were carried out, showing the danger of water intrusion into the open underground areas [5–8]. In some places, the coal seam is practically in contact with aquifers. The open subsurface areas are threatened by aquifers in both overburden and bedrock. The following warrant the greatest attention:

- Pliocene sands: they are in the overburden above the insulating layer surrounding the coal layer, and drainage is carried out with hanging and impressed filters;
- Lithotamnium limestone: it is in the bedrock, and drainage is carried out with impressed filters;
- Triad base: it is in the bedrock, and drainage is carruied out with impressed filters.

1.2.1. Overburden Aquifer

The overburden aquifers in the Velenje basin are of Quaternary and Pliocene age. The Pliocene aquifers used to be further subdivided into aquifers just above the coal (Pl_1), aquifers 20–80 m above the coal (Pl_2) and upper Pliocene aquifers (Pl_3). Several criteria were used for this subdivision, namely the following:

- the water level in an individual aquifer;
- modeling of water pumping into underground mine spaces;
- logging measurements and chemical analyses of the water.

However, after the analysis of key parameters, the classification according to layer packages within the adapted geological columns, to which the aquifer belongs, becomes increasingly clear.

In the Pliocene aquifer package, the aquifer sands directly above the coal seam are the most interesting from the point of view of the Velenje coal mine, as the water pressures in the Pliocene overburden aquifers are one of the most important parameters when calculating the criteria for safe coal mining under the overburden aquifers.

The entire package of aquifers, from which the dewatering is carried out with hanging filters into the mine, is up to 150 m thick. The normal thickness of the aquifers is generally much less, as there are impermeable or poorly permeable layers of clay and sandy clay, silt, claystone and silt between the sand layers. The aquifers labeled Pl_2 and partly Pl_3 are hydrodynamically much more homogeneous than the first aquifer sands above the coal, although they consist of several layers of sand and gravel that are partially or in places completely separated from each other.

The aquifers that drain into the underground areas of the Velenje coal mine are only indirectly fed by seepage water from higher-lying aquifers. Only the Quaternary aquifer is fed directly from precipitation or surface water. The Pliocene aquifers can only be fed downwards by vertical seepage through a semi-permeable layer.

The water, which either seeps slowly locally from the aquifers into the underground spaces or is drained by the relief of the mining fields, is not aggressive in terms of its chloride and sulfide content.

1.2.2. Triad Bedrock

Most of the eastern, northern and north-western margins of the basin and a large part of the pre-Pliocene bedrock, are built by triad layers of different ages and lithology. The middle and upper Triad limestones and dolomites form a system of aquifers which, due to their close proximity to the mine spaces and the thin intermediate protective layer, pose a potential risk of water infiltration into the underground spaces [9,10].

Most of the hydrogeological activity takes place in dolomites and limestones of the Middle and Upper Triassic, which are generally very permeable aquifers. The lower Triad layers are less or poorly permeable, as well-permeable layers of limestone and dolomite alternate with intervening poorly or impermeable layers of marl or clay. However, they still represent an aquifer, which is dangerous for the intrusion of water into underground lines and excavation areas.

In the area of the Škale mine, there is the greatest risk of infiltration of triadic aquifers, as the overlying layer lies directly on the triadic aquifers in some places or is only separated from the triadic aquifers by a protective layer of clay a few meters thick.

In the north, the Triad aquifers are bounded by Permo–Carboniferous strata; in the south, the boundary is a fault or the so-called Triad sill, which separates the Triad and Tertiary layers. In the east, the boundary is formed by the area where the Triad aquifers are in direct contact with the Paka river [11]. In the west, the boundary is less clear.

1.2.3. Lithotamnian Limestone

In the bedrock of the northern part of the Preloge mine, south of the Velenje fault, there are water-bearing layers of lithotamnian limestone dating from the Oligocene and Miocene. They are separated from the overlying layer by a thin insulating layer but are still in direct contact with the overlying layer in some places.

2. Materials and Methods

2.1. Hydrogeological Preparation of the Excavation Field

At the Velenje coal mine, mining coal under aquifers with a thin insulating layer of clay requires thorough hydrogeological preparation. This includes preliminary investigations, preparation of mathematical models [12], forecasts, definition of drainage systems and monitoring. Based on the data obtained, optimal project solutions can be determined and safe excavation under aquifers can be ensured. The problems that can arise when digging under aquifers can be divided into the following three groups:

- problems related to the prevention of water penetration from the overburden, especially in the area of the relatively thin roof insulating layer of clay;
- problems related to the prevention of water penetration from the bedrock;
- problems related to the prevention of water penetration from the bedrock represented by water-bearing bedrock sands and sands reaching the coal layer (interlayer sands).

For the successful and economic extraction of coal under the aquifers, special consideration must be given to all the aquifers listed from the point of view of protection against the intrusion of water, mud and silt. In addition to hydrogeological investigations, geological and geomechanical investigations of the area are also important for the design of a new excavation field [13–15].

Data collection in this study was carried out in the following manner:

- Structural drilling in the area of the planned excavation front to determine the quality and thickness of the insulation layer;
- Installation of piezometers in the area of the planned excavation front and installation of pressure sensors for pressure measurement;
- Checking and recording data on the water status at existing measuring points in underground spaces that are part of the hydrogeological network.

All hydrogeological work serves as a basis for planning solutions. A schematic representation of the hydrogeological activities required when planning a new excavation field can be seen in the organization chart Figure 3.

2.2. Criteria for Safe Mining under Aquifers

Following extensive and demanding investigations into geological, hydrogeological, geomechanical and mining parameters and analyses of water and silt intrusions, criteria for safe extraction have been established to date, which are being verified by additional analyses at individual excavations [16].

On the basis of extensive in situ investigations (expansion of the demolition zone, changes in the stress deformation field and changes in the properties of the rocks involved in the demolition), it was found that the maximum height of direct demolition, measured from the level of the excavation, is 2.2 to 2.5 excavation heights in overcast wide-faced mining and 1.5 to 2.0 excavation heights in wide-faced excavation. The consolidation process is longest under fresh overburden and shortest in classic excavations with vertical concentration and under several levels. Measurements of water permeability with water injection showed that the water permeability of the old part (old works) drops below 10–4 m/s just three excavation heights after excavation and to 10^{-9} m/s just seven excavation heights after excavation. In the zone before and above the excavation, the clay is practically impermeable to water.

2.2.1. Excavation under Overburden Aquifer Layers

The criteria for the safe mining of coal under aquifers are based on research into geological, hydrogeological, geomechanical and mining parameters as well as on the analysis of previous water and silt intrusions into excavations [17]. The sum of these efforts is a proposal for determining the height of excavation depending on the thickness of the insulating clay layer between the lignite layer and the overburden sand, the water pressure in the nearby sandy aquifers, the depth of excavation and technological requirements or conditions of excavation. The calculated depressions in the overburden aquifers are shown in Figure 4.

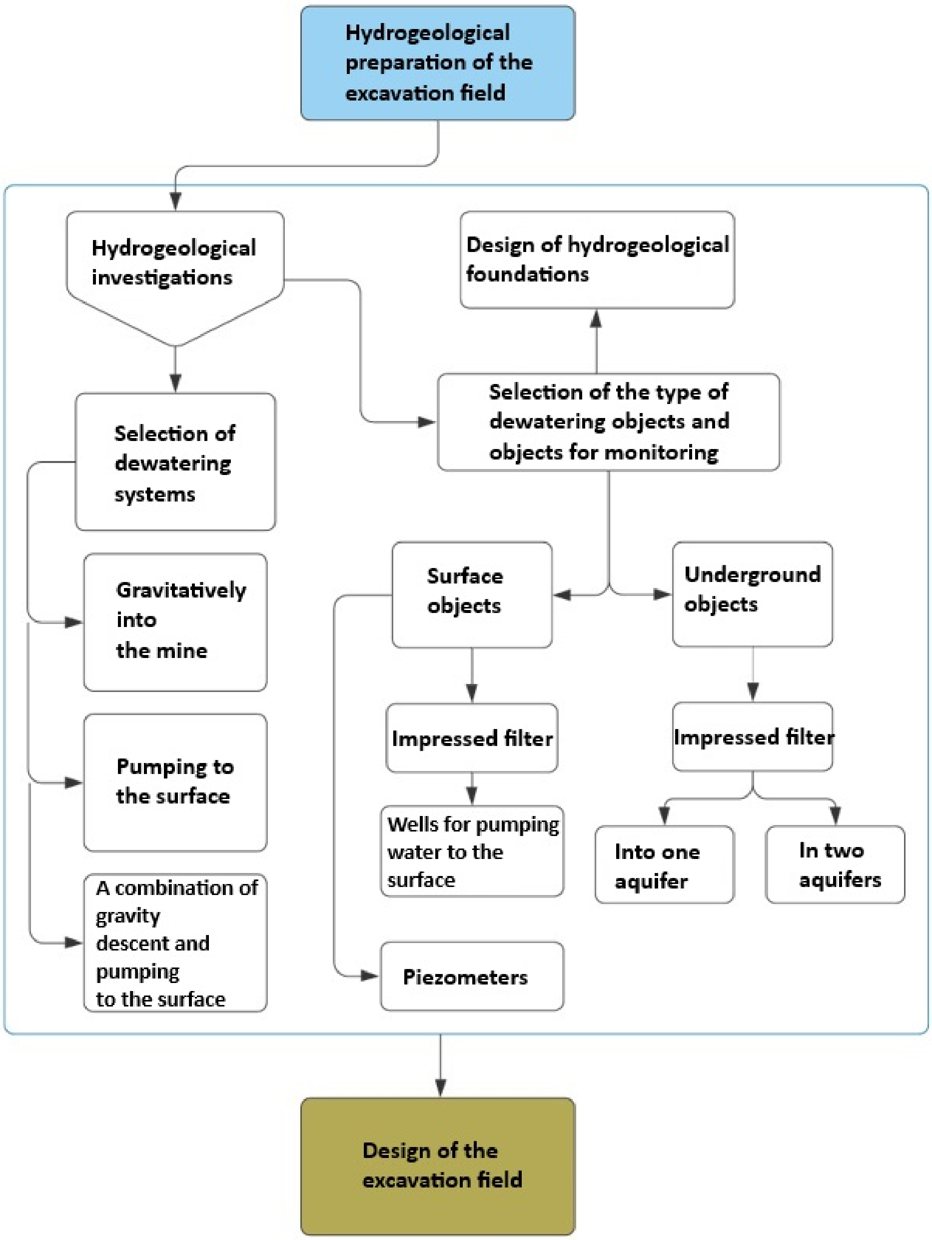

Figure 3. Hydrogeological activities for the design of a new excavation field.

Here it is possible to move the excavation deeper into the coal layer so that the direct demolition does not or only partially covers the clay layer between the coal and the sand. This causes the coal to collapse and the clay layer to gradually settle.

With technological interventions, e.g., the laying of a net on the excavation area, such excavation heights of the lower floors that correspond to the given hydrogeological conditions are also ensured in these cases. The excavation conditions, such as excavation height, water pressure in the sands and position of the excavation in relation to the overburden, are determined analytically from the equilibrium state between the load on the clay layer with irrigated sands and its own weight and the shear resistance of the clay along the vertical surfaces above the conditionally unsupported part of the ceiling in the space behind the excavation, which has plan dimensions.

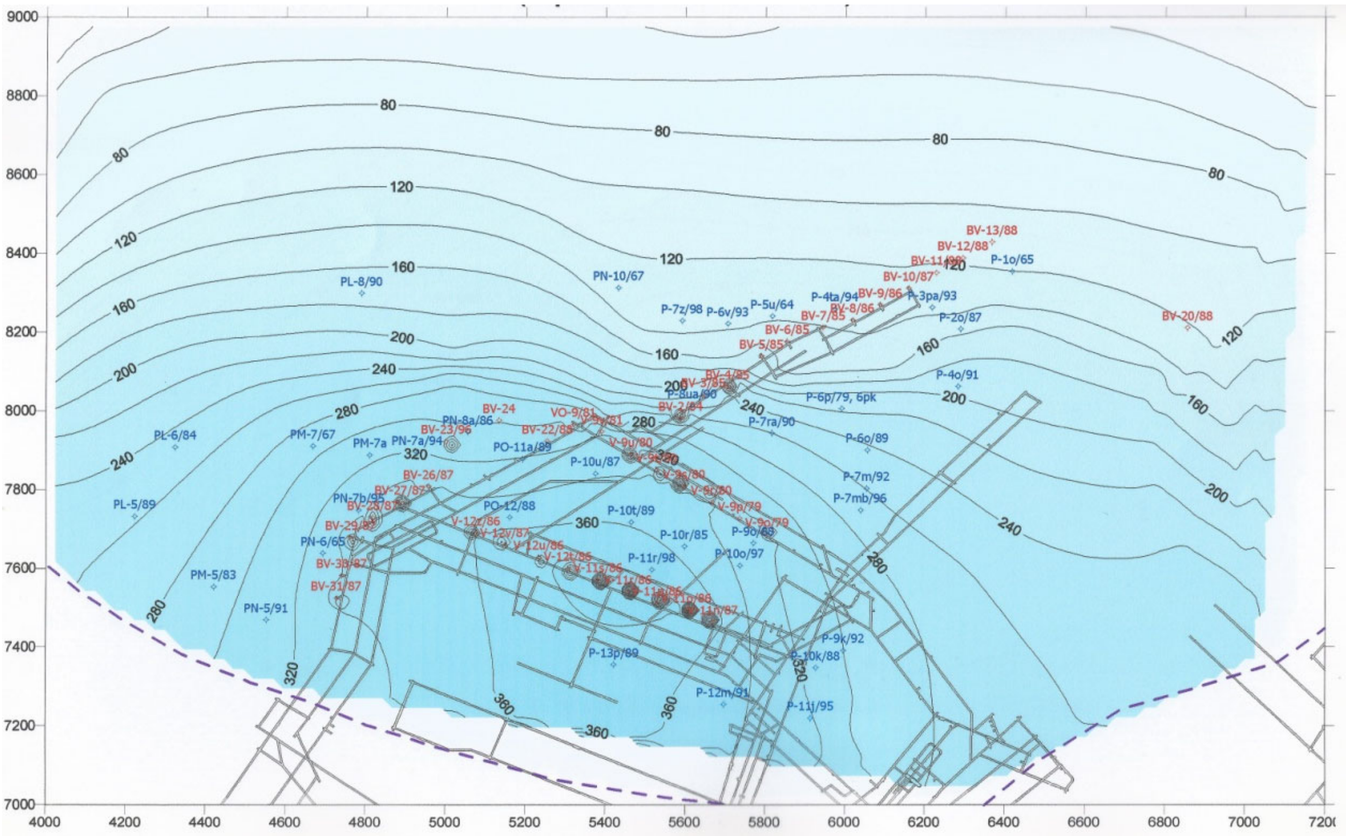

Figure 4. Calculated depressions in overburden aquifers.

2.2.2. Excavation under Surface Water Reservoirs

Exploratory drilling from the surface revealed that the bottoms of the lakes in the Velenje basin are practically impermeable. With multiple collapses, the maximum possible depth of the crack is 21 m, and deeper deformations are plastic [11].

For safe excavation under lakes, there must be a sufficiently thick clay layer between the demolition zone above the excavation and the surface demolition zone, which is determined in the same way as according to the criteria for excavation under overburden sands. The thickness of the layer between the bottom of the lake and the excavation field is therefore the sum of the calculated thickness of the protective layer and the depth of the collapse zone at the surface. In this way, the minimum excavation depth is determined to ensure safe excavation.

As far as the geological and hydrogeological conditions are concerned, these are met everywhere in the Velenje mining area, as the excavation depths are significantly greater than calculated. There is no need to pump water from surface accumulations or fill lakes.

2.3. Drainage Systems

As we mentioned earlier, water intrusion into open underground areas is a major hazard both to the health of workers and to the equipment, and this makes mining difficult. In places where the insulating clay layer is thinner, this danger is even greater, as well as under aquifers when the pressure reaches high levels. For this purpose and to improve the economic efficiency of mining (higher excavation heights), it is necessary to carry out dewatering measures. Three dewatering systems are used at the Velenje coal mine (Figure 5):

- gravity descent of water into the open underground areas (through hanging and impression filters) and conveyance to the surface via underground pumping stations and pipelines;
- direct pumping of water to the surface via wells;
- a combination of both.

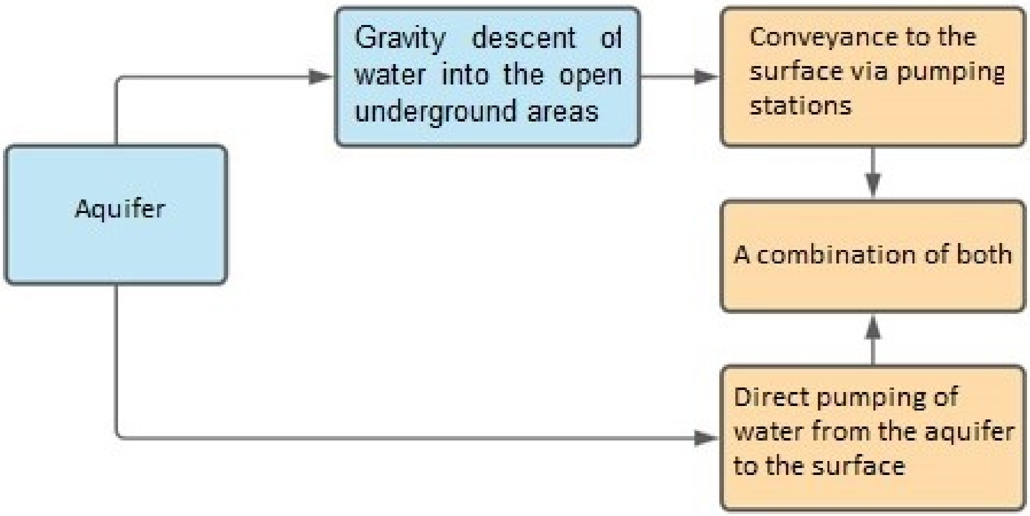

Figure 5. Scheme of the drainage systems.

System of Gravity Lowering Water into the Open Underground Areas

For the selection of a system using drainage technology with hanging filters, we can consider the optimal model of pumping water into the underground areas and then from the main underground pumping station to the surface, as gravity drainage of water from the overburden aquifers through the hanging filters into the underground spaces is the optimal drainage method. With gravity drainage into the open areas, we avoid the cost of constructing a new drainage network required for direct pumping to the surface. At the Velenje coal mine, the water-bearing sands are no longer dewatered using the technology of pumping from dewatering wells.

According to the criteria for safe excavation under aquifers, requirements for the degree of drainage of the aquifer are imposed before excavation of individual areas, and in the hydrogeological part of the project, the micro-locations of individual impression filters must be processed. These must be determined in such a way that the conditions for safe mining are met even before excavation begins.

In the Velenje coal mine, there are three typical examples of the installation of impressed filters (Figure 6):

- in the overburden sands;
- bedrock aquifers;
- interbedded sands.

The drainage system of an individual excavation field is determined on the basis of previous hydrogeological investigations, the observation system and the hydrological modeling of the excavation field. The preparations and procedures for the dewatering of each excavation field are adapted to the local conditions of the coal seam and the risk assessment. For this reason, the procedures are not standardized with regard to uniform measures for the entire coal mine.

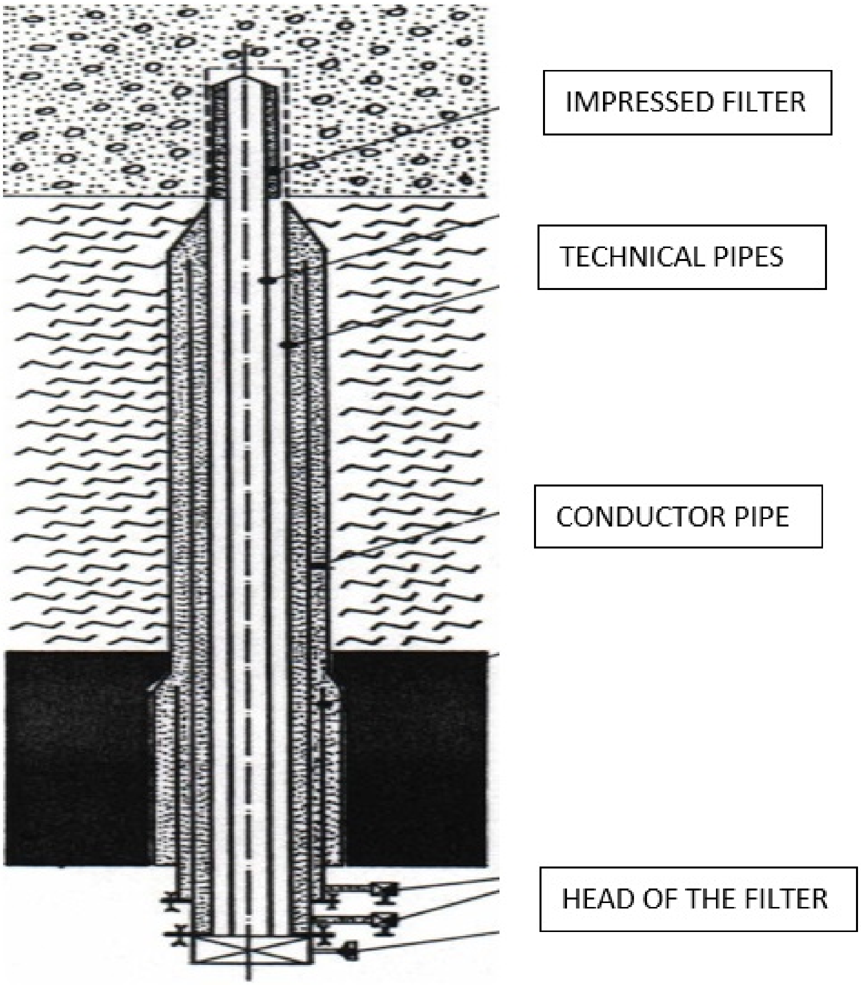

Figure 6. An impressed filter.

3. Results with Discussion

3.1. Groundwater Level Measurement

Piezometric wells are used to measure the underground water level or pressure in aquifers. Changes in water pressure in aquifers provide information on whether the strata are draining properly (Figure 7). The results obtained are compared using the observation network of piezometric wells [18]. In this way, the suitability of a single piezometer can also be verified. The piezometers for monitoring the water level in the aquifers are produced in the Velenje coal mine area during the whole period of the coal mine operation. Some of them are already worn out and do not show realistic results according to the monitoring network. Since it is necessary to monitor the hydrogeological conditions of the area, it is necessary to replace worn piezometers with new ones.

Water Level in the Sands of Pl_1 Just above the Coal

In addition to the lower level of the water-bearing sands above the coal, the water level in these layers is also required to calculate the pressure. The data on the groundwater level were obtained from piezometric wells covering the Pl1 aquifer. In addition to the piezometric wells, it was taken into account that the borehole for the impressed filters at level G4/C was dry, which means that there was no water in this area. Table 1 shows the values of the results obtained from the piezometric wells.

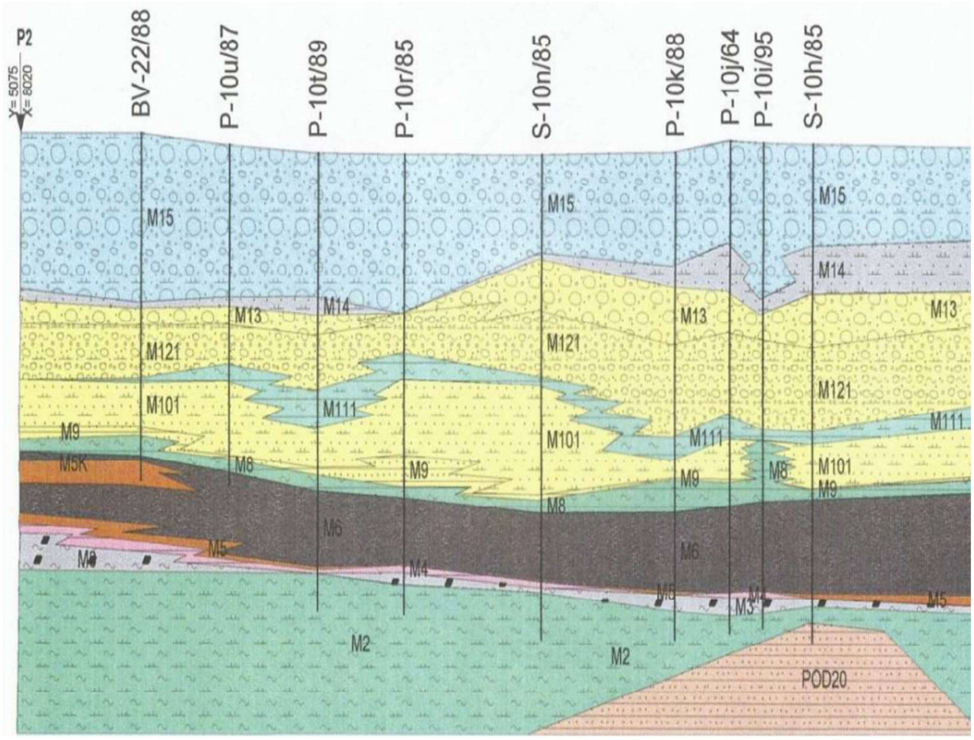

Figure 7. Part of the piezometer network of Velenje coal mine.

Table 1. Data obtained from piezometric wells.

Name	Type	Y	X	Z	Level (Z)	Level (Measured from the Wellhead)
P-0m/90	PL1	506695.43	138415.75	432.04	197.68	234.35 m
P-1o/65	PL1	506418.72	138355.52	400.51	160.73	239.78 m
PB-5/86	PL1	502332.49	139346.69	366.37	335.26	31.11 m
PD-6/83	PL1	502873.40	139261.00	362.53	323.77	38.76 m
PF-6/83	PL1	503236.48	138864.09	359.68	270.26	89.42 m
PG-5/84	PL1	503263.43	138573.10	358.02	258.65	99.37 m
PG-6/89	PL1	503430.35	138736.29	361.64	265.89	95.75 m
PI-5/82	PL1	503598.38	138236.30	400.43	234.11	166.32 m
PI-7/91	PL1	503961.23	138675.94	401.65	257.93	143.72 m
PM-5a/05	PL1	504414.91	137568.77	401.26	229.27	171.99 m
PM-7/67	PL1	504669.05	137911.47	373.17	97.09	276.08 m
PM-7a/01	PL1	504811.37	137888.62	412.07	144.86	267.21 m
PM-8a/04	PL1	504760.65	138104.82	362.99	117.49	245.50 m

The last column shows the water level values measured at the wellhead. Wellhead level values are also known. If the information on the underground water level measured at the wellhead is subtracted from the Z coordinate of the well, the height at which the underground water is located in the Pl1 aquifer is obtained.

In addition to the water level data obtained from the piezometric wells, the values obtained from the impressed filters were also taken into account. It is known that the wells that penetrated the first sands above the coal did not reach a water level above the overburden. From this, it can be concluded that there is no water level in these locations.

For safety reasons, we nevertheless considered that there was water at a pressure of 1.5 bar at these locations, which corresponded to a water column of 15 m. To obtain information about the water levels on the impressed filters, 15 m of water column must be added to the lower levels of the sands above the coal. The lower sand levels and the calculated water levels are listed in Table 2.

Table 2. Water level into the impressed filters.

Name	jv3603	jv3604	jv3605	jv3606	jv3607	jv3608	jv3610	jv3611	jv3612	jv3613	jv3614	jv3615	jv3616
Sand level	−33.9	−22.2	−11.2	7.9	29.1	49.2	72.2	45.6	29.5	4.5	−23.3	−33.8	−45.3
Water level	−18.9	−7.2	3.8	22.9	44.1	64.2	87.2	60.6	44.5	19.5	−8.3	−18.8	−30.3

Using the Surfer software, we created a new network from the data of the piezometric wells and impressed filters and then contours showing the groundwater levels in the sands of the aquifer directly above the coal.

One of the parameters for calculating the pressure values (Figure 8a,b) is the lower level of the water-bearing sands above the coal. We obtained this information with the help of boreholes drilled at the intact boundary between the first sands above the coal and the insulating clay layer. They were made before coal mining began, both from the surface and from underground spaces, and show the intact state of the area. Using the data obtained from the wells that crossed the intact boundary, a network of the lower level of the aquifer sands above the coal was then created using the Surfer software. Based on the data from the research wells, the program provided the lower level of the sands in the form of a grid with points spaced 25 m apart in X and Y values. The X and Y values represent the coordinates of the point and the Z value, in this case, the lower level of the first sands above the coal.

In determining the required number of piezometer observation points, the aquifers were divided into the following categories based on the hydrodynamic character of the observed aquifer system:

1. aquifers with low permeability to semipermeable (k = 10^{-6}–10^{-8} m/s);
2. aquifers with good permeability (k = 10^{-4}–10^{-5} m/s);
3. aquifers with a heterogeneous structure.

As can be seen in Figure 8a,b, pressures in area G4/C rarely exceeded 3 bar, indicating intensive drainage in the past. Low pressures imply favorable conditions for excavation because the probability of water intrusion is therefore unlikely. The model of expected pressures using the Surfer program showed very good agreement with the measured groundwater levels from the piezometers. The calculations are crucial for the design of the excavation heights [3,12,19].

The permissible excavation heights for an excavation 450 m to 500 m below the surface are listed in Table 3. As can be seen from the table, the excavation heights increased in proportion to the thickness of the insulating layer and inversely proportional to the water pressure in the aquifers. In other words, as the water pressure increased, the permissible excavation heights decreased, which means that the water pressure in the first sands may have to be reduced by dewatering in order to achieve greater excavation heights.

The results obtained are the result of modeling based on measurements and historical data. Of course, we cannot be satisfied with the results obtained, as this represents a safety risk. The results obtained provide us with a fairly reliable basis for the prediction and simulation of hydrostatic pressures above excavation fields, the determination of the safe height of the excavation front and the safe thickness of the insulation layer. Measurements during excavation and real-time data accumulation will provide a feedback analysis for the current real-time adjustment of excavation front parameters and future data collection for excavation fronts which are to be realized in the immediate vicinity in the future.

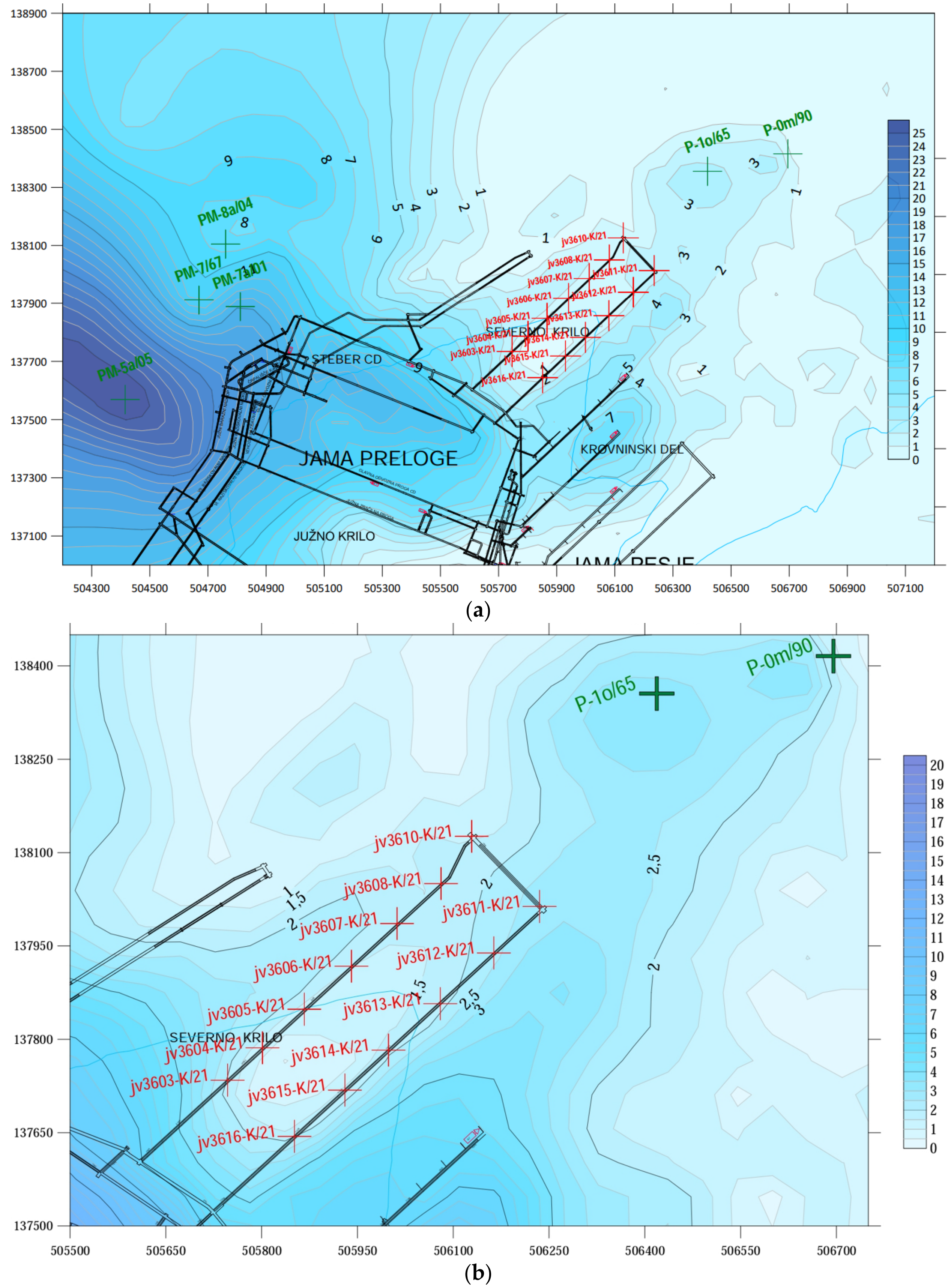

Figure 8. (**a**) Hydrostatic pressures above the excavation field. (**b**) Hydrostatic pressures above the excavation field.

Table 3. Permissible excavation heights at a certain water pressure and a certain thickness of the insulation layer.

Thickness of the Insulation Layer (Hg) (m)	Water Pressure on the Insulating Layer (pw) (bar)												Max. Water Pressure (bar)
	2	4	6	8	10	15	20	25	30	35	40	45	
	Permitted Excavation Height (V) (m)												
1	1.7	1.4	1.1	0.9	0.8	0.6	0.5	0.4	0.3	0.3	0.2	0.2	44.8
2	3.1	2.5	2.1	1.8	1.5	1.2	0.9	0.8	0.6	0.6	0.5	0.4	44.7
3	4.3	3.5	3	2.6	2.3	1.7	1.4	1.1	1	0.8	0.7	0.7	44.5
4	5.3	4.5	3.8	3.3	2.9	2.3	1.8	1.5	1.3	1.1	1	0.9	44.4
5	6.3	5.4	4.6	4.1	3.6	2.8	2.3	1.9	1.6	1.4	1.2	1.1	44.2
6	7.1	6.2	5.4	4.8	4.2	3.3	2.7	2.3	1.9	1.7	1.5	1.4	44.1
7	7.9	6.9	6.1	5.4	4.9	3.8	3.1	2.6	2.3	2	1.8	1.6	34.9
8	8.7	7.7	6.8	6.1	5.5	4.3	3.6	3	2.6	2.3	2	1.9	43.7
9	9.4	8.4	7.5	6.7	6	4.8	4	3.4	2.9	2.6	2.3	2.1	43.6
10	10.1	9	8.1	7.3	6.6	5.3	4.4	3.7	3.2	2.8	2.5	2.4	43.4
12	11.5	10.3	9.3	8.5	7.7	6.3	5.2	4.5	3.9	3.4	3.1	2.9	43.1
14	12.7	11.5	10.5	9.6	8.8	7.2	6.1	5.2	4.5	4	3.6	3.4	42.8
16	13.9	12.7	11.6	10.6	9.8	8.1	6.9	5.9	5.2	4.6	4.1	3.9	42.4
18	15	13.8	12.7	11.7	10.8	9	7.7	6.7	5.9	5.2	4.7	4.5	42.1
20	16.1	14.8	13.7	12.7	11.8	9.9	8.5	7.4	6.5	5.8	5.2	5.1	41.7
22	17.1	15.9	14.7	13.7	12.7	10.8	9.3	8.1	7.2	6.4	5.8	5.6	41.4
24	18.1	16.9	15.7	14.6	13.7	11.7	10.1	8.9	7.9	7	6.4	6.2	41
26	19.1	17.8	16.7	15.6	14.6	12.5	10.9	9.6	8.5	7.7	6.9	6.8	40.7
28	20.1	18.8	17.6	16.5	15.5	13.4	11.7	10.3	9.2	8.3	7.5	7.5	40.3
30	21.1	19.7	18.5	17.4	16.4	14.2	12.5	11.1	9.9	8.9	8.1		40
32	22	20.7	19.4	18.3	17.3	15.1	13.3	11.8	10.6	9.6	8.8		39.6
34	22.9	21.6	20.4	19.2	18.2	15.9	14	12.5	11.3	10.2	9.4		39.2
36	23.8	22.5	21.2	20.1	19	16.7	14.8	13.3	11.9	10.8	10.1		38.9
38	24.7	23.4	22.1	21	19.9	17.6	15.6	14	12.6	11.5	10.8		38.5
40	25.6	24.2	23	21.8	20.8	18.4	16.4	14.7	13.3	12.1	11.5		38.1
45	27.7	26.4	25.1	24	22.9	20.4	18.3	16.5	15	13.8	13.2		37.2
50	29.9	28.5	27.2	26	24.9	22.4	20.2	18.4	16.8	15.4	15.1		36.2

4. Conclusions

In order to prevent the intrusion of water into the working areas of the mine site, the criteria for safe excavation in the Velenje coal mine under aquifers were established. The scientific research approach to determining the criteria for safe mining enables the safety and determination of excavation heights in coal mining.

The Surfer software was used to model the parameters required for further calculation of the excavation height on the floors. Many boreholes drilled to dewater and obtain data about the area did not reach the sand layers above the coal, so we had to refer to the intact state of the area prior to mining. The intact state of the lower sand layer above the coal had to be brought up to date by subtracting the excavation heights of the floors that were operated in the past in the area of the north wing of the Preloge mine. This was carried out with the help of the Surfer software. In addition to the lower level of the sands, data on the water levels in these sands also had to be determined in order to calculate the pressures. The data originated from piezometric wells in the area of the north wing of the Preloge mine and from impressed filters that were made before the start of the excavation of the G4/C mining field.

The article describes the criteria for safe digging under aquifers, the types of drainage systems, which are divided into gravity-lowering water into the underground spaces and pumping water directly to the surface, and the behavior of water pressure below the surface. It also describes how underground wells are built and why they are used. They are important for obtaining the parameters required for the design of the excavation field and dewatering. The most important parameters for determining the criteria for safe excavation are the water pressure in the first sands, the excavation depth below the surface, the thickness of the insulating layer and the excavation method or the course of the demolition processes. Modeling with the Surfer software enabled the researchers to plan the excavation heights in advance. The modeling of the expected pressures with the Surfer software showed very good accuracy with the measured groundwater levels from the piezometers.

Using modeling based on the data obtained from the observation network and the historical data of excavations already carried out, a correct estimate of the permissible excavation heights can be made for each insulation layer thickness at a known pressure, as shown in Table 3. This allows the excavation limit to be adjusted in advance in order to optimize and determine the amount of coal extracted while ensuring safe excavation.

Author Contributions: Conceptualization, Ž.V. and J.Š.; methodology, Ž.V. and J.Š.; software, J.Š.; validation, Ž.V.; formal analysis, Ž.V. and J.Š.; investigation, Ž.V. and J.Š.; resources, Ž.V. and J.Š.; data curation, Ž.V. and J.Š.; writing—original draft preparation, Ž.V.; writing—review and editing, J.Š.; visualization, J.Š.; supervision, Ž.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to specificity and comprehensiveness.

Conflicts of Interest: The authors declare no conflicts of interest.

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