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Cost Analysis in the Construction of Underground Mining Structures and Opportunities for Their Reduction

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Abstract
The construction of underground mining facilities is of essential importance to the exploitation of mineral resources. Confirmation of this is the fact that construction costs of main mining facilities occupy 40 -60% of the underlying investments in mine construction and equipping. The main underground mining facilities are: shafts, drifts, raise, pump chambers, warehouses etc. This paper presents a detailed analysis of an underground mining facility - drift construction costs per individual working operations, following their change which depends on the rock type and profile size of the underground mining facility, as well as possibilities for reducing these costs.

Keywords
Underground exploitation, drift construction costs, construction of drift.

1. Introduction

The construction of underground mining workings, including horizontal mining facilities, presents a complex system of many interdependent elements, such as:

- rock type
- depth of the horizontal facility;
- profile size;
- cross-sectional shape;
- construction technology;
- work organization;
- energy supply and others.

The project of constructing mining facilities sets requirements relating to the speed, quality and costs of construction per 1 m' (Doneva et al, 2011). If construction technology is adopted, then rock type and cross-section - profile present the most influential factors in mining workings costs.

The analysis that has been conducted in this paper is based on the results of extensive scientific research (Doneva, 2011). This research has been extended to the analysis of individual work operation costs, and the change of their share of the total costs, with the changing rock type and profile size of the underground facility. Also, several opportunities in terms of reducing the amount of horizontal mining workings construction are proposed.

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2. Tools and techniques to estimate costs

The estimate costs process develops a cost estimate for the resources (human and material) required for each schedule activity.

The estimation of costs has more tools and techniques used to derive estimates:

- Expert judgment
- Analogous estimating
- Parametric estimating
- Bottom-up estimating
- Three-point estimate
- Reserve analysis
- Cost of quality
- Project management estimating software
- Vendor bid analysis

The bottom - up estimating is the technique that is used to estimate the costs in this paper.

This technique estimates costs associated with every activity individually and then rolls them up to derive a total project cost estimate. Bottom-up estimating will generally provide you with the most accurate cost estimates, but it is the most time-consuming estimating technique of all those mentioned here. However, the size and complexity of the project impacts the accuracy you can achieve using this technique.

2.1. Input system parameters

Listed below are the rock types in which the mining facility construction will be performed:

- massive lead-zinc ore,
- gneiss and
- schist

Table 1 shows physical and mechanical properties obtained by laboratory tests that are required for this survey as follows: bulk density γ [t/m^3], uniaxial compressive strength σ_c [MPa], tensile strength σ_t [MPa], cohesion C [MPa], angle of internal friction φ [°], Poisson`s coefficient ν and modulus of elasticity E [MPa].

Table 1: *Physical and mechanical* properties *of the adopted rocks type*

Rock type	γ [t/m^3]	σ_c [MPa]	σ_t [MPa]	C [MPa]	φ [°]	ν	E [MPa]	Tag of rocks type
Lead and zink ore	3.77	142	17.00	28.50	46.50	0.245	69500	**A**
Gneiss	2.75	127	14.50	20.50	37.50	0.170	42000	**B**
Schist	2.70	98	6.10	14.00	32.00	0.120	32000	**C**

For each of these rock types Bieniawski classification has been made, depending on the conditions in this quasi homogeneous zone in terms of the cracks, the ground water, discontinuities etc. The lead-zinc ore and gneisses are classified in II class of rock material, and schist in class III **(Bieniawski, 1989; Cummings, 1982; Doneva et al, 2013)**.

The analysis of construction costs for adopted rock type have been made for capital drifts with cross-section dimensions shown in Table 2, so we get 9 variants of underground facilities **(Doneva, 2011)**.

Table 2: *Standard of the size of cross section with horse-shoe shaped: МКС Б. М2 (Macedonian standard)*

Width B [mm]	Height H [mm]	Height of vertical side H_1 [mm]	Radius R [mm]	Cross-section area S [m^2]	Tag of size cross area
3200	3500	1900	1600	10.10	**1**
3600	4200	2400	1800	13.73	**2**
4000	4600	2600	2000	16.68	**3**

Construction system includes these fixed parameters:

- cross-sectional shape of the mining facilities – horse – shoe shaped;
- the average depth of the same route - 500 m;
- usage of the mining facility – 15 to 20 years;
- method for excavation of the mining facilities – drilling and blasting operations.

2.2. Technology of drift construction

Drilling and blasting technology is applied as the technology for the construction of all drift variants.

In all variants, blasting holes with diameter of 45 mm and length of 2.7 m were applied. Advance length for one blasting was 2,3 m.

Prismatic cut type with empty central hole was applied. Explosive AMONEKS-3, produced by "Trayal" Corporation of Krusevac, Serbia were used for blasting. Cartridges with a 38 mm diameter were used for auxiliary and cut holes, while for flanking blast holes, cartridges with a 28 mm diameter were used. Calculations for required time, drilling and blasting parameters are performed using the same formulas and reviewed by using experienced data (for all working operations and all variants).

After drilling and blasting, a break of 30 minutes follows (adopted time for all variants) when compression LVS (local ventilation system) is used for releasing the dust from the workplace and harmful gases from the blasting. Ventilation wages are not included because they present a part of general mine working.

Diesel mechanization, a combination of LHD machines and mine trucks, will be used for loading and transportation.

For all drifts variants under consideration, an average transport distance of 800 m for underground trucks and 100 m for the LHD machines is adopted because every 200 m, reloading chambers are proposed . **Table 3** shows applied loading and hauling machinery depending on the size cross area and the dimensions of machines.

Table 3: *Type and capacity of applied loading and hauling machinery*

Tag of size cross area	Type of LHD machines	Capacity of LHD machines [t]	Type of mine tracks	Capacity of mine tracks [t]
1	ST 2G (Atlas Copco)	3,6	Sandvik 417	15,4
2	S7 LP (Atlas Copco)	6,8	MT 2010 (Atlas Copco)	20
3	R1600 G (Caterpillar)	10,2	AD 30 Caterpillar	30

Elastic support will be applied (sprayed concrete + steel mesh + bolts + steel ribs). The presence of individual support elements depends on calculations for required support loads, bearing in mind rock type features **(Jovnovic, 1994)**.

Based on a previously established methodology, the costs for any working operation are calculated, using empirical formulas and experience data from the lead and zinc "Sasa" mine, M.Kamenica.

Table 4 shows the important calculated parameters for all basic work operations.

3. Results of cost analysis

As shown in the table (**Table 5**) the main working operations costs are: drilling and blasting, ventilation, loading and transportation, supporting and total construction costs **(Doneva, 2011)**.

Table 4: Important calculated parameters for all basic work operations

The parameters for all basic work operations	Variants								
	A			B			C		
	Sub-variants			Sub-variants			Sub-variants		
	A1	A2	A3	B1	B2	B3	C1	C2	C3
The parameters for drilling and blasting									
Number of blast holes	33	39	46	29	33	40	19	21	27
Number of cuts blast holes	8	8	8	6	6	6	4	4	4
Time for drilling and blasting per 1 m' drift [h/m']	1.94	2.20	2.50	1.77	1.94	2.24	1.3	1.38	1.63
Quantity of explosive per one blasting [kg]	62.40	75.20	90.50	54.60	61.30	77.70	32.90	40.70	45.00
Normative of wages [wages/m']	0.97	1.1	1.25	0.89	0.97	1.12	0.65	0.69	0.81
The parameters for ventilation									
Fan type Zitron 7-30/2 [piece]	1	1	2	1	1	2	1	1	2
Power of electric motor of the fan [kW]	30	30	2 x 30	30	30	2 x 30	30	30	2 x 30
Flow fan - Q_v [m^3/s]	9,3	12	22	9,3	12	22	9,3	12	22
Air quantity of work face – Q_e [m^3/s]	8,86	11,74	20,98	8,86	11,74	20,98	8,86	11,74	20,98
Diameter of pipeline - d [m]	0,7	1	1,2	0,7	1	1,2	0,7	1	1,2
The parameters for loading and hauling									
Volume of the bulk material from one blasting [m^3]	36.6	50.0	60.4	36.6	50.0	60.4	36.6	50.0	60.4
Material weight of one blasting [t]	92.0	125.2	152	67.10	91.30	110.83	60.5	82.24	100.0
Time for loading and hauling material per one blasting with load haul dump machine [h]	1.5	1.43	0.98	1.32	1.29	0.84	1.11	1.05	0.73
Time for hauling material per one blasting with mine track [h]	1.73	1.92	1.48	1.50	1.70	1.26	1.26	1.42	1.1
Total time for loading and hauling per 1 m' drift [h/m']	1.4	1.47	1.09	1.22	1.30	0.91	1.04	1.08	0.78
Normative of wages [wages/m']	0.47	0.49	0.36	0.41	0.49	0.3	0.34	0.36	0.26
The parameters for supporting									
Total thickness of shotcrete layer [m]	0.03	0.03	0.03	0.07	0.07	0.07	0.14	0.14	0.14
Usage of cement per 1 m' drift [kg/m']	110	127	140	257	297	327	513	593	655
Usage of sand per 1 m' drift [m^3/m']	0.31	0.35	0.39	0.72	0.83	0.91	1.43	1.66	1.83
Usage of accelerator per 1 m' drift [kg/m']	6	7	7	13	15	17	26	30	34
Usage of steel grid per 1 m' drift [kg/m']	/	/	/	20.39	23.56	26.02	20.39	23.56	26.02
Usage of bolts per 1 m' drift [n/m']	/	/	/	4	5	6	9	10	11
Usage of steel ribs per 1 m' drift [kg/m']	/	/	/	/	/	/	73	84.9	93.7
Total time of supporting per 1 m' [h/m']	0.34	0.37	0.39	1.5	1.6	1.7	4.7	5.0	5.2
Normative of wages [wages/m']	0.17	0.18	0.20	0.73	0.8	0.86	2.36	2.49	2.59
Total time for construction 1 m' drift [h/m']	4,18	4,54	4,48	4,99	5,34	5,35	4,54	7,96	8,11

Table 5: Total construction costs

Total construction costs [€/m']		Variants								
		A			B			C		
		Sub-variants			Sub-variants			Sub-variants		
		A1	A2	A3	B1	B2	B3	C1	C2	C3
Costs for drilling and blasting										
Costs for materials and energy		90.51	108.4	118.4	93.66	98.61	109.5	80.05	84.69	89.63
Costs for wages		38.87	43.91	49.91	35.48	38.87	44.87	26.17	27.65	32.52
Cost of means for work	Costs for maintenance	0.63	0.82	0.58	0.58	0.74	0.84	0.44	0.54	0.62
	Costs for amortization	12.59	16.40	11.59	11.59	14.70	16.72	8.76	10.73	12.34
	Costs for insurance	0.13	0.16	0.12	0.12	0.15	0.17	0.09	0.11	0.12
Total		**151.5**	**169.4**	**187.9**	**141.4**	**153.1**	**172.1**	**115.6**	**123.7**	**135.2**
Costs of ventilation										
Costs for materials and energy		14.94	20.55	32.7	15.83	21.45	34.80	18.91	24.52	41.25
Costs for wages		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cost of means for work	Costs for maintenance	0.05	0.1	0.06	0.06	0.06	0.08	0.08	0.09	0.17
	Costs for amortization	0.96	1.04	2.05	1.11	1.20	2.40	1.62	1.71	3.47
	Costs for insurance	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.03
Total		**16.00**	**21.70**	**34.9**	**17.00**	**22.72**	**37.34**	**20.63**	**26.33**	**44.93**
Costs of loading and hauling										
Costs for materials and energy		77.24	77.24	77.24	77.24	77.24	77.24	77.24	77.24	77.24
Costs for wages		18.70	19.45	14.26	16.36	17.16	12.16	13.72	14.37	10.55
Cost of means for work	Costs for maintenance	0.66	0.83	0.71	0.53	0.73	0.61	0.44	0.61	0.53
	Costs for amortization	12.06	16.61	14.24	10.55	14.65	12.14	8.85	12.27	10.53
	Costs for insurance	0.12	0.17	0.14	0.11	0.15	0.12	0.09	0.12	0.11
Total		**108.7**	**114.3**	**106.6**	**104.8**	**109.9**	**102.3**	**100.3**	**104.6**	**99.0**
Costs of supporting										
Costs for materials and energy		52.65	59.85	66.35	124.8	142.1	156.4	240.7	276.1	304.4
Costs for wages		6.70	7.34	7.83	29.12	32.00	34.22	94.35	99.53	103.5
Cost of means for work	Costs for maintenance	0.29	0.33	0.36	0.48	0.55	0.60	1.06	1.20	1.31
	Costs for amortization	5.71	6.60	7.29	9.61	10.98	12.04	21.20	24.00	26.16
	Costs for insurance	0.06	0.07	0.07	0.10	0.11	0.12	0.21	0.24	0.26
Total		**65.40**	**74.2**	**81.90**	**164.1**	**185.7**	**203.4**	**357.6**	**401.1**	**435.7**
Total costs for the main work operations		341.62	379.53	411.31	427.31	471.43	515.05	594.1	655.7	714.8
Costs of auxiliary work operations		34.01	34.90	37.28	42.10	45.37	49.00	57.65	63.58	68.50
Total construction costs for 1 m' horizontal mining drift		**375.63**	**414.43**	**448.60**	**469.4**	**516.8**	**564.1**	**651.74**	**719.31**	**783.27**

Costs of auxiliary work operations are adopted as 15% of the total cost of materials.

3.1. Structure of construction costs

Figure 1 shows the percentage share of individual working operations costs in the total underground drift construction costs, with 13.73 m^2 profile size, in lead-zinc ore rock type.

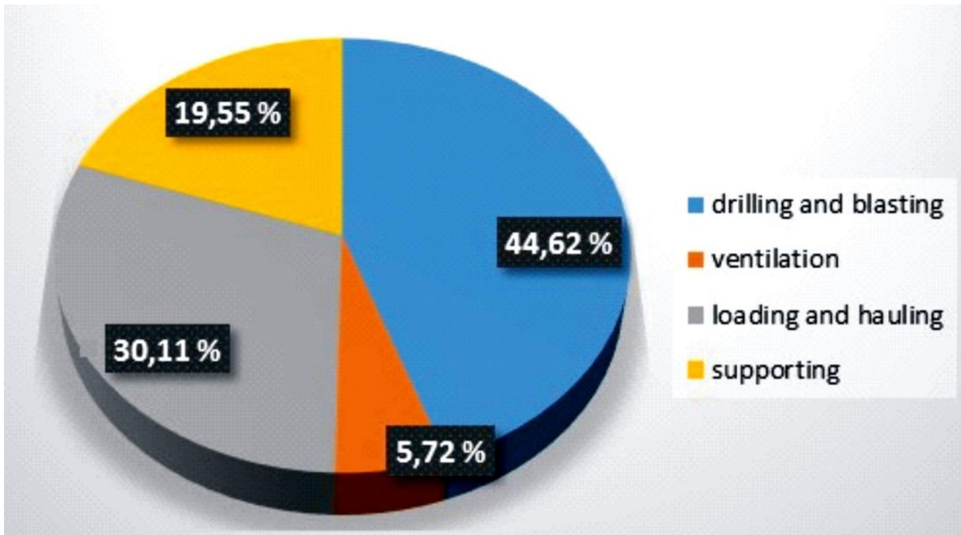

Figure 1: Share of individual working operations costs in the total underground drift construction costs in lead-zinc ore rock type

Figure 1 shows that, drilling and blasting costs, with 44.6% have the highest share in the lead-zinc ore rock type at the same cross-section size. This large percentage arises from the larger strength characteristics of this working environment. For the same reason, the supporting costs are lower (5.7%).

Figure 2 shows the percentage share of individual working operations costs in the total underground drift construction costs, with 13.73 m^2 profile size, in gneiss rock type.

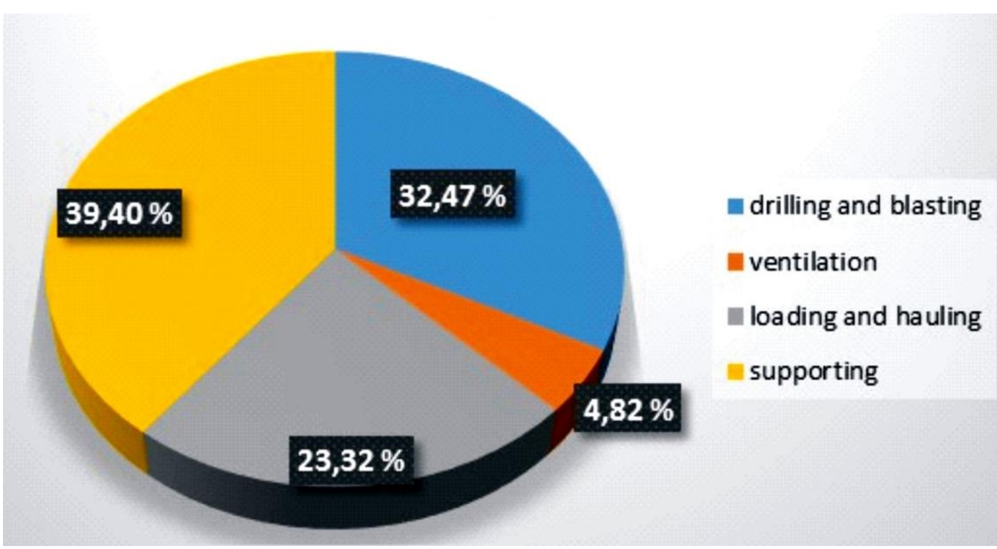

Figure 2: Share of individual working operations costs in the total underground drift construction costs, with 13.73 m^2 profile size, in gneiss rock type

Figure 2 shows that in gneiss rock type, at the same cross-section size, drilling and blasting (32.5%) and loading and transportation costs (39.4%) have a relatively uniform percentage share. Unlike the previous working environment the supporting costs rise from 5.7% to 23.3%. This increase in percentage share comes from the reduced strength characteristics of this working environment.

Figure 3 shows the percentage share of individual working operations costs in the total underground facility construction costs, with 13.73 m^2 profile size, in schist rock type.

Figure 3 shows that in schist rock type, at the same cross-section size, supporting costs (61.2%) have the highest percentage share. The large percentage arises from increased needs of support construction because of reducing strength characteristics of this working environment. Drilling and blasting (18.9%) and loading and transportation costs (16 %) have a relatively uniform percentage share.

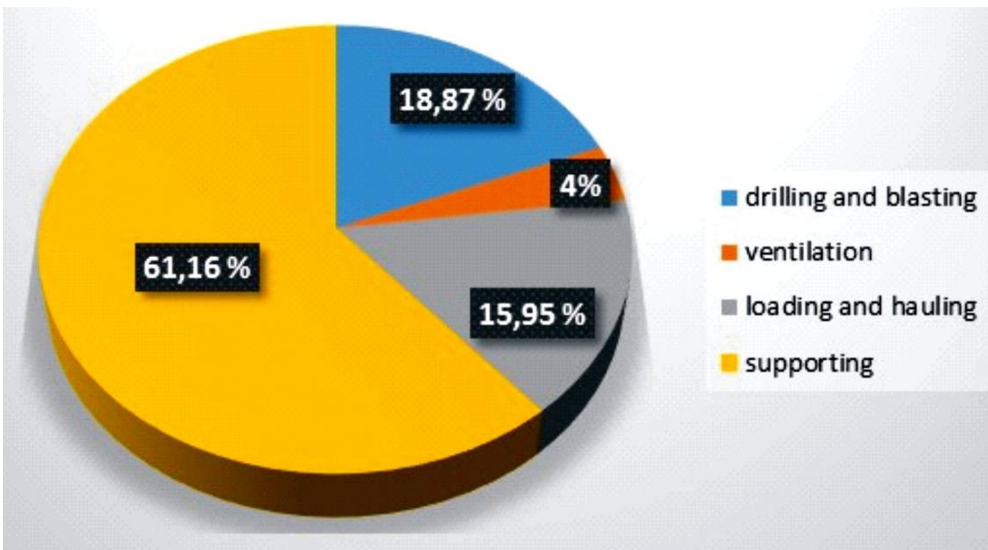

Figure 3: Share of individual working operations costs in the total underground drift construction costs, with 13,73 m^2 profile size, in schist rock type

Ventilation costs depend on the required amount of air flow on the work forehead, while the required amount of air flow depends on the amount of explosives, the profile size, engaged diesel machinery power, etc. So in terms of the same mechanization level in all variants of the same profile size, there are not significant differences in ventilation costs, and their percentage changes depend on the change in costs primarily in drilling and blasting as well as in supporting.

The same can be said for the cost of loading and transport, because in the facility with the same profile size, the same type of loading and hauling equipment has been applied, aiming for result comparison.

3.2. Dependence of the individual working operations costs from the rock type and underground facility profile size

Figure 4 shows the dependence of the drilling and blasting costs from the rock type and underground facility profile size for all variants.

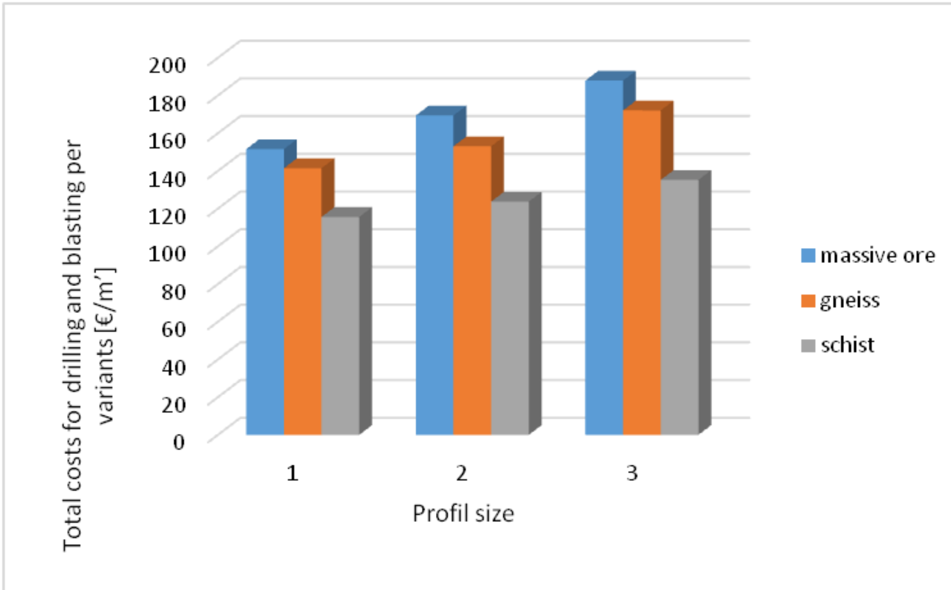

Figure 4: Total costs for drilling and blasting per variants

The analysis of drilling and blasting costs, given in **Table 5** and **Figure 4**, shows that the drilling and blasting costs are highest in the strongest working environment, lead - zinc ore. These costs at the biggest profile are increased by 31% compared with the same variant with the lowest profile in the schist working environment.

The drilling and blasting costs are decreased because the smaller requirements of weaker working environments, in terms of this working operation i.e. the number of needed holes and quantity of explosives, is lower. Within the same working environment, drilling and blasting costs grow with profile size growth, so at the biggest profile size, they are 17-23% higher (depending on working environment) than the ones with the smallest profile. Costs are increased because of profile size increases i.e. number of blast holes and quantity of explosives". **Figure 5** shows the dependence of the ventilation costs from the rock type and underground facility profile size for all variants.

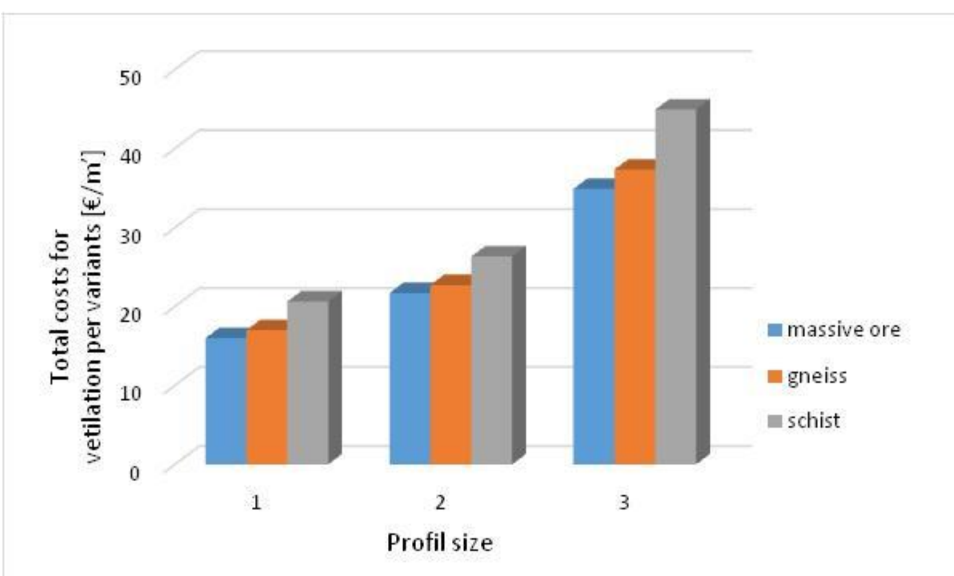

Figure 5: Total costs for ventilation per variants

During the calculation of the ventilation costs for profile 1 and 2, it should be considered that the smaller amount of fresh airflow is needed on the working face, because of the smaller cross-section, the usage of diesel machinery with less power and smaller amount of needed explosives, so fan type ZITRON 7-30 / 2 (with power of 30 W), satisfies all these variants, while profile 3 requires two parallel bound fans of the same type.

Table 5 and **Figure 5** show clearly that, because of this, the costs are highest for the largest profile - 3, and are 2.2 times larger than those for profile 1. The difference in ventilation costs between profile 1 and 2 is primarily due to longer time for preparation of 1 m 'of the facility construction (during analyzing all costs were reduced to 1 m' performed facility).

Figure 6 shows the dependence of the loading and hauling costs from the rock type and underground facility profile size for all variants.

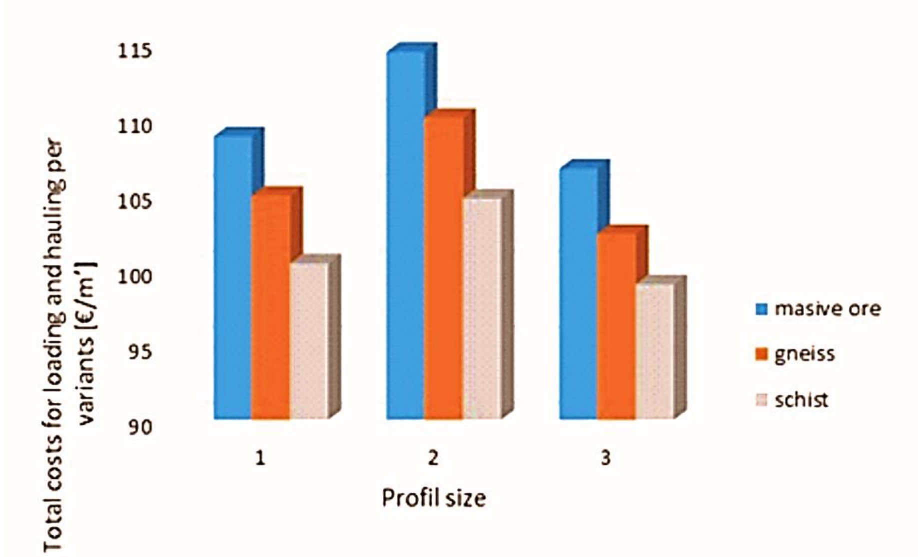

Figure 6: Total costs for loading and hauling per variants

Table 5 and **Figure 6** show that the costs for loading and hauling are relatively uniform, for all variants. Going from a working environment A to C for the same cross section size, the costs have a slight decrease because the density is largest for lead - zinc ore and smaller for schist, which affects the number of cycles required for the loading and hauling machinery.

Cost analysis of the same variant shows an increase of costs for profile 2 rather than costs for profile 1 because of a larger cross-section as well as a larger amount of blasted material. The percentage of costs increasing amounts are 4-5 % (depending on the working environment).

Some deviation occurs at profile "3" where the costs of loading and transport are decreased again, even though the amount of material that must be transported is higher, due to the considerably higher loads of the adopted loading and transport machinery. This is possible due to the larger cross section. **Figure 7** shows the dependence of the supporting costs from the rock type and underground facility profile size for all variants.

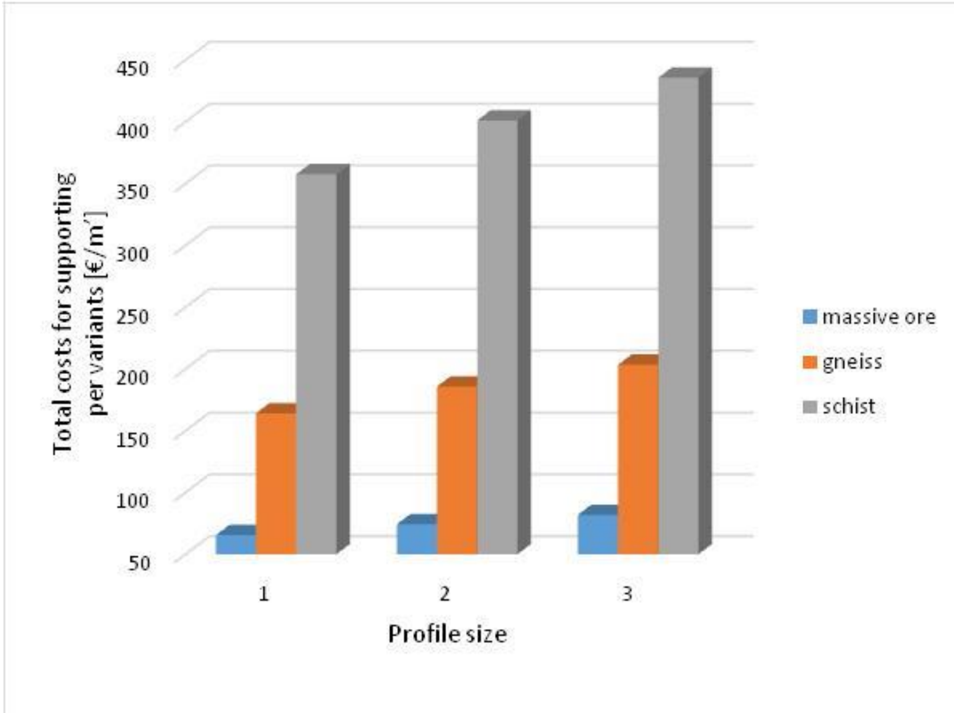

Figure 7: Total costs for supporting per variants

Table 5 and **Figure 7** show that the biggest cost variations occur at supporting due to large differences in applied supporting construction **(Doneva, 2009)**. For variants in working environment A, sprayed concrete is used as supporting material due to its higher strength features, while B variants, except sprayed concrete, the supporting construction includes rock bolts and wire mesh.

Working environment C has the extensive support system construction and consists of sprayed concrete, bolts, wire mesh and steel arches because of its weakest strength features. Supporting costs are 5.5 times larger in the weakest (C) working environment than those for the strongest (A) working environment for the same cross section **(Doneva et al, 2013)**.

Supporting costs are increased in the same working environment due to the increasing cross-section. So the costs at the largest cross-section - 3, are 18 - 20% larger (depending on the working environment) than the costs in cross-section 1.

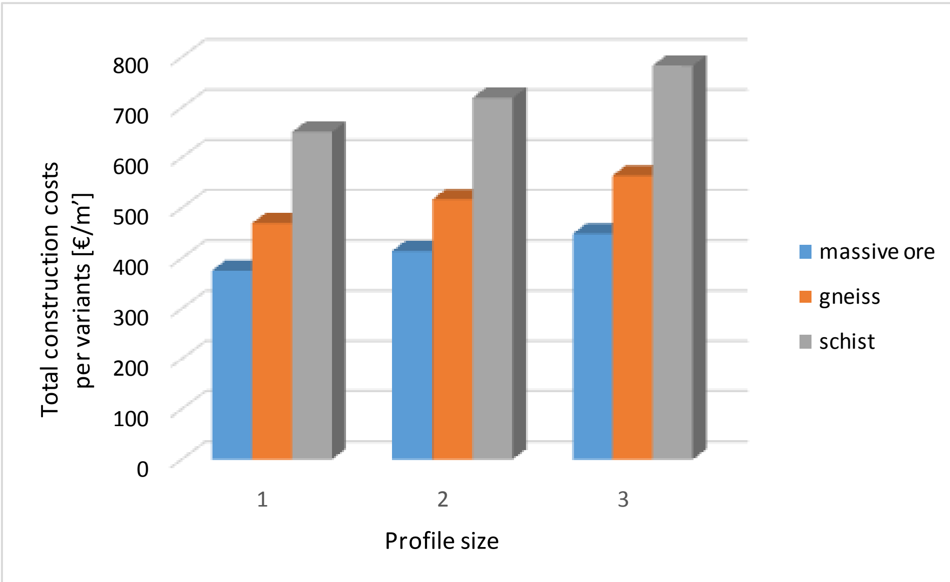

Figure 8: *Total construction costs per variants*

Table 5 and **Figure 8** show total construction costs per variants. From research results it can be concluded that different rock material type, as well as different profile size, lead to differences in the construction costs of 1 m' underground drifts. The biggest total cost of construction is for schist due to its high supporting costs.

4. Opportunities to reduce the construction costs of underground mining structures

The management of every mining company aims to reduce the total exploitation costs, including the construction costs of underground mining structures. Below are mentioned some manners that will allow for the reduction of construction costs for underground mining structures.

1. Well-chosen drilling-blasting parameters prevent the excavation outside of the profile, which results in the reduction of supporting costs;
2. The monitoring state of stress and proper dimensioning of support system construction also allows for a reduction of supporting costs;
3. Accurate determination of all physical - mechanical characteristics of rock mass along the facilities route (construction of engineering geological section) and a selection of the best variety solution for objects route, both in terms of opportunities for the deposit exploitation, and in terms of the characteristics of the rock material. Passes through the route would allow a reduction of the construction costs;
4. Good work-organization, well-trained staff and a high level of construction process mechanization, would also allow for the reduction of the underground facilities construction costs.

5. Conclusions

Based on carried out research in this paper,the following can be concluded:

- Changing the type of working environment and horizontal mining facilities profile size leads to differences in the costs in individual working operations and total construction costs;
- The largest cost variations occurred at supporting, due to careful attention on the dimensioning of support construction because every over dimensioning leads to increased underground facility construction costs;
- The identified costs for all working operations show that the cost changes are more pronounced with the change of the working environment than with the change of the cross-section of a horizontal mining facility, which is especially pronounced at the drilling and blasting costs as well as supporting costs;
- The underground facility construction costs will decrease if the appearance excavation outside of the profile is avoided, if the supporting construction is well-dimensioned, the structure's route is properly chosen, the mechanization level is raised and there's good work-organization.

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Sažetak

Izgradnja podzemnih rudarskih prostorija je od najveće važnosti za eksploataciju mineralnih sirovina. Troškovi izgradnje osnovnih rudarskih prostorija predstavljaju 40 do 60 % investicijskih ulaganja tijekom izgradnje i opremanja rudnika. Osnovne podzemne rudarske prostorije su: okna, hodnici, uskopi, pumpne komore, skladišta i sl. U ovom radu dana je detaljna analiza troškova gradnje podzemnih rudarskih prostorija (hodnika), po pojedinim radnim operacijama, a njihova promjena ovisi o vrsta stijene i veličini profila podzemnog rudarskog objekta. Također navedene su i mogućnosti smanjenja tih troškova.

Ključne riječi

Podzemna eksploatacija, troškovi izgradnje podzemnih prostorija, izgradnja podzemnih prostorija