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Rockburst experiences in Cheves Hydropower Project, Perú

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ABSTRACT
Cheves Hydropower Project is located in Peru and consists in approximately 20 km of tunnels and two caverns. Most of the Headrace tunnel has been excavated in igneous and metamorphic rocks with high overburden. A high number of stress release events took place during the excavation of the tunnels and caverns. The intensity of these events varies from acoustic emission to a violent rockburst. The paper describes the methodology developed to mitigate the rockburst hazard.

1. INTRODUCTION

Cheves hydropower project is located on Huaura River and Checras River, under the Andean Mountains of Peru, North of Lima (see Figure 1).

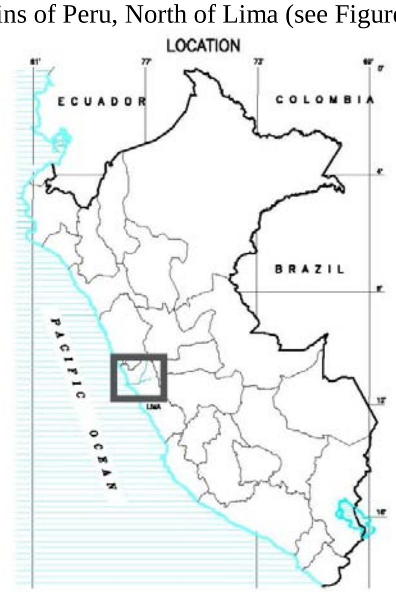

Figure 1: Cheves Hydropower Project location.

Cheves Project was developed by Empresa de Generación Eléctrica Cheves S.A, a company of the Statkratf Group. The construction was executed by Constructora Cheves, SAC (joint venture Hochtief Solutions AG, SalfaCorp SA and ICCGSA).

In reference to the design of the project, Empresa de Generación Eléctrica Cheves engaged Norconsult with responsibility for the design of the permanent works including the layout, overall stability, and permanent support of the underground works.

Meanwhile Subterra Ingeniería developed the initial support design to Constructora Cheves SAC according to the scope including in the contract signed between the Owner and the Contractor. Constructora Cheves and Subterra Ingenieria didn't have responsibility for the final layout and the long term stability of the works.

This paper and all the above comments are referring only to the scope of work carried out by Constructora Cheves and Subterra Ingeniería.

The project is composed of three small dams and the underground works that dominate the infrastructure, representing approximately 20 km of tunnels:

- Transfer tunnel, between the Huaura Intake and the Checras reservoir presents a length of 2,580 m.
- Headrace tunnel is 9,693 m long (22.6 m^2 and 30.1 m^2), with an upper section at a grade of 2 % and a lower section inclined 14 %. An intermediate adit with a length of 700 m, and a surge tunnel were built at the junction of the lower and upper tunnels, with approximately 700 m long, also inclined 14 %. The end of the Headrace tunnel splits into two short penstock tubes, taking the flow to the generating units in the

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powerhouse cavern (60 m long by 32 m high and 15.5 m wide). The transformer cavern (27.5 m long by 14 m high and 11.2 m wide) is immediately adjacent, connected both caverns through an access tunnel. A tunnel access as well as several tunnels completes the Power House complex.

- Tailrace tunnel is 3,312 m long (24.9 m^2 cross section) tailrace tunnel discharge the water downstream the project.

Kaiser and Cai (2013) define a rockburst as damage to an excavation that occurs in a sudden and violent manner and is associated with a mining-induced seismic event. This general term 'rockburst' is independent of the cause of damage and thus is used for strain, pillar, and fault slip bursts.

During the construction of the Cheves Project more than 850 stress release events were recorded. The most important part of these events took place in the Headrace Tunnel, and a large number of them were recorded around the Powerhouse complex.

Initially, the stress events turned out in the area under the influence of the Powerhouse, especially when the excavation of the cavern began. In December of 2011 and during January 2012 several stress relief events were reported and described as banging or cracking sounds. On January 2012 a minor rockburst with projections of rocks and shotcrete occurred at the access tunnel about 15 m behind the face.

During the followings months, evidence of stress releases continued with events of low intensity, mainly loud relief, slight crumbling, crackling and banging sounds. These events were mainly reported in the by-pass tunnels around the powerhouse. Consequently, these areas were reinforced.

However, on the 21st of March 2012 a strong stress event occurred in the Powerhouse area affecting various tunnel sections. The main stress discharges were reported as two short delayed bursts in the tunnel access and by-pass tunnels. A follow up investigation at the same day in the afternoon revealed that after the main bursts further cracking and minor bursting occurred in the powerhouse cavern.

The areas around the powerhouse were reinforced as a consequence of these events. The excavation of the Powerhouse continued, whereas the works in some tunnels were stopped.

Figure 2: Areas affected by the stress event occurred on 21/03/2012 and a picture of the effects in the by-pass tunnel.

Once the excavation of the Headrace tunnel started from the Powerhouse complex towards the Checras dam, stress events were reported continuously during the excavation, mainly as banging or cracking sounds (acoustic emissions). Finally, a rockburst from the face took place at the tunnel face on July 2012. A complete methodology was developed to mitigate the rockburst hazard during the excavation of the tunnels after this event.

Figure 3: Rockburst at the tunnel face in the Headrace tunnel.

2. GEOLOGICAL AND GEOTECHNICAL FRAME

Cheves Hydropower Project is located in the Huaura basin in the Andes. The Geology is complex with sedimentary, volcanic, igneous, and metamorphic formations along the project. According with its position in the Andes, the area is under active tectonic and seismicity is moderate in the project area.

The Headrace tunnel and the Powerhouse complex have been excavated in relatively hard rock. The geology in the area of the caverns proved to be structurally complex given the presence of major tonalites intrusions with associated sub-horizontal shear joints. Careful consideration was given to aspects such as in situ stresses and rock mass strength. Figure 4 shows the geological section of the Headrace tunnel.

Figure 4: Headrace tunnel geological profile.

2.1 Lithologies and Basic geomechanical data

In this section a geotechnical characterization of the different rocky formations that were found in the downstream part of the Headrace Tunnel are described.

- Churin Bajo Stock. Consist in intrusive rocks with tonalite / quartz-monzonite composition. In general, they show a high strength, low to moderately weathered in the surface, showing thin coats of iron oxides in fractures, which are persistent. The contact with Casma Group andesites produces silicification processes resulting in hornfels, which present highly brittle behaviour and severe fracturation.
- Casma Group. This group corresponds to stratified sequences of volcanic rocks with interbedded sedimentary rocks. Volcanic rocks consist mainly in andesites which appear severely brecciated with a porphyritic texture. In general, they show a high strength, except when intercalations of sedimentary rocks are detected. Sedimentary rocks consist in sandstones, white quartzites, brown to grey shales and layers of limestone with isolated intercalations of marls.
- Chimu Formation. It is composed by quartzite banks with interbedded with thin quartzose sandstone strata, bituminous shale and occasional coal lenses. In general, quartzites banks show very high strength but brittle behaviour with many fractures showing thin coats of iron oxides. Shales and quartzose sandstones appear highly fractured, with low strength and stiffness and also ductile behaviour.
- Hornfels. The contact with Casma Group andesites produces silicification processes resulting in hornfels, which present highly brittle behaviour and severe fracturation.

The representative values for these formations at intact rock level are shown in Table 1 below:

Table 1: Intact rock properties.

LITHOTYPE	LITHOLOGY	OVERBURDEN (m)	RQD (%)	ρ_{ap} (t/m^3)	σ_{ci} (MPa)		Modulus Ratio	E_i (MPa)	v	mi
					RANGE	VALUE				
Churin Bajo Stock (KsTi-qzmo)	Tonalites	580-700	40-60	2.62	100-150	110	400	44,000	0.24	25
		700-780	70-90			125		50,000		
	Tonalites (Fault zone)	1100-1200	30-50	2.62	80-120	90	400	36,000	0.24	25
Churin Bajo Stock (KsTi-hf)	Hornfels	525-700	30-50	2.62	80-120	90	550	49,500	0.24	19
Casma Group (Ki-ca)	Andesites (Fault Zone)	135-200	30-50	2.62	70-120	80	400	32,000	0.24	25
		250-350	40-60		100-150	110		44,000		
	Andesites	175-525	60-80		120-200	130		52,000		
Chimu Formation (Ki-ch)	Quartzites with shales and sandstones interbedded (Fault Zone)	500-525	10-30	2.62	30-80	40	375	15,000	0.24	20
	Quartzites with shales and sandstones interbedded	25-200	10-30		30-80	40		15,000		
		200-450	30-50		60-120	70		26,250		
		450-600	10-30		30-80	40		15,000		

2.2 Structure

The Headrace tunnel presents a complex geological structure as it is excavated in sedimentary deposits (coal seam included), volcanic rocks, igneous rocks and metamorphic rocks.

The initial part of the tunnel excavated in the Chimu formation is strongly folded and affected by fault systems. The contact between volcanic materials and sedimentary deposits is also defined by fault systems. An igneous intrusion (Churin Bajo Stock) is in contact with the volcanic deposits (Casma Group). The contact with Casma Group andesites produces silicification processes resulting in hornfels, which present highly brittle behaviour and severe fracturation.

2.3 Overburden and natural stress field

Initially, the natural stress field assumed was derived from regional information as well as from the tectonic frame. It was considered an unfavourable scenario with the vertical stress according to the overburden (lithostatic load) and the following ratio between horizontal and vertical stresses: K_H=1.5 (with a strike of N-60º-E) and K_h=1.0.

This stress frame is a key matter for design purposes, thus three different stress measurements were developed, the first using overcoring techniques and the last two using hydro fracturing stress measurements.

The measurements using overcoring provided magnitudes of the maximum principal stress σ1 ranging between 18.6 to 59.8 MPa. According to the mean value the resulting relation between horizontal and vertical stresses would be around 1.2 and an orientation quite similar to the one obtained by geological estimations (N-45º-E), but the scatter of the results was relatively high.

For this reason, two different on site measurements using hydro-fracturing were established. The obtained magnitudes were similar in both cases, with relatively low values of horizontal stresses. Consequently, the natural stress field was defined as follows:

- σ_v between 21.7 and 22.1 MPa
- σ_h between 12.8 and 13.7 MPa (Kh=0.62)
- σ_H between 20.3 and 21.3 MPa (KH=0.96)

The orientation of the maximum horizontal stress was N-95º-E.

3. ROCKBURST HAZARD MITIGATION METHODOLOGY

Rockburst and stress releases took place mainly in the Headrace tunnel and the powerhouse complex. Headrace tunnel was excavated in sedimentary deposits (coal and sandstones), andesite, volcanic breccias, granodiorites, and hornfels. Most part of the events took place in areas excavated in igneous and metamorphic rocks.

A specific stress risk assessment was done in addition to the geological assessment at the tunnel face during the tunnel excavation, in order to collect all the information coming from the tunnel. Three stages were defined to manage the risk of rockburst or stress releases. These measures can be classified in prediction, prevention and protection.

3.1 Prediction

It was considered that rockburst and/or stress releases are highly unpredictable. Basically, the unique method for rock burst prediction that is considered as partially efficient is to implement a microseismic monitoring net. These systems have been developed in deep mines and require long record periods with some years for calibration to perform reliable predictions. It must also be considered that a mine usually has a well-developed layout of roadways and excavation allowing the installation of seismic nets. For these reasons the application of this technique to Cheves was considered unreal.

The proposal for prediction is the systematization of all the stress events, registering them in a systematic and precise way from simple noises, fissures progression on the shotcrete, minor projections and spalling or popping. Consequently, it is proposed to increase the efficiency of the high stress events records to ensure that all of them are duly registered:

- Stresses events at the face: noises, rock cracks, minor projections, spalling or presence of platy rock chips.
- Stresses events behind the face: fissures and cracks at the shotcrete, spalling at the walls.
- Statements from key personnel in the vicinity.

According to Kaiser and Cai (2012) there are many factors that have an influence on rockburst damage and the severity of the damage. Table 2 summarizes the main factors and groups them into four categories, i.e. seismic event, geology, geotechnical, and mining. Factors in the first two groups (seismic event and geology) determine the intensity of dynamic load at the damage locations, and the factors in the last two groups (geotechnical and mining) determine site response due to seismic impulses.

Table 2: Main factors influencing rockburst damage (modified from Kaiser and Cai, 2012)

Seismic event	Geology	Geotechnical	Mining
Event magnitude Seismic energy release Distance to seismic source	In situ stress Rock Type Beddings Geological structures (dykes, faults, and shears)	Rock Strength Joint fabric Rock brittleness	Mining induced static and dynamic stresses Excavation span Extraction ratio Mine stiffness Excavation sequence (stress-path), blasting Installed rock support system Backfill Production rate

A sheet record was defined to collect all valuable information after every stress event:

- Production: Date/Time; Blast time; Phase of production cycle;
- Geometry: chainage, section, area affected, overburden.
- Geology: lithology, structural geology

- Stress classification: stress effect and consequences.

A stress release classification was developed for the project based on previous experiences from the main contractor in the Gothard Tunnel. This classification was divided in four categories according to the characteristics and effects of stress releases.

Table 3: Stress Release Classification developed for Cheves Hydropower Project.

Stress Class	Description
0	Loud Relief, slight crumbling: crackling, banging, crumbling in surrounding rock mass
1	Stress-induced spalling without rock fall: rock surface cracks suddenly, creating scales up to 5cm, appearance of dust clouds
2	Stress-induced loosening or rock fall at lateral rock surface or face in unsupported area: rock breaks rough and very loud. Rock support system might be slightly damaged (Fissures in shotcrete).
3	Heavy Bangs with explosive rock fall: pieces or slabs of rock are thrown suddenly with loud bangs in radial direction from lateral rock surface (in supported and unsupported areas). The rock support system is damaged (Cracks in shotcrete, torn-off anchors, bent ring beams).

3.*2 Prevention*

The prevention of these types of stress phenomena is rather complicated but some techniques can be implemented. The three following measures were recommended:

- Preconditioning blasting ahead of the face
- Change of the shape of the face to a concave geometry
- Reduction of the round length

In relation to the use of preconditioning blasting ahead of the tunnel face, these blasts can minimize the effects of future possible rockbursts at the face (face burst), reducing the stress magnitudes at and ahead the face. This technique consists basically in the execution of blast drill holes ahead of the face at specific depths and locations using high velocity detonation explosives and full confinement of it. As a result, the rock mass quality beyond the face is decreased artificially, "distressing" the rock mass in the vicinity of tunnel to be excavated, and allowing the release of tension that otherwise could result in a rock burst.

The design of the preconditioning blast is based on the following criteria:

- Not generate an intense fracture the rock but yes "distressing" the rock mass, in order to not difficult following blast and support at face
- Focus the decompressing effect within the perimeters of the tunnel section by generating fractures in the rock that allow to adjust the stress.

The preconditioning blast was executed by 3 holes of 51 mm and 4 m long, loaded on the last 2 meters with bulk Slurrex explosive. These holes were proposed to be drilled on a vertical alignment with the tunnel axis, in between production holes.

Analysing the energy distribution, we can predict that energy from production holes interacts with pre-conditioning holes. These combinations of energies are expected to create a tunnel free face with a set of cracks concentrated vertically. After a first test shot it must be evaluated how those perform. Proper performance implies both a continuous set of vertical cracks interconnected and a good enough rock mass to be drilled around pre-conditioning holes.

Because cracks induced on fully confined holes are due to tension created by a shock wave, it is not intended to use the gas energy of the explosive for either crack extension or rock displacement. For this reason, explosive charges can be unconfined. Expect however a flyrock potential increase that can damage equipment or infrastructure if not properly protected.

Figure 5 below shows the energy distribution at -2.2 m (top left), -3 m (top centre) and -4 m (top right) with a 3-hole configuration at 51 mm with Slurrex.

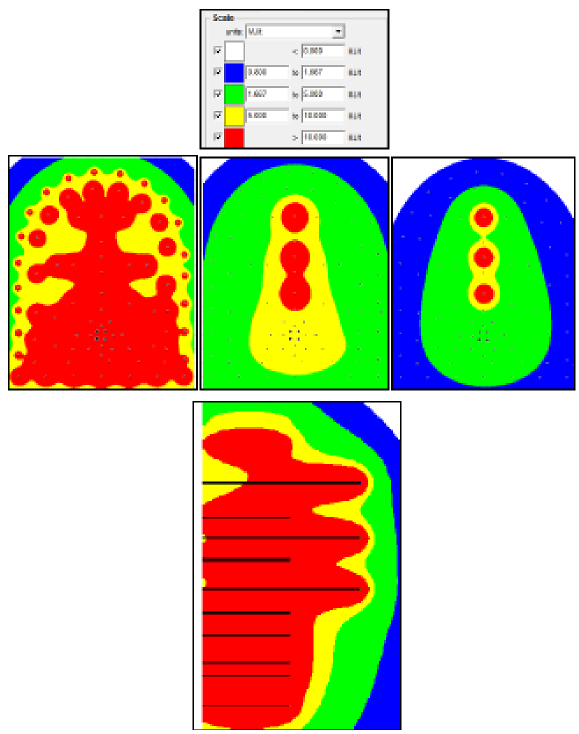


Figure 5: Energy distribution of preconditioning blast with a 3-hole configuration at 51 mm with Slurrex.

A second measure recommended was to change the face excavation shape from planar to a concave geometry as planar planes always accumulate higher stresses than curved planes. In relation with this same effect it was also suggested to the Owner the possibility of changing the shape of the tunnel section to a Horse-shoe or even more, with curved walls with high potential risk of rockburst. Nevertheless, this measure was not finally implemented.

Finally, the reduction of the round length was considered a less effective measure with a minor effect in the release of stresses and consequently in the rockburst occurrence, but it has a notable effect on shortening the construction cycle and therefore decreasing the exposure of the personnel at the face.

3.3 Protection

Two different types of measures were proposed in order to protect the tunnel workers at the face:

- To reduce the vulnerability and exposure of the personnel.

It was recommended to reduce the vulnerability and the exposure of the tunnel workers at the tunnel face as risks factors. For this reason, basic measures were adopted, as to carry out scaling using mechanical facilities and protective cages for workers and machinery.

- To install a temporary support at the face.

Two different support elements were basically used: shotcrete and/or rock bolts (swellex). In both cases the purpose was to avoid rock fragment ejections from the face.

According to previous experiences in Gothard Tunnel, it was recommended that a layer between 5.0 and 10.0 cm of shotcrete with steel fibres, as well as a variable number of swellex bolts be installed at the face. These bolts were always longer that the advance round length.

4. ROCKBURSTS RECORD AT THE HEADRACE TUNNEL

As mentioned before, 859 stress events were reported between Aug. 2012 and Jul. 2014, 48% of which were recorded as banging noises without rock ejections or support damages, 41% of the events were classified as Stress Class 2 and 3 with rock support damages, and only 16% of the events involved violent rock ejections or/and support. Figure 6 shows the distribution of the events according to intensity.

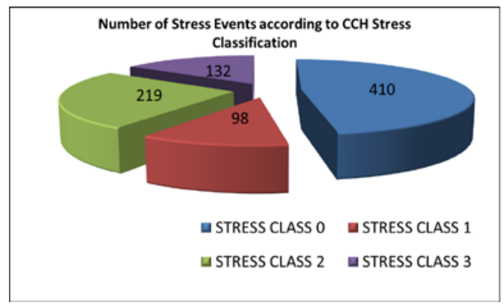


Figure 6: Stress Events intensity distribution according to CCH classification.

About 90% of the events were recorded in the Headrace tunnel. The rest of the events were recorded in the tunnels surrounding the Powerhouse.

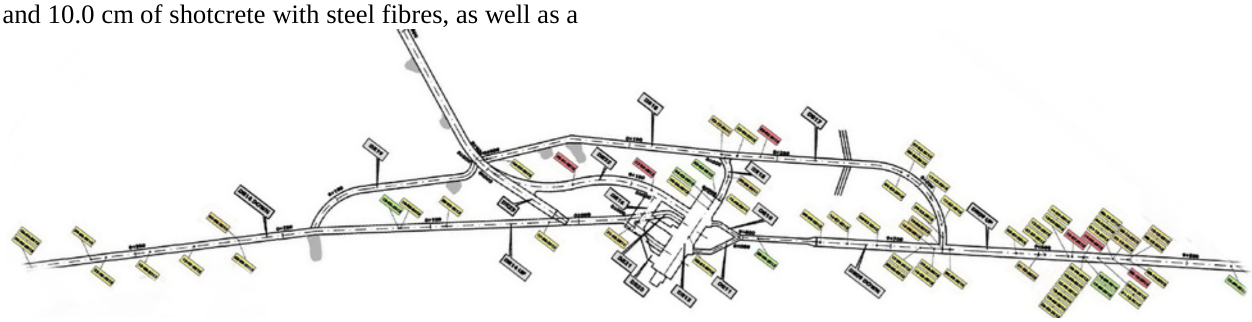


Figure 7: Distribution of stress events around the Powerhouse.

An analysis of the stress events over time shows an erratic distribution of events. There were several months in which the stress events had more influence over the project. Figure 8 shows the distribution of the stress events and the number of events in each tunnel over time.

The data demonstrates that Headrace tunnel has been the most affected by stress events, and the influence of these events has three clear steps. From Jan. 2012 to Dec. 2012 it is possible to define an increasing tendency, a quiet period during Jan. 2013, and an increasing tendency from Feb. to Apr. 2013.

The chart also shows that the stress events continued after the tunnels completion, when the support was removed in some tunnels to execute the required concrete plugs.

CHEVES HIDROPOWER PROJECT - STRESS EVENTS SUMMARY

Drive	Previous	08/2012	09/2012	10/2012	11/2012	12/2012	01/2013	02/2013	03/2012	04/2013	05/2013	06/2013	07/2013	08/2013	09/2013	10/2013	11/2013	12/2013	01/2014	02/2014	03/2014	04/2014	05/2014	06/2014	07/2014	Total
DR02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DR04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DR05	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
DR07	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
DR08	0	8	6	2	10	8	4	2	5	10	2	1	3	3	7	4	5	6	0	0	0	0	0	0	0	86
DR09 US	11	1	21	68	49	103	9	39	111	120	13	25	12	18	10	10	36	25	0	0	0	0	0	0	0	685
DR09 DS	7	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	8	0	24
DR10	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
DR11	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
BD01	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
BD02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DR13	4	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
DR14 US	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
DR14 DS	3	4	2	6	3	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21
DR15	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
DR16	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
DR17	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
DR18	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
DR19	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	1	0	1
DR22	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
DR23	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
																										859
Total	44	23	37	79	63	113	14	42	117	130	16	25	15	21	17	14	41	35	0	0	0	3	0	9	0	859

STRESS CLASS	Previous	08/2012	09/2012	10/2012	11/2012	12/2012	01/2013	02/2013	03/2012	04/2013	05/2013	06/2013	07/2013	08/2013	09/2013	10/2013	11/2013	12/2013	01/2014	02/2014	03/2014	04/2014	05/2014	06/2014	07/2014	Total
STRESS CLASS 0	29	21	30	61	21	45	6	8	45	62	5	17	7	8	12	11	11	4	0	0	0	3	0	4	0	410
STRESS CLASS 1	3	1	3	1	7	5	2	13	13	23	0	1	0	0	0	0	0	26	0	0	0	0	0	0	0	98
STRESS CLASS 2	5	1	3	16	26	20	2	17	34	16	11	7	8	11	5	1	26	5	0	0	0	0	0	5	0	219
STRESS CLASS 3	7	0	1	1	9	43	4	4	25	29	0	1	0	2	0	2	4	0	0	0	0	0	0	0	0	132
Total	44	23	37	79	63	113	14	42	117	130	16	25	15	21	17	14	41	35	0	0	0	3	0	9	0	859

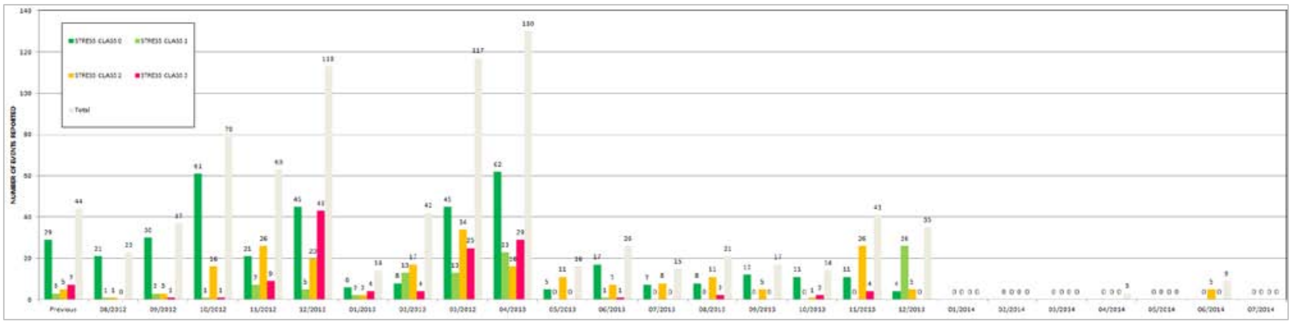


Figure 8: Stress Events distribution according to CCH classification and tunnels.

5. PARAMETRICAL ANALYSIS OF THE STRESS EVENTS

A detailed record of all stress events was carried out and statistical analysis was implemented to understand the rockburst phenomena in the project. The analysis confirmed that the overstress in the tunnels was related with the following factors:

- Overburden
- Lithology
- Jointing and other structures
- Rock mass quality
- Time after blasting
- Round length

The follow describes the particular analysis for Headrace tunnel.

5.2 Overburden

Headrace tunnel was designed with a positive slope of 14%. The overburden considered in the vertical tunnel axe shows an increasing tendency. The overburden is close to 850 m at the powerhouse area and rises to approximately 1.450 m. Figure 9 shows the topographical longitudinal section with the overburden.

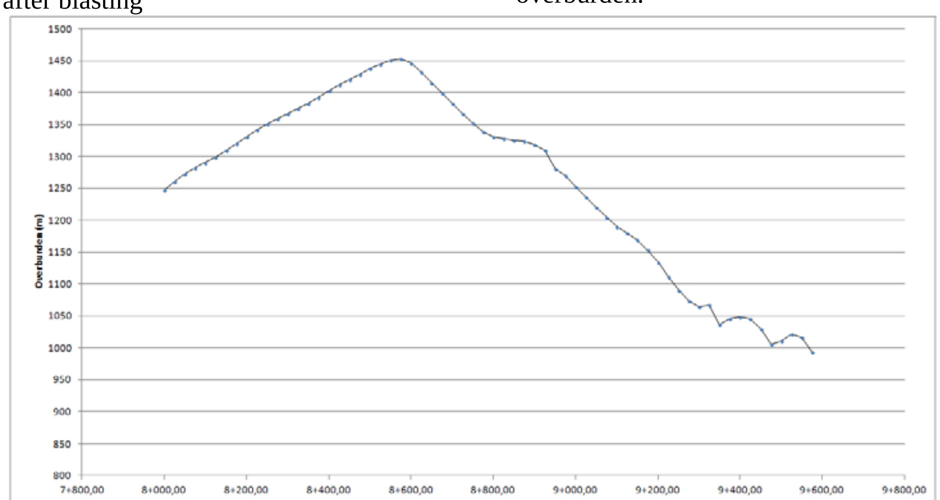


Figure 9: Headrace tunnel overburden.

It will be shown later that minor changes in the overburden due to the presence of irregular topography will have a significant influence on the stress release.

The next figure shows the relationship between stress events and depth. It would be expected that there would be more events deeper is the excavation, however, it was observed that major events occurred between 1000 and 1150 m in the Headrace tunnel and about 800 m around the Powerhouse.

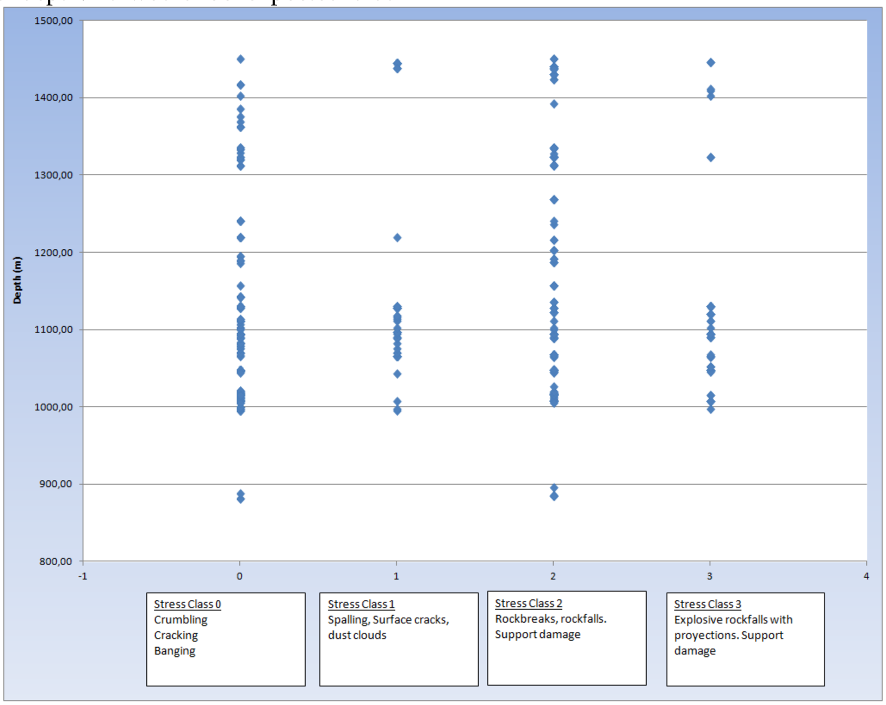


Figure 10: Stress Events vs. Depth.

5.3 Lithology

Headrace tunnel has been excavated in different lithology: hornfels, quartzmonzonite, subvolcanic breccias, and granodiorite. The influence of the stress events on each lithology has been different along the excavation period. The geological conditions after each event were recorded, considering the lithology and the rock mass quality.

A statistical analysis of the results clearly shows that lithology with higher brittle behaviour had suffered a higher number of stress events. It has also been checked that not only areas with good rock conditions are affected by overstress, but also zones where rock mass quality in terms of RMR values are considered fair ground. Figure 11 shows the distribution of stress events in relation to lithology.

Figure 11: Stress Events vs. Lithology.

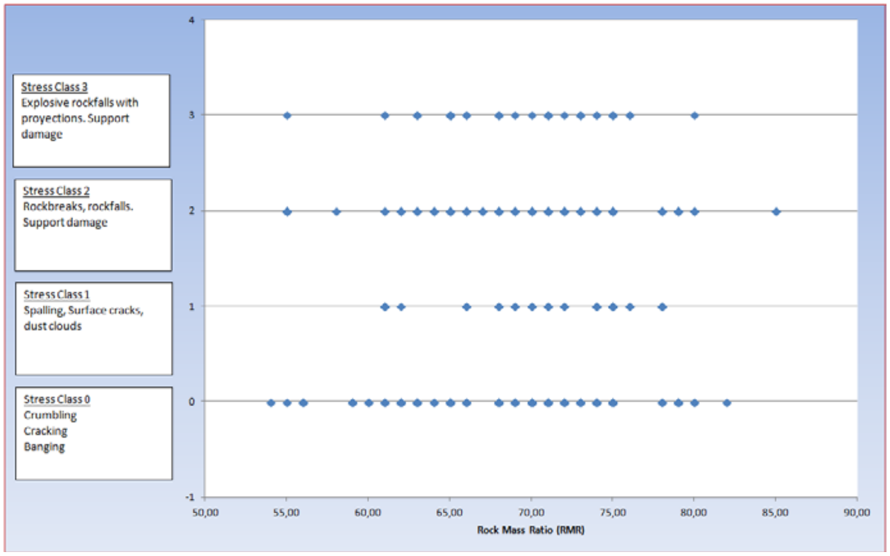


Figure 12: Stress Events vs. RMR.

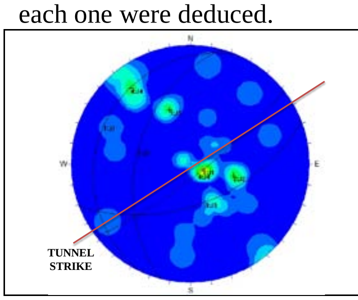
5.4 Geological Structure

The presence of the same joint set family was detected in most of the stress events. An analysis of the stronger events and information from core drillings executed at the tunnel face confirmed that rockbursts are highly controlled by the geological structures. Only eleven (11) events represent the 60% of the events described in Headrace tunnel and sum the 79% of the Stress Class 3 events reported. The joint system at the areas where this rockburst took place was analyzed, as shown in Table 4.

Table 4: Structural data mapped after rockburst events.

CH		Lithology	JOINTS					
			J1		J2		J3	
Start	End		DIP	DIP DIR.	DIP	DIP DIR.	DIP	DIP DIR.
9+557,50	9+555,50	Metamorphic Rock-Hornfels	10	320	75	220	80	190
9+555,50	9+553,00	Metamorphic Rock-Hornfels	11	308	49	347	74	140
9+553,00	9+550,20	Metamorphic Rock-Hornfels	18	300	50	155	45	280
9+490,70	9+487,80	Subvolcanic breccia contact with Hornfels	45	295	60	5		
9+487,80	9+485,50	Metamorphic Rock-Hornfels	75	5	60	305		
9+408,30	9+405,50	Metamorphic Rock + Qz-Monzonite	65	100	15	300		
9+405,50	9+403,30	Metamorphic Rock + Qz-Monzonite	72	115	35	240		
9+403,30	9+400,70	Metamorphic Rock + Qz-Monzonite	35	328	55	154	5	140
9+297,90	9+295,10	Metamorphic Rock + Qz-Monzonite	70	140	20	290	45	200
9+295,10	9+292,50	Metamorphic Rock + Qz-Monzonite	83	148	11	109	50	320
9+246,40	9+244,20	Metamorphic Rock + Qz-Monzonite	35	280	55	165	80	55
9+226,10	9+223,80	Metamorphic Rock + Qz-Monzonite	20	260	85	320		
9+208,70	9+205,90	Metamorphic Rock + Qz-Monzonite	25	220	70	250	43	330
9+203,60	9+201,20	Metamorphic Rock + Qz-Monzonite	44	285	84	140		

Figure 13 shows the stereographic analysis of these joints system. As it can be observed the presence of two joint sets with two parallel systems each one were deduced.



Joint Set	Dip	Dip Direction
J1	13	294
J2	41	285
J3	52	159
J4	78	142

Figure 13: Stereographic analysis.

According to this analysis, the presence of sub-horizontal joints dipping to the left wall, and sub-vertical joints dipping to the right wall of the tunnel have to be considered as a sign of possible stress release.

It was also detected that when shear zones associated to the joints system were encountered at the face, the stress events usually turned out. This fact was also detected in the core drillings carried out at the tunnel face. This is clear in the photos shown in Figure 14.

Figure 14: Tunnel face at rockburst events in Headrace tunnel.

5.5 Rock mass quality

The rock has been described according the Rock Mass Rating. In all cases the RMR represents a good quality rock mass. Figure 15 shows the relation between the stress events and the RMR value.

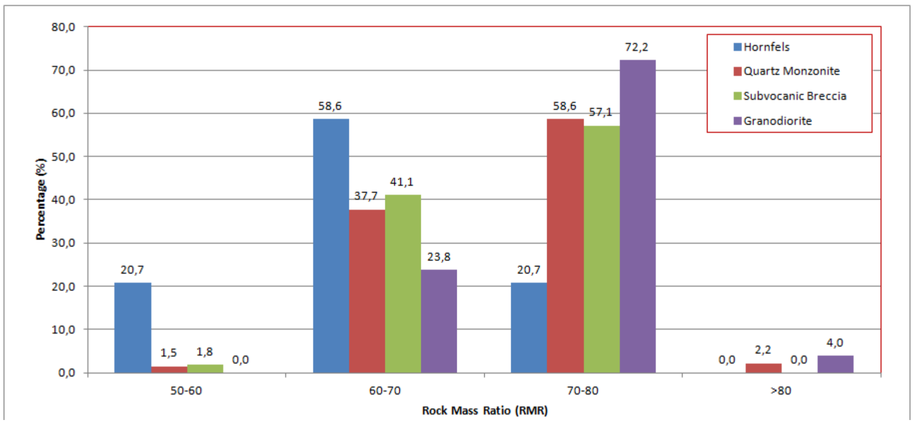


Figure 15: Rock Mass rating (RMR) vs. Lithology.

5.6 Time after Blasting

A detailed analysis of the time in which the event took place after blasting was carried out for the stress events that took place in the Headrace tunnel. In a first analysis the relationship between the stress class of the event and the time in which it took place was analysed. Figure 16 shows this analysis.

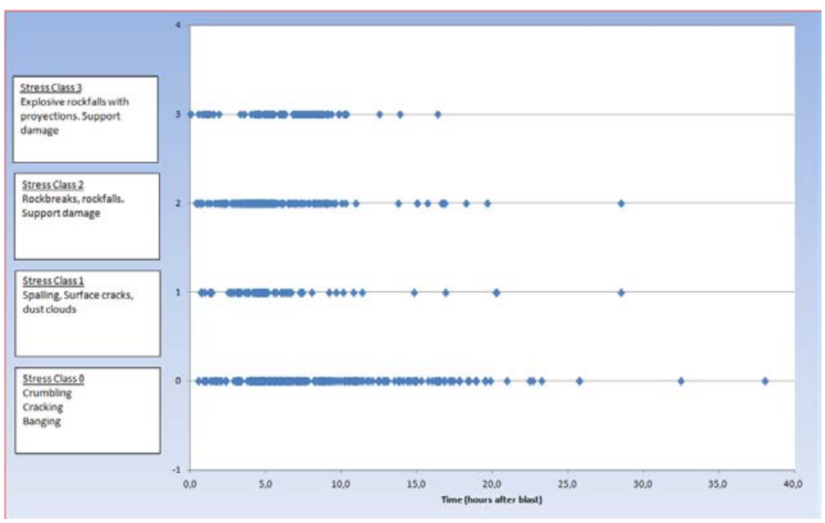


Figure 16: Stress class vs. Time Event.

The chart shows that the violent events occurred in range of 10 hours after blast; meanwhile it is possible to detect lighter stress releases in a wide range of more than 24 hours.

A statistical analysis of these events were carried out in order to analyse the possibility of implementing a re-entry strategy as it is usual in other projects or in mining activities. Figure 17 shows the distribution of the stress events in relation with time after blasting.

Both analyses show that the time event occurrence after blast presents a broad range that makes difficult to define a re-entry strategy.

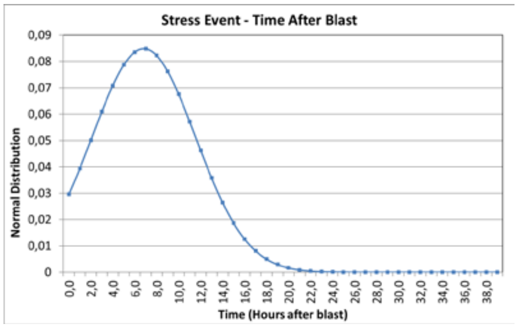


Figure 17: Normal distribution of the Stress Event time after blast. (Theoretical curve).

5.7 Round Length

A rounds length analysis was carried out during the excavation of Headrace tunnel in cases with stress releases as a first step. Figure 18 presents the normal distribution of round length in those cases in which a stress releases occurred.

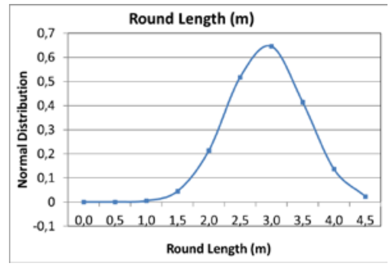


Figure 18: Normal distribution of the round length in rounds with stress event. (Theoretical curve).

According to the results, rounds in which stress releases turned out are between 2.5 and 3.5 m long. In Figure 19 the number of stress releases per round is presented. This chart shows clearly that the major part of the events occurred with rounds longer than 2.5 m. However, the tendency is not so clear.

The distribution of events according to stress classes established by CCH and in relation with the round length has been analyzed. The Figures 20(a)-(d) represent these analyses. The charts clearly show that stress releases are more likely in longer rounds, from 2.5 to 3.5 m.

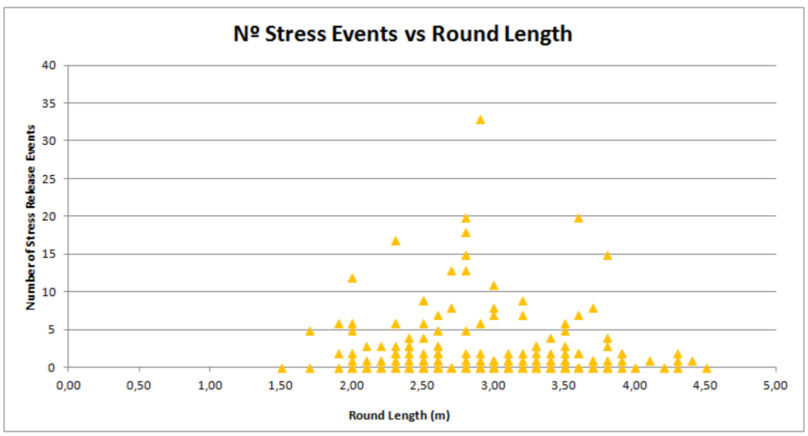


Figure 19: Number of stress events vs. round length.

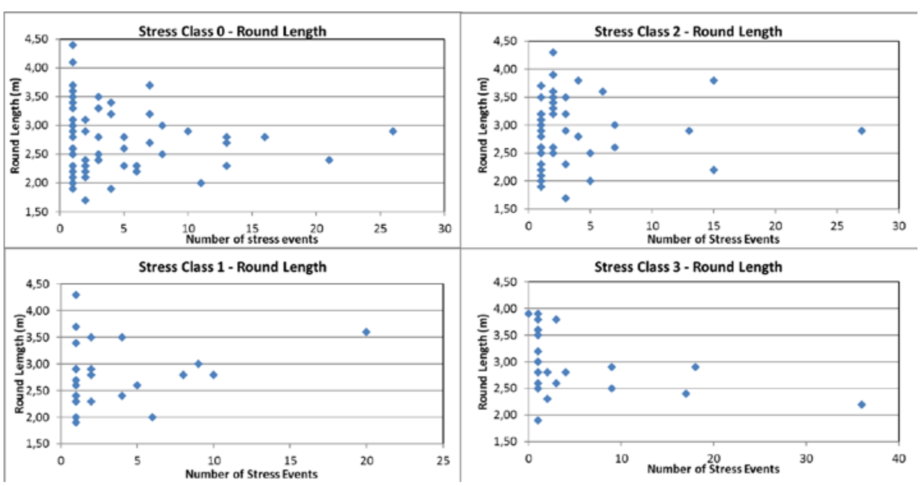


Figure 20(a)-20(d): Number of stress events per each stress class vs. round length.

5.8 Global analysis

A final analysis considering all the previous described parameters was done in order to define the weight of each factor and in order to define alarm signs that permit to anticipate risk areas.

The overall analysis for the Headrace tunnel is shown in Figure 21. The stress events recorded at each chainage have been represented in this chart, according to the stress event classification developed, in conjunction with the rock mass rating (RMR), the overburden, the round length, and the lithology.

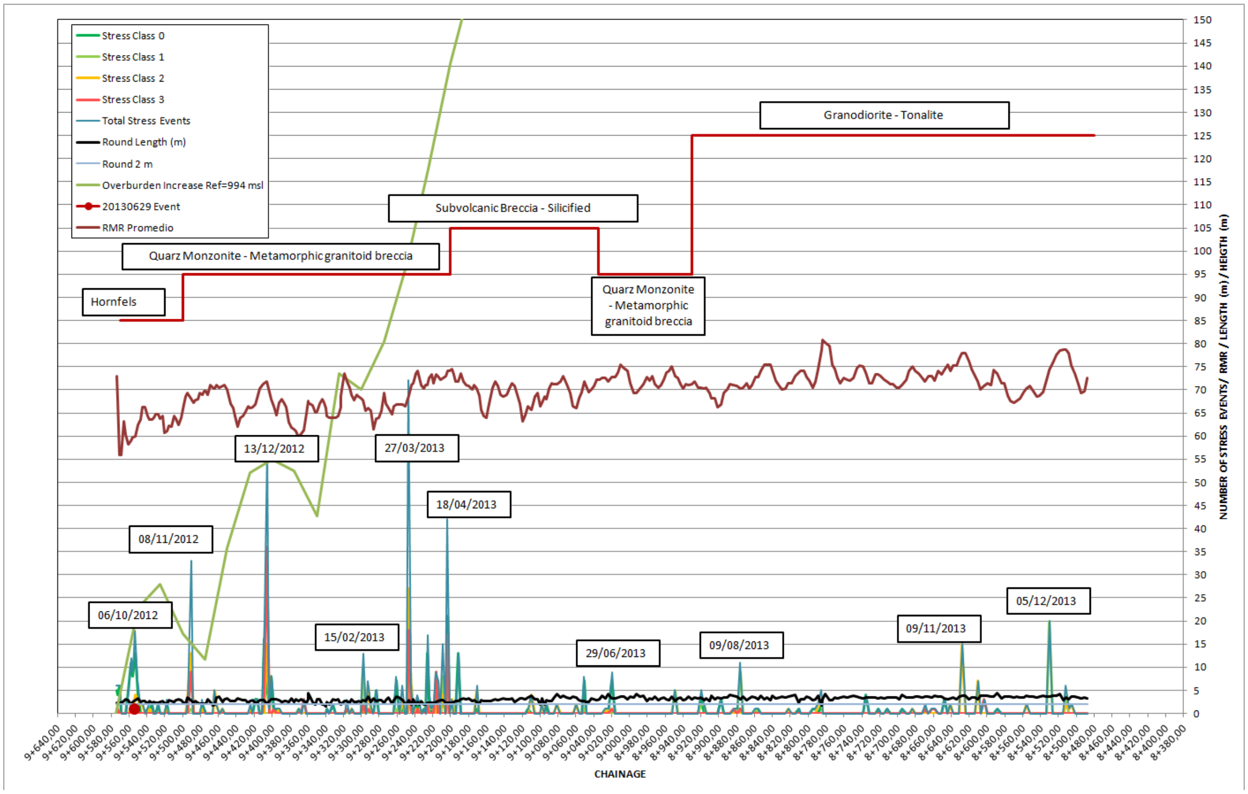


Figure 21: Stress factors comparison.

Based in the results, it is clear that the main factor was the lithology, as most of the events and intense events were recorded in quartzmonzonite, meanwhile other lithologies such as volcanic breccias presented less rockburst prone conditions. In Quartzmonzonite, rockburst and/or stress release occurred systematically. Meanwhile in subvolcanic breccias "quiet periods" were recorded for a stretch of approximately 60 m. In massive intrusive rock (granodiorite) some periods without stress released evidences were detected, however it is not clear the reason for this lack of stress activity.

6. ROCKBURST PRONE CONDITIONS SUPPORT

Several support measures were implemented to mitigate the rockburst prone conditions during the excavation of the tunnels in the Cheves project, both at the face and behind the face. The support design included the following items:

- Reduce the round length
- Destress the rock in advance with pre-conditioning blasting
- Pre-stabilise the face with swellex bolts, longer that the round length
- Double shotcrete layer and welded wire mesh to support the advanced section in combination with rockbolts

During the excavation of the Headrace tunnel and due to the intensity/severity of the stress events several changes were introduced in the support with successful results.

- Continuous monitoring of stress releases
- Increased the bolt pattern in some areas
- Fully grouted bolts (with a sleeve to protect the beginning of the bolts) were implemented in fault/shear areas with a huge improvement in the rock support
- The use of a high tensile chain link mesh fixed to the section with split set bolts and mechanically installed
- Modifications in the shotcrete thickness were also implemented with good results

- Additional swellex (3 m long) were instructed to provide a pre-stabilization of the section with good results
- Different rounds length according to the reported stress behaviour

However, the design support has been working out on the limit of its capacity as it has been affected several times by huge stress events with dramatic consequences. The designed system consisted of two layers of shotcrete and welded wire mesh has been affected several times in such way that it was required a complete repair works in order to provide enough safety environments to continue with the advance of the tunnel.

The damages on the rock support have varied from fissures on the shotcrete to collapse/projection of concrete slabs, going through the welded wire mesh.

7. CONCLUSIONS

Rockburst has been extensively described in deep mining, but nowadays there are several civil projects that require the construction of deep tunnels. Under these circumstances it is necessary to consider an overstress analysis of the projects in the design stage.

It is important to establish an adequate classification of the stress release events that take place during the excavation of the tunnels, and record all relevant information in order to carry out a continuous analysis of the project.

The stress classification developed for the Cheves project has provided good results to avoid misunderstanding of what is a stress release and what can be considered a rockburst. However, it needs to be improved and for this reason it has been considered to subdivide the stress class 3 in three categories considering the intensity of the damage. Moreover, the damage severity classification established by Kaiser et al. (1996) has been considered.

It is important to differentiate between stress releases, that not caused damaged (only cracking and banging sounds), and rockburst where a damage to the excavation and/or support took place.

Table 5: Stress classification proposed.

<table>
<tr><th>Stress Class</th><th colspan="3">Denomination</th><th>Description</th></tr>
<tr><td>0</td><td colspan="3">Stress relief</td><td>Loud Relief, slight crumbling: crackling, banging, crumbling in surrounding rock mass</td></tr>
<tr><td>1</td><td colspan="3">Spalling</td><td>Stress-induced spalling without rock fall: rock surface cracks suddenly, creating scales up to 5cm, appearance of dust clouds</td></tr>
<tr><td>2</td><td colspan="3">Intense Spalling</td><td>Stress-induced loosening or rock fall at lateral rock surface or face in unsupported area: rock breaks rough and very loud. Rock support system might be slightly damaged (Fissures in shotcrete).</td></tr>
<tr><td rowspan="3">3</td><td>3.I</td><td>Minor Rockburst</td><td>Damage severity > 0.25 m</td><td rowspan="3">Heavy Bangs with explosive rock fall: pieces or slabs of rock are thrown suddenly with loud bangs in radial direction from lateral rock surface (in supported and unsupported areas). The rock support system is damaged (Cracks in shotcrete, torn-off anchors, bent ring beams).</td></tr>
<tr><td>3.II</td><td>Moderate Rockburst</td><td>Damage severity > 0.75 m</td></tr>
<tr><td>3.III</td><td>Major Rockburst</td><td>Damage severity > 1.50 m</td></tr>
</table>

Support measures to mitigate the rockburst conditions have to be continuously adapted to the stress and ground conditions. However, it has been proven that welded wire mesh provides safe conditions to avoid rock and shotcrete slabs ejections.

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