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Rockburst mitigation experiences on underground projects in the Cheves Hydropower project in the Peruvian Andes

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ABSTRACT
The main problems related with the design and construction of tunnels and caverns under high overburden are analyzed in this paper. As an example, the recent experiences during the construction of the Cheves Hydropower project in the Peruvian Central Andes are described. During its construction, 850 rockburst events were recorded, enabling designers to collect data and make some correlations that may be useful for future projects.
KEYWORDS: tunnel, cavern, depth, rock support, rockburst.

1. INTRODUCTION

Cheves Hydropower plant is located in the central highlands of Peru, close to Lima, in the basins of the Huaura and Checras rivers. The project was developed by the “Empresa de Generación Eléctrica Cheves SA”, a company of the Norwegian group Statkraft. The construction, with a $400 million budget for the civil works, is currently in operation.The company responsible for construction is a consortium (Constructora Cheves) formed by Hochtief Solutions AG (Germany), SalfaCorp (Chile) and ICCGSA (Peru). In relation to the project design, Norconsult, as Owner Engineering, was the consultant company in charge of the permanent works design, including the layout, the long-term stability and the final support of the underground works. Subterra, acting as the Contractor Engineering, was in charge of the initial support of the underground works, as well as of the geotechnical engineering during the construction. This article therefore only describes the work developed by both the Contractor and Subterra.

The project includes the construction of two concrete dams upstream from the headrace tunnel (Huaura and Checras dams), interconnected through a transfer tunnel of 2.58 m long. The second dam leads the water to the headrace tunnel of about 10 km long. The project also considered a third dam downstream from the powerhouse (Picunche dam), whose function is regulation and irrigation.

To summarize, the Cheves Hydropower project’s components are described as follows:

- Huaura dam (concrete dam of 13 m high),
- Transfer tunnel (hydraulic channel that leads the water form Huaura dam to Checras dam, with a length of 2.580 and a cross section of 16 m^2),
- Checras dam (concrete dam of 25 m high),
- Headrace tunnel (9.693 m long and cross sections between 22 and 30 m^2, where the first stretch has an inclination of 0.9% and the last one 14%),
- Surge tunnel of 700 m long and 14% and one adit tunnel with similar dimensions but no so step,
- Powerhouse cavern (60 m long, 32 m high and 15.50 m width) and Transformer cavern (27.5 m long, 14 m high and 11.20 m width),
- Access tunnel to the powerhouse and drifts (1.700 m in total),
- Tailrace tunnel (3.312 m long and 25 m^2) and
- Picunche dam (earth dam of 15 m high).

Therefore, the total length of the tunnels, considering the access tunnel and all the drifts is about 20 km.

Figure 1 shows a longitudinal section of the project showing all the already described components of the hydropower project.

As it can be observed, there is a section in the Headrace tunnel, linked to the steepest stretch where the overburden is systematically above 1.000 m, being the maximum around 1.500 m. Basically, the dynamic or stresses related events took place in that tunnel section as well as in the cavern complex at the Powerhouse area.

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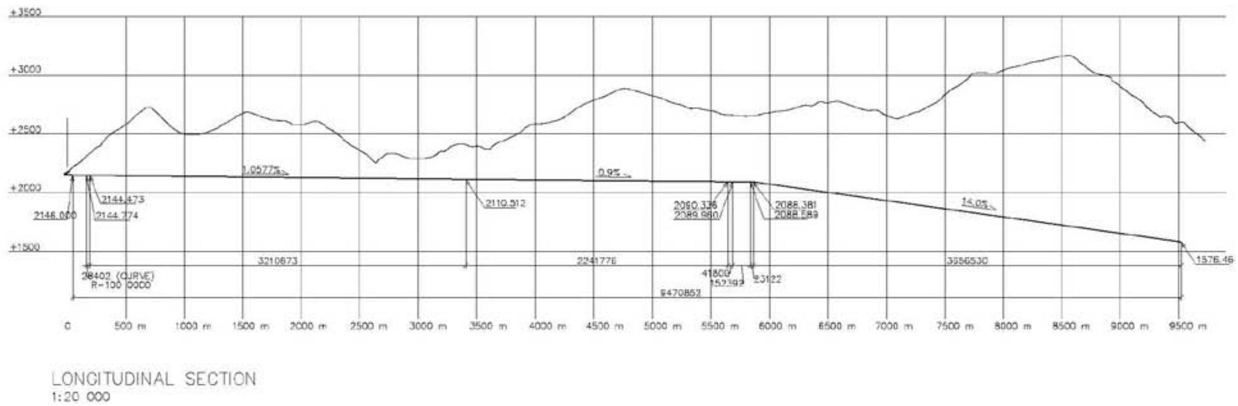

Figure 1: Longitudinal section of Cheves Hydropower project.

2. GEOLOGY

Cheves Hydropower project is located in the Huaura River Basin, within the Central Andean Range. This region is close to the Nazca plate, and therefore affected by active tectonics and high seismicity.

The geology of the area is complex, with volcano-sedimentary, volcanic rocks; plutonic and related contact metamorphic groups.

Figure 2 shows a longitudinal section of the project showing all the described geological groups.

The headrace tunnel and powerhouse area, in which the dynamic events were recorded, have been excavated in hard rock: granites and hornfels.

In the case of the caverns, both are located in a structurally complex area due to the presence of intrusions of tonalite associated with subhorizontal shear joints and metamorphic rocks.

The properties of the geological groups are as follows:

- Chimu Formation: formed by quartzite banks interbedded with layers of quartz sandstone, shale, and occasionally coal layers. Quartzite has a high strength and a brittle response, with multiple fractures filled with iron oxide.
- Volcano-sedimentary rocks: belonging to the Chimu formation, are formed by blocks embedded in a green matrix, with a moderate-high level of fractures and weathering.
- Casma Group: andesite with a porphyry texture.
- Stock Churin Bajo: formed by intrusive rocks as tonalite, granodiorite and quartz-monzonite. These rocks have high strength, and low to moderate weathering, with iron oxides fillings in the fractures.

Hornfels: metamorphic rocks resulting from the contact between the andesite and the intrusive rock. They are very silicified and brittle. The representative values for these formations at intact rock level are shown in Table 1.

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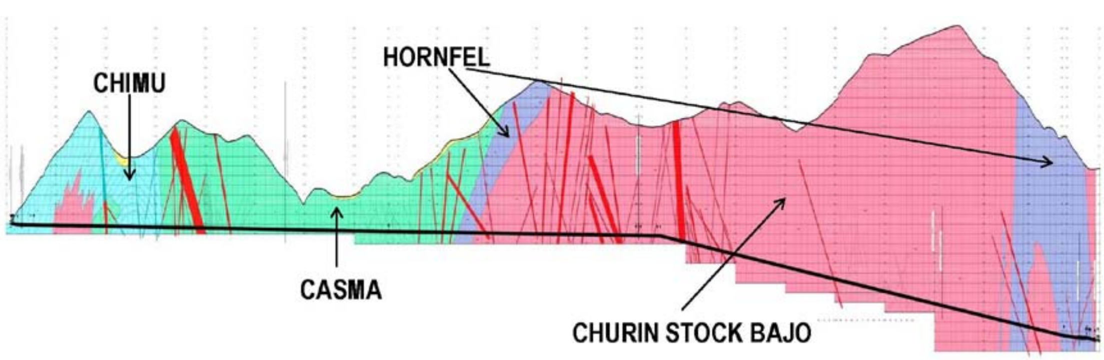

Figure 2: Geological longitudinal section of the project

Table 1: Intact rock properties.

LITHOTYPE	LITHOLOGY	ρ_{ap} (t/m^3)	σ_{ci} (MPa) RANGE	σ_{ci} (MPa) VALUE	E_i (MPa)	v	mi
Churin Bajo Stock (KsTi-qzmo)	Tonalites	2.62	100-150	110	44,000	0.24	25
				125	50,000		
	Tonalites (Fault zone)	2.62	80-120	90	36,000	0.24	25
Churin Bajo Stock (KsTi-hf)	Hornfels	2.62	80-120	90	49,500	0.24	19
Casma Group (Ki-ca)	Andesites (Fault Zone)	2.62	70-120	80	32,000	0.24	25
			100-150	110	44,000		
	Andesites		120-200	130	52,000		
Chimu Formation (Ki-ch)	Quartzites with shales and sandstones interbedded (Fault Zone)	2.62	30-80	40	15,000	0.24	20
	Quartzites with shales and sandstones interbedded		30-80	40	15,000		
			60-120	70	26,250		
			30-80	40	15,000		

As it was explained before, rockburst events were related to the two latest groups, high strength and stiff lithology.

3. ROCKBURST AND OTHER STRESS RELATED EVENTS

Rockburst was first recorded in the deep mines of South Africa, but is now becoming more important in the Civil Engineering sector due to the construction of deep tunnels. Rockburst is defined as a violent and sudden failure of the rock mass, clearly linked to excavations in competent rock with significant overburden, as well as in the presence of structures and dykes. As long as the overburden goes up, the connection between the natural stress and the strength and/or stiffness of the rock mass increases, and therefore the likelihood of rockburst increases as well.

Figures 3 and 4 show an example of two rockbursts that happened in Cheves project, the first one behind the excavation face, near the Powerhouse cavern, and the second one at the excavation face during the construction of the Headrace tunnel.

Figure 3: Rockburst in a drift near the Powerhouse Complex.

The impact of this phenomenon can be summarized in the following points: accidents in the tunnel that may affect the workforce, costs linked to the production stoppage, damage in the facilities and extra charges due to the repair works in the tunnel and replacement of equipment and machinery.

Figure 4: Rockburst at the face excavation in the headrace tunnel.

3.1. *Description of the recorded stress events*

Rockburst events in Cheves project took place in the tunnels excavation with overburdens above 900 m, mainly in two geological formations, the intrusive and the metamorphic rock.

These events boost themselves in the presence of brittle rock and geological structures, happening either at the face excavation or behind the face in the reinforced sections. Most of the events occurred after the blasting in the unsupported area, provoking events ranging from sounds and cracks to violent rock ejections. In some cases the events happened behind the excavation, up to 500 m, damaging the installed rock support. Other dynamic events were induced by the simultaneous excavation of multiple drifts, principally in the powerhouse area.

All the recorded events were assessed and a classification was performed in order to establish the magnitude of the event and take actions directed to define suitable rock support and to ensure safety (Figure 5).

Stress Class	Description
0	Crackling and bangs in the surrounding rock mass.
1	Stress-induced spalling without rock fall: rock surface cracks suddenly, creating scales up to 5cm, dust clouds.
2	Stress-induced loosening or rock falls at lateral rock surface or face in the unsupported areas. Rock support system may be slightly damaged.
3	Heavy bangs and violent rock falls. Rock blocks and slabs are violently ejected. The rock support system is damaged.

Figure 5: Rockburst at the face excavation in the headrace tunnel.

3.2 *Variables involved in Cheves Hydropower project*

There are many aspects involved in the rockburst phenomenon. Kaiser and Cai (2012) summarized all of the related causes, namely: seismic events, geology (in situ stress, lithology, beddings, dykes, faults, etc.), geotechnical features (rock strength, joint fabric, rock brittleness, etc.), and mining (static and dynamic stress induced by mining, excavation span, extraction ratio, excavation sequence, rock support, etc.).

Records and analysis of all the rockbursts that happened during the construction of Cheves Hydropower project enabled the designers to determine the most significant variables involved in the phenomenon and establish control and mitigation procedures as well as designing special rock supports to ensure safe excavation.

It must be emphasized that about 850 rockbursts were recorded during the construction.

The main variables are summarized as follows:

a) **Overburden**: rockbursts started to happen above 850 m of overburden, where the natural stress is particularly high at about 23 MPa.

b) **Horizontal in situ stress**: the knowledge of the natural in situ stress field is essential for the numerical design of the excavations. For this reason, overcoring and hydro-fracturing tests were performed in the vicinity of the powerhouse, obtaining the following principal stresses: σ_1 = 21.7 - 22.1 MPa, σ_2 = 20.3 - 21.3 MPa, σ_3 = 12.8 - 13.7 MPa. The stress ratios K_0 vary from 0.62 to 0.96, showing a relatively low value. The in situ stress measured presents an orientation similar to the one obtained by geological estimations (N-45º-E).

c) **Lithology**: the most severe rockbursts turned up in the most brittle rock, linked to the Hornfel group. There were also rockbursts, but less severe, in the intrusive rocks (granodiorite and quartz-monzonite), but in these cases always with overburdens above 1.000 m. For this reason, the relation between rockburst and geomechanical rock mass quality has been analyzed.

d) **Joint sets and related structures**: there were very unfavorable joint systems during the tunnel excavation, like subhorizontal joints and subvertical and subparallel to the axis tunnel. In particular, the more severe rockbursts were recorded in relation with low dip structures.

e) **Induced stresses**: the excavation of multiple faces at the same time, as well as the existence of close excavations played a key role in the probability of rockburst events. This issue had a significant impact on the powerhouse area due to the great number of close drifts, as can be observed in Figure 6, in which the rockburst events are highlighted in orange (medium intensity) and red (high intensity).

f) **Seismicity and active tectonics:** Cheves hydropower project is located in a highly seismic area, where a correlation between natural seismicity and rockbursts was clearly observed.

Figure 6: Rockbursts record in the Powerhouse area.

4. ROCKBURST ANALYSIS

The assessment of 850 rockbursts in Cheves hydropower project enabled the designers to collect some results and conclusions that may be useful for other projects. The following charts provide the most relevant results obtained after analyzing the data.

Figure 7 compares the rockburst intensity and the overburden. It is noticeable that 75% of the events took place between 1,000 to 1,150 m of overburden. In this stretch the average was more than 1.0 events per linear meter of tunnel, and events between 1,100 and 1,150 m of overburden took place at a ratio of 3.5 events per linear meter of tunnel.

This distribution is strongly conditioned by others factors, in particular by the lithology.

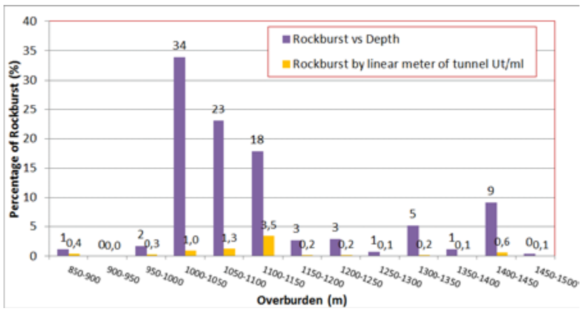

Figure 7: Overburden vs. rockburst and event by meter.

The rock mass rating (RMR) and the rockburst intensity are analyzed in Figure 8. Most of the severe events (stress class 3) belong to rock class II and I, i.e. when the RMR is higher than 61.

Another interesting analysis is the relation between the rockburst intensity and the time after blasting (Figure 9). It must be highlighted that the most severe events are located in the first ten hours after the blasting was carried out.

Finally, the relation between the blasting length and the number of events is analyzed in Figure 10. It´s worth mentioning an increase in the number of rockbursts in parallel to the increase of the blasting length. It can be observed that there is no clear relation between rockburst occurrence and the blasting length

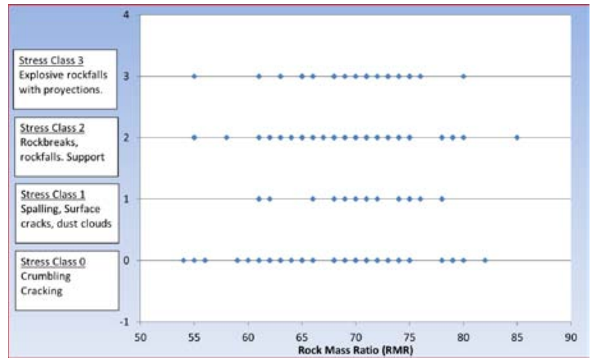

Figure 8: Rockburst intensity vs. RMR index.

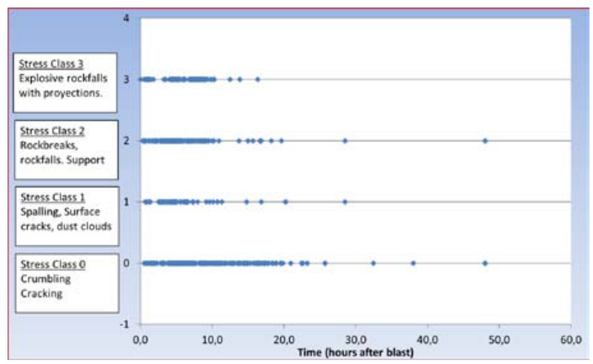

Figure 9: Rockburst intensity vs. time after blasting.

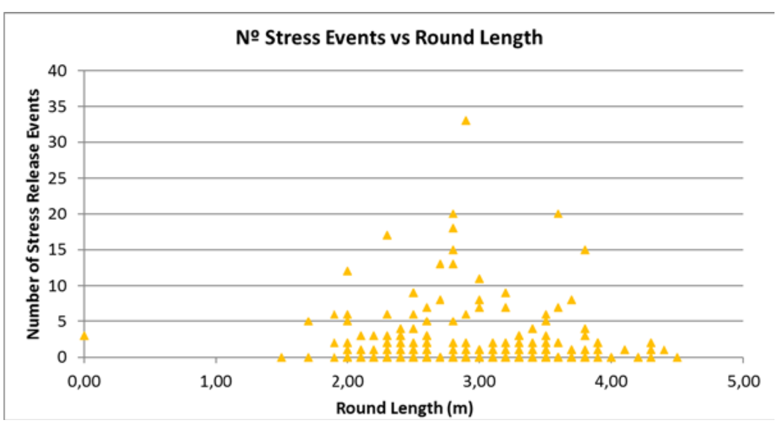

Figure 10: Blasting length vs. number of events.

5. ROCK SUPPORT AND MITIGATION PROCEDURES

Worldwide research on controlling the rockburst phenomenon provides guidelines to minimize the consequences and mainly guarantee the safety of the workforce inside the tunnel.

Rock supports will inevitably be damaged after a rockburst event, requiring repair works and reinforcements, but a proper design must provide a flexible support that is enough to resist the dynamic loads set by the rockburst, and therefore comply with the following aims: reinforce, retain (rock mass bulking) and hold, avoiding violent rock projections. Figure 11 shows this concept.

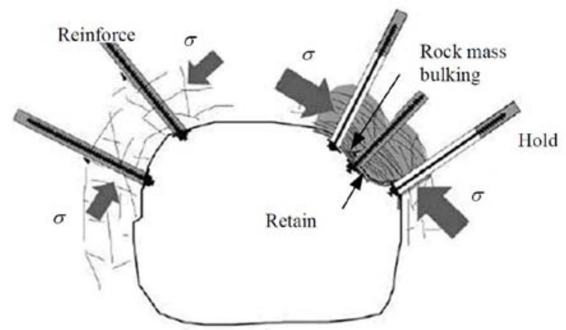

Figure 11: Requirements for an adequate support for dynamic events (Kaiser and Cai, 2012).

In the particular case of Cheves Hydropower project, the rock support was specifically designed to cope with rockburst events and high stress levels, consisting of long grouted rock bolts and double layer of fibre reinforced shotcrete with a welded wire mesh embedded in the shotcrete, which provided the required ductility against the dynamic loads.

The rock support was made of a high performance shotcrete with an UCS between 40 and 50 MPa and 6-7 kg/m^3 of plastic fibers or alternatively 40 kg/m^3 of steel fibers, obtaining more than 1.400 J in the panel test, according to the EFNARC requirements. Figure 12 shows this concept of a double-layered support.

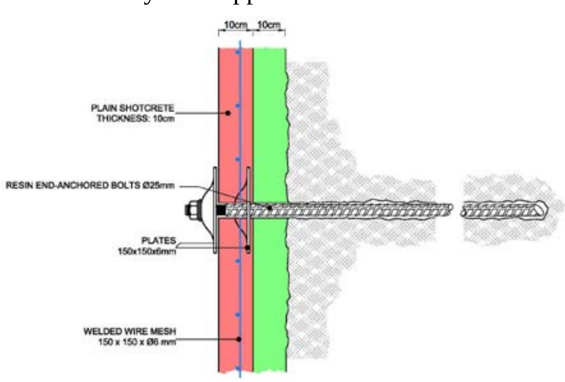

Figure 12: Rocksupport designed for high stress levels.

Additional protection measures were also considered during the excavation in rockburst prone conditions:

a) Mechanical scaling and reinforced machinery in order to protect the workforce at the tunnel face.
b) Apply a "sacrificial" layer of fibre reinforced shotcrete at the face and install temporary swellex rockbolts also at the face, with the aim of avoiding rock ejections from the face.
c) Install temporary swellex rockbolts in the cross section just after shotcreting the first layer, in order to stabilize the section and ensure the safety of the workforce during the process of finishing the installation of the remaining rock support.

The following procedures were also implemented as prevention measures against the rockbursts:

a) Preconditioning blasting ahead the excavation face, performed before the regular blasting, with the aim of reducing the rock mass quality by creating new cracks (Figure 13).

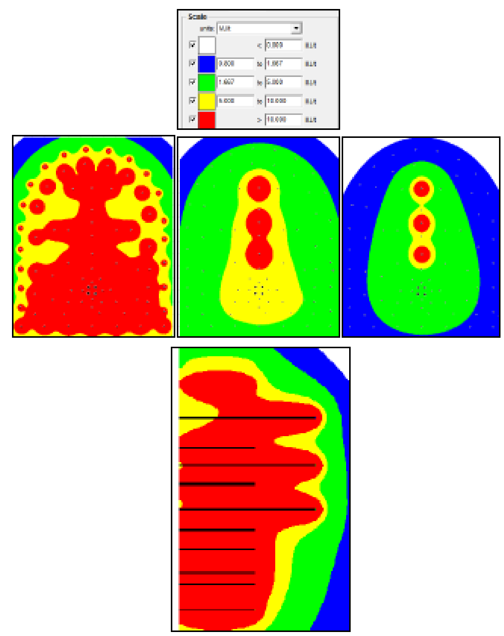

Figure 13: Energy distribution in a preconditioning blasting with 3 holes of 51 mm diameter charged with Slurrex.

b) Change the shape of the section to a concave geometry, as straight sidewalls always accumulate higher stress than a curved geometry.
c) Reduction of the blasting length. As it was mentioned before, a reduction of the blasting length may help to decrease the likelihood of severe dynamic events. It will also shorten the construction cycle and the time

that the workforce is exposed under an unsupported section.

The following figure shows a scheme of the temporary rock support installed at the face and the preconditioning blasting layout:

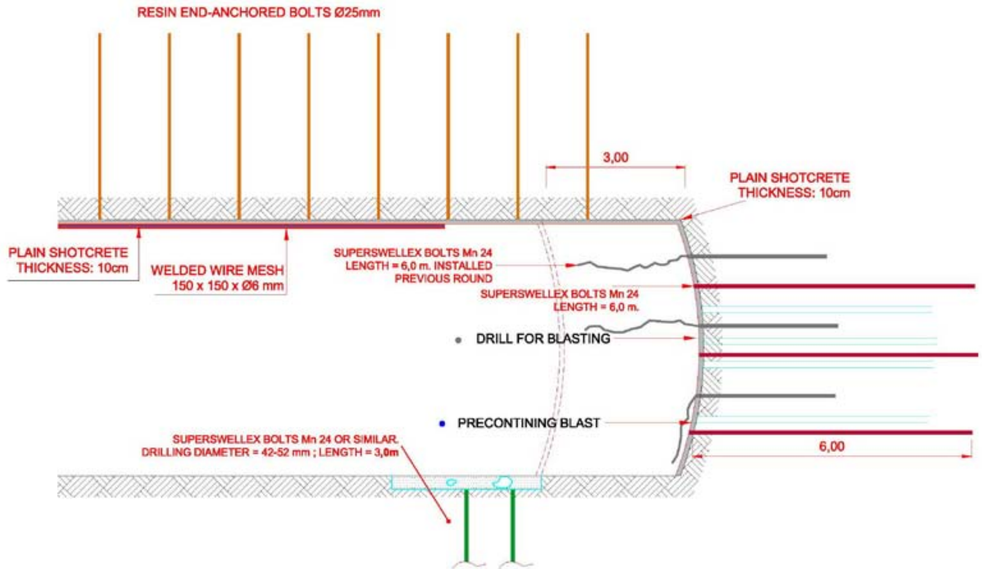

Figure 14: Combination of protection and prevention measures at the excavation face in rockburst prone conditions.

6. 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.

Specific support measures shall be implemented in the tunnel design in order to mitigate the adverse effects of the rockburst and stress releases, especially to provide a safe environment for workers.

Each project shall be analyzed, however the experiences from Cheves Project specifically can be used for extrapolation.

The support measures described in this paper were effective during the construction period. The support consisted of an integrated system (1) reinforced the rock mass to strengthen it, (2) retained broken rock to prevent fractured block failure, and (3) held fractured blocks and securely tied back the retaining element(s) to stable ground.

7. ACKNOWLEDGEMENT

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