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Geotechnical instrumentation in high seismic risk tunnels and support replacement criteria

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Abstract

The Andes Norte project is developing a tunnel located in a high seismic risk zone with two excavation faces. This access tunnel will be used to transport future production from sectors of Division El Teniente de Codelco via a conveyor belt.

Both development faces are located in a complex environment dominated by high stress and anisotropy in rock masses with fragile behaviour, in addition to complex geological and structural conditions. This produces an unfavourable seismic response, with high event frequency, high local magnitude and different types of focal mechanisms.

The unfavourable seismicity recorded through tunnel construction has resulted in the consumption of support capacity which could result in the development being unfit for service in a worst-case scenario. This has driven Codelco to implement support systems with higher energy dissipation capacity, which currently makes this tunnel that with the highest installed support capacity in Division El Teniente.

In order to understand the behaviour of the reinforcement system installed and its consumed capacity after a seismic event, a monitoring system has been deployed that includes load cells and dataloggers capturing data at a high frequency rate. In addition, topographic data has been collected on a regular basis using a laser scanner, allowing the deformation measured in the tunnel due to seismic events to be recorded and analysed.

This paper will describe the installation methodology, information analysis and the resulting support replacement criteria, and present two case studies.

Keywords: *geotechnical instrumentation, load cells, deformation, seismicity, reinforcement, energy dissipation*

1 Introduction

Codelco VP Chile's Andes Norte project is developing a conveyor tunnel (TC) that is part of the main infrastructure and will be used to transport ore from Andes Norte and other productive sectors of Division El Teniente for the next 50 years. The construction faces of the tunnel are located in an environment with high stress, high stress anisotropy, and complex geological and structural conditions. This has generated an unfavourable seismic response, with a high frequency of seismic events having high local magnitude.

This unfavourable seismic response has caused the capacity of the support system to be consumed to a lesser or greater extent, leading to failure and causing rockbursts in the worst case.

To properly assess the behaviour of the installed support system and its capacity to resist deformation due to seismic events, a monitoring system has been implemented using load cells connected to dataloggers for

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capturing data at high frequencies. Additionally, topographic surveys with laser scanners are conducted to record tunnel deformations caused by seismic events.

With back-analysis of the data collected it is possible to estimate and quantify the support capacity consumed by a seismic event, and to establish criteria for either complete replacement of the support system or to complement it with additional reinforcement to maintain the original design support capacity.

This document will address the methodology of installation, information analysis, case studies, and criteria for the complete or partial replacement of the support system.

2 Geotechnical instrumentations

Geotechnical instrumentation for monitoring within the TC consists of the following:

- load cells with sample rates of 2,400 Hz and one measurement every 10 minutes
- topographic surveys using a laser scanner and deformation analysis.

2.1 Load cells

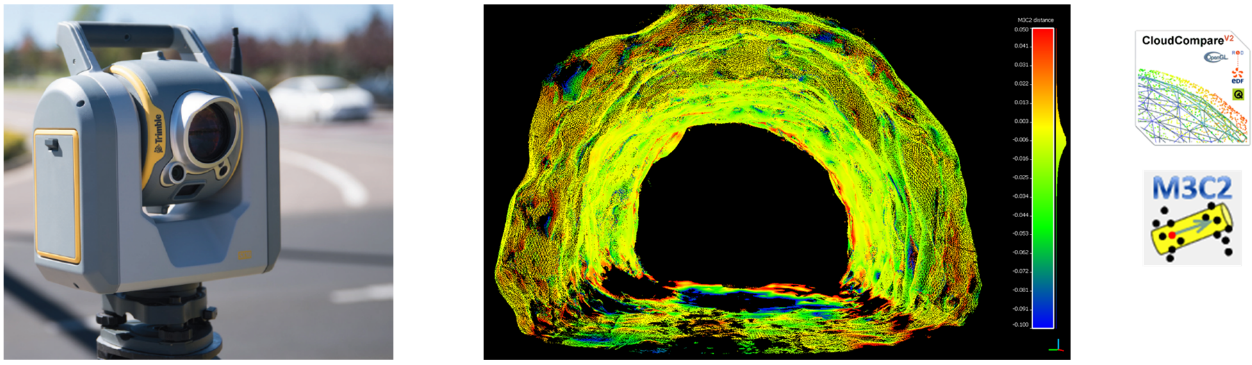
Electronic load cells from Sisgeo (Model 0L207V05000) with 4–20 mA output have been implemented in the monitoring system. The 500 kN model was chosen because the helical bolt used in the support system has a maximum capacity of 37 t. A 71 mm diameter has also been selected for use in the support system, which is comprised of double cable bolt. A Loadsensing wireless node (model LS-G6-ANALOG-4) with capacity for four sensors has been used for storage of the collected data (Figure 1). In addition, an HDM datalogger (model Quantum CX-22B-W) with a sampling rate of up to 4,800 Hz and a capacity for eight sensors has been used.

(a) (b)

Figure 1 (a) Sisgeo 500 kN load cells; (b) Loadsensing four-channel datalogger

2.2 Topographic survey with laser scanner

For the point cloud recording of the tunnel, a Trimble laser scanner (model SX10) is used, with monitoring stations spaced 15 to 20 m apart. This avoids having sectors without coverage in areas with irregular tunnel geometries (Figure 2).



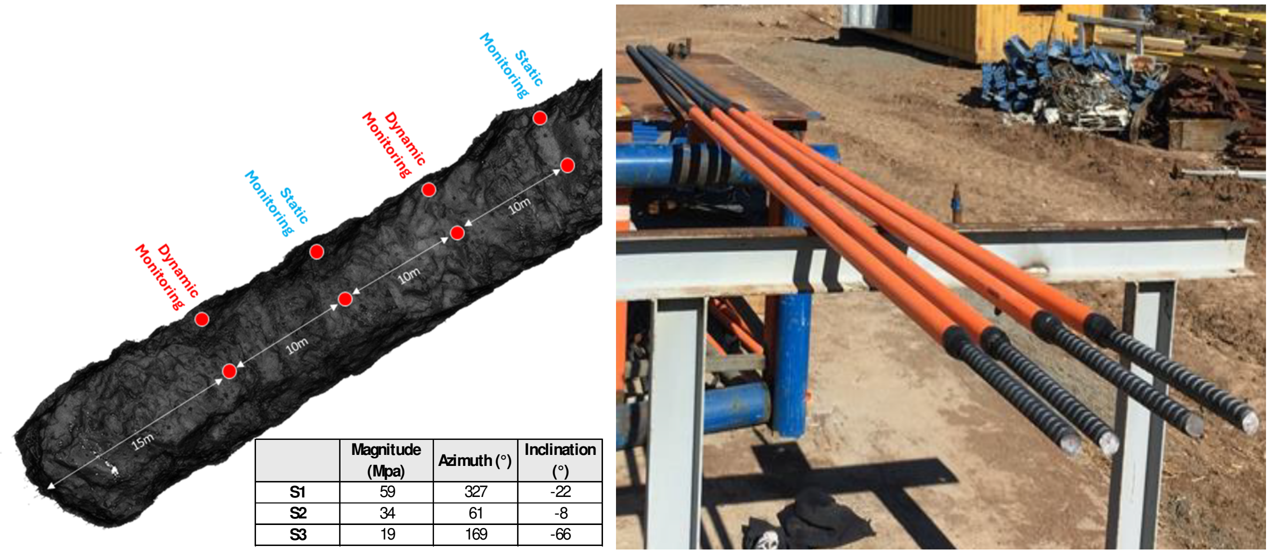
(a) (b)

Figure 2 (a) Trimble SX10 laser scanner; (b) Point cloud analysed

3 Installation methodology

3.1 Load cells

Load cells are installed as the tunnel construction progresses, following a defined spatial configuration which is shown in Figure 3. This configuration was chosen based on the direction of principal stress and the location of observed overbreak. relative to the design tunnel geometry. To install a load cell on a helical bolt, the bolt must be sheathed for 50% of its length and at least 12 hours of setting time should be allowed. It is recommended to do the drilling as perpendicular as possible to the geometry of the tunnel. Once the helical bolt, load cell, plate and nut assembly have been installed, the bolt should have a torque applied to induce a preload of approx. 50 kN (Aguilera et al. 2022).



	Magnitude (Mpa)	Azimuth (°)	Inclination (°)
S1	59	327	-22
S2	34	61	-8
S3	19	169	-66

(a) (b)

Figure 3 (a) Typical distribution of load cells in the tunnel; (b) Sheathed helical bolt for load cell

3.2 Sample rate frequencies and data records

Once installed, the load cell will continue monitoring constantly with time, which allows detection of changes due to seismic events. All data collected is stored in a datalogger and then is extracted and analysed.

Load cells are currently configured for two types of monitoring:

- Static monitoring – load cells are configured with a sample rate of one measurement each 10 minutes. This is the most common use of this instrument. The mean goal of this measurements is to evaluate how much of the reinforcement system capacity has been consumed over long periods of time.

- Dynamic monitoring – load cells are configured with a sample rate of 2,400 Hz. The mean goal in this type of monitoring is to visualise and analyse how the ground support system behaves in the specific moment a seismic event occurs. The ground support or reinforcement system behaviour is typically evaluated during blasts and when a relevant seismic event occurs. The load cells are connected to a datalogger that stores all the data recorded. When a blast or a seismic event occurs, the data is extracted from the datalogger and then analysed in detail.

4 Information analysis methodology

Data collected from load cells configured in static mode are analysed to obtain the entire history of support system behaviour over time and evaluate significant variations.

The principal innovation implemented in main infrastructure tunnels comes from load cells configured for dynamic monitoring, where the main goal is analysing support system behaviour in higher detail. To achieve this, a time series of the recorded signal is analysed, estimating the difference in load before and after a seismic event or blast, and the maximum amplitude recorded. In addition, a spectrogram of the signal is calculated to determine the dominant frequencies, which provides information on how the support system is affected by a low or high frequency vibration. In some cases important transient variations in load have been observed over very short time periods during a seismic event, lasting seconds or milliseconds, but after the event the cell recovers its initial load. Those changes can't be observed through static monitoring. Therefore, if only static monitoring is used, the impact of the seismic events on the support system might go unnoticed, leading to an overestimate of its useful service life.

Having studied several events it is clear that a support system behaves differently depending on the seismic source mechanism of the event. Differences detected between the two most common seismic source mechanisms identified in main tunnels follow:

- Crush type (strainburst) – this seismic source is associated with a rock mass deformed by stress and dominated by the stress direction over the tunnel. Given a certain orientation of principal stress, deformation will occur perpendicular to the axis of principal stress. Crush-type seismic source mechanisms require a cavity that allows deformation of the rock mass towards the tunnel (source dominated by implosive component), transforming the excavation geometry near the source of seismic event. One hypothesis proposed is that this type of event causes the highest impact on the support system, consuming a significant amount of its capacity. Data analysed has confirmed this statement.

- Slip type (fault slip) – this seismic source mechanism describes a rupture along an existing structure; for example, a fault plane. The main characteristic of this type of event is that they cause a significant vibration in the area where rupture begins. Therefore, the transitory vibration causes the most significant impact on the support system. However, these types of events rarely cause important volumetric deformation around the excavation.

Observation of seismic events recorded in tunnels during crush-type events shows that there is a significant change in the load imposed on the support system. However, it is not common to observe high frequency vibration during the event. On the other hand, for slip-type events, low changes in load have been observed before and after the event but high amplitude vibration with high frequency have been observed during the event. Figures 4 and 5 show the differences between both seismic sources and how the load behaves over time in each case.

From these results, the importance of knowing the type of seismic source provides information on how the support system is affected by each type of event. If the event is a crush type, a volumetric deformation process is produced on the tunnel itself, causing greater damage than observed for a slip-type event of the same order of magnitude and energy. On the other hand, if the recorded seismic event is a slip type it will impact the support system through the vibration generated on the tunnel during the rupture process, which generates a lower stress change on the support system once the event ends.

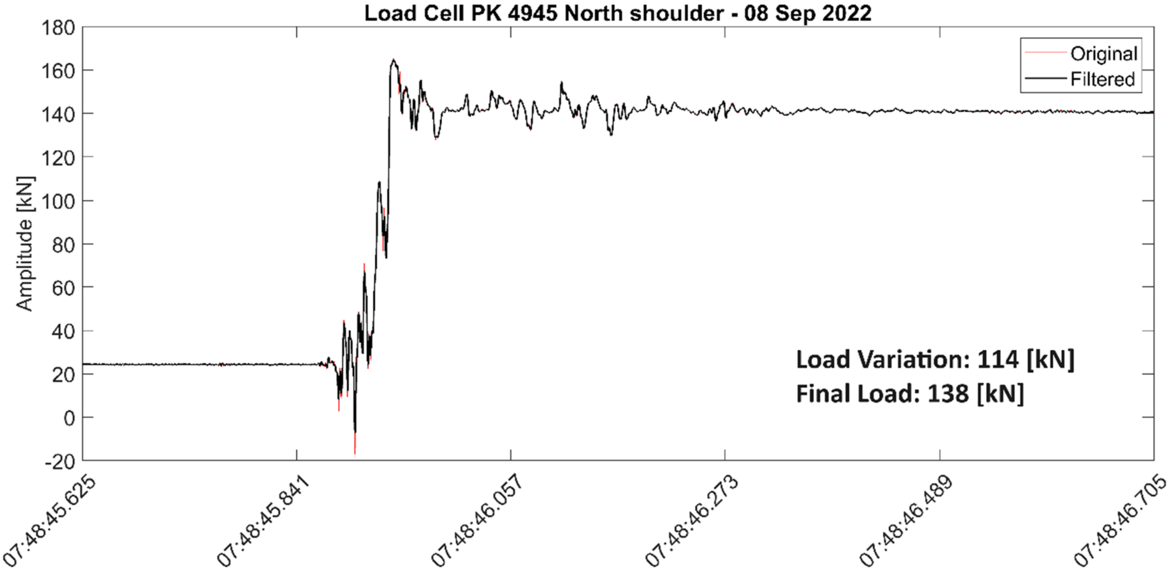


Figure 4 Signal recorded from dynamic monitoring for a crush-type event. Data shows a significant change in load that remains after the event

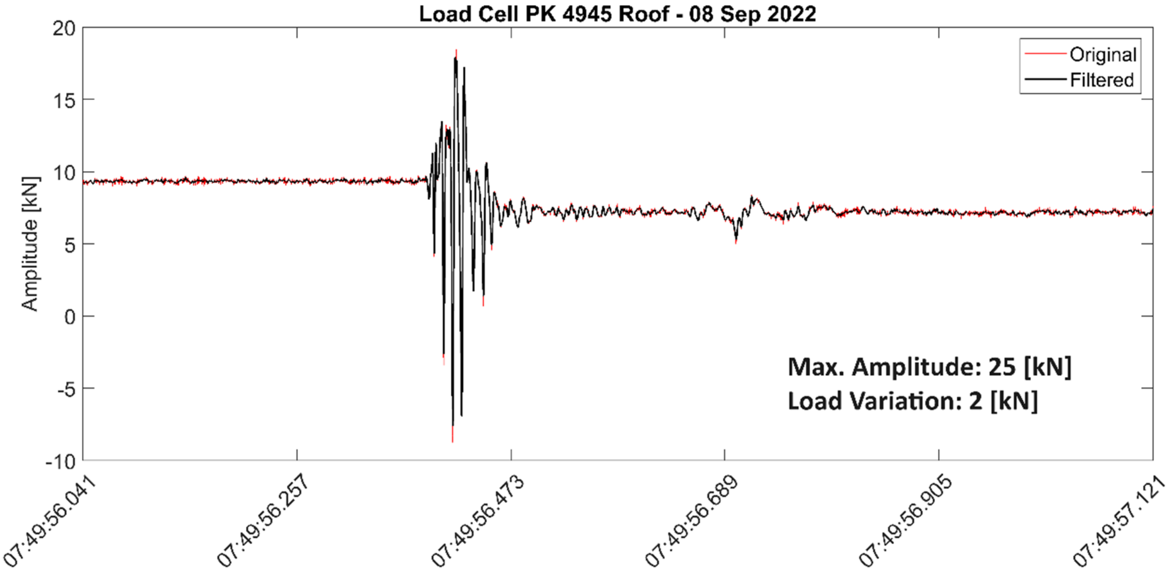


Figure 5 Signal recorded from dynamic monitoring for a slip-type event. Data shows amplitude variations during a seismic event, but low changes in load before and after the event

5 Case studies and discussion

5.1 Seismic events MW1.2 and MW1.7, conveyor tunnel P0 front

As a result of development blasts #235 and #236 in the CT front P0 (TC-P0), two seismic events with magnitudes of MW1.2 (crush type) and MW1.7 (slip type) were recorded. The events had energies of 8.7*10^5 (J) and 5.1*10^6 (J), respectively (see Figure 6). For the slip-type event, one of the solution planes agrees with the structural set 15/280 (dip/dipdir) orientation, which is sub-horizontal and predominant in some locations within the tunnel. It is worth mentioning that the presence of this structural set is associated with a greater frequency of slip-type events (Figure 7) (Bahamondes et al. 2022a).

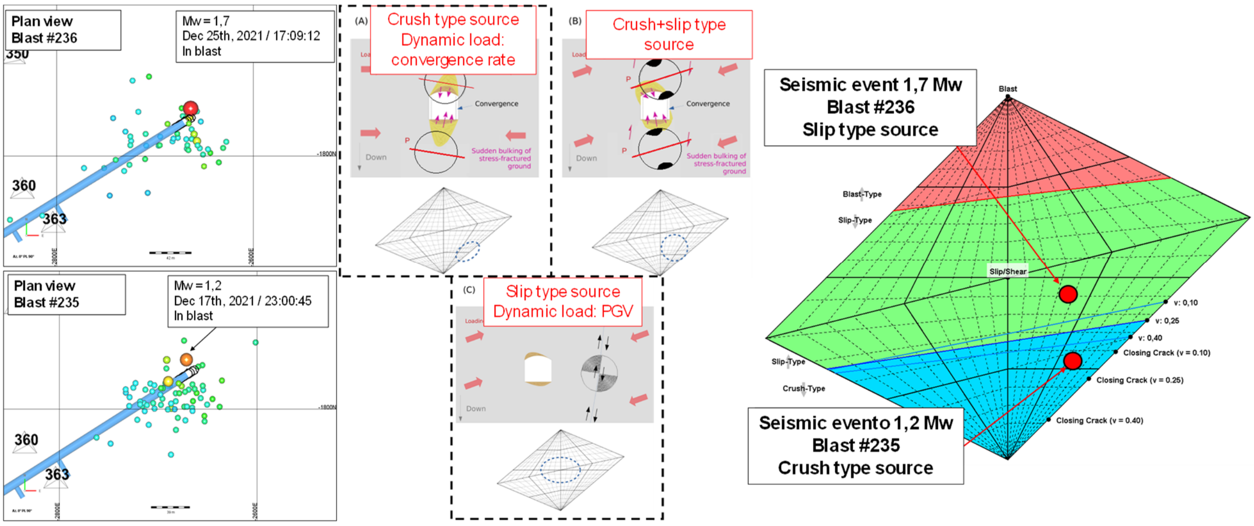


Figure 6 Seismicity associated with blasts #235 and #236 TC-P0. Seismic events of MW1.2 magnitude (crush-type source) and MW1.7 magnitude (slip-type source), respectively, were recorded

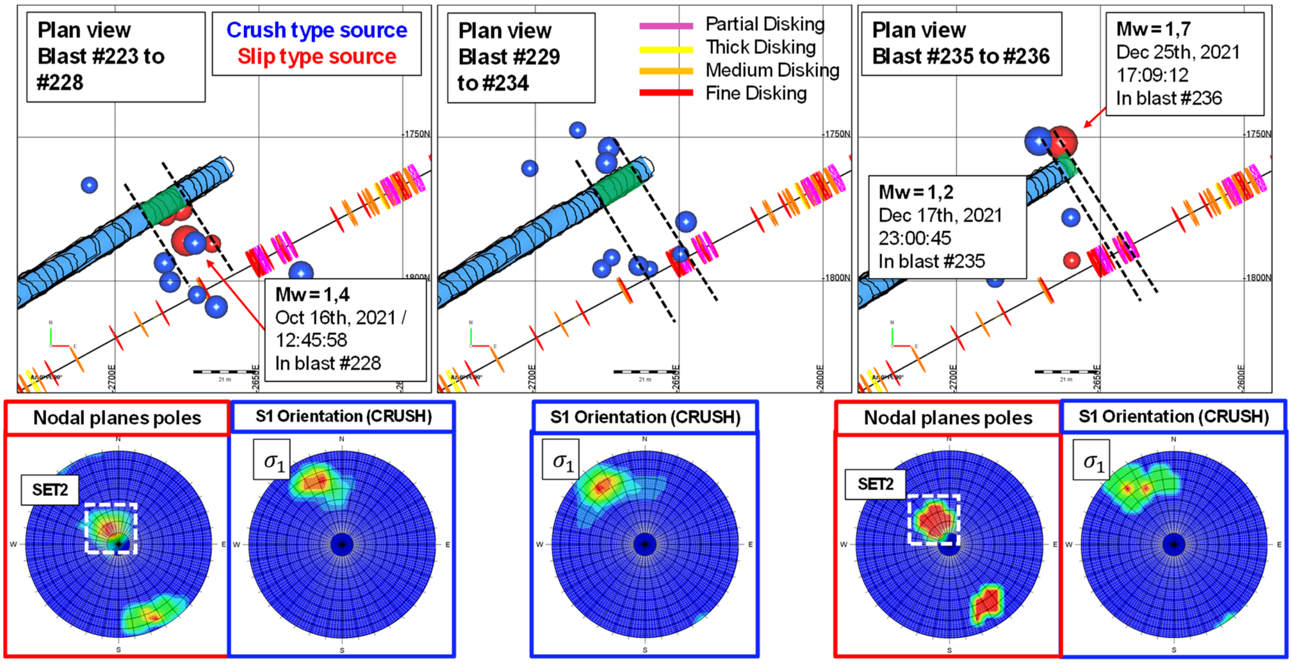


Figure 7 Seismic source types identified from blast #223 to #236 and their relationship with the presence of set two (sub-horizontal)

From the monitoring carried out using load cells (Figure 8) it has been verified that the type of seismic source is important to understand the dynamic load experienced by the support system. In the case of the MW1.2 crush-type event, the tunnel perimeter failure forms the seismic source and the dynamic load corresponds to the convergence rate during deformation, which implies a high probability of damage generation. On the other hand, the MW1.7 slip-type event that occurred in the next tunnel development blast shows lower load changes on the support system than the MW1.2 event, although its energy and magnitude are greater.

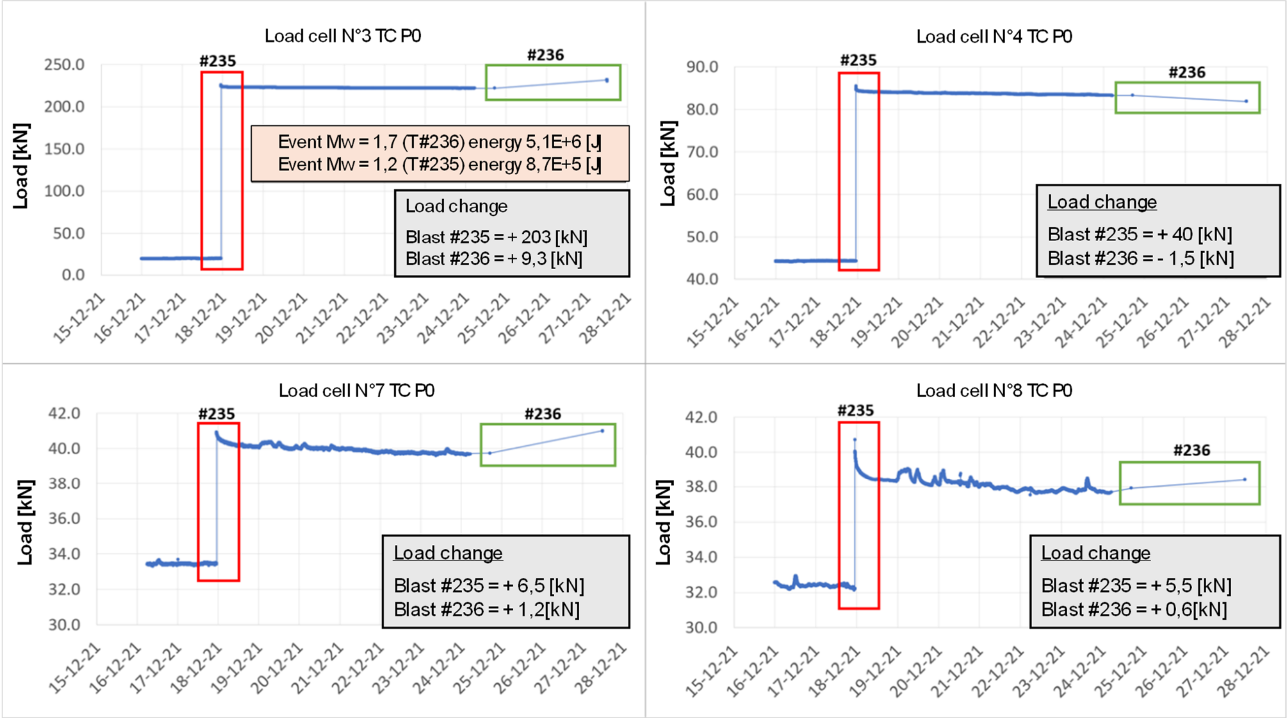


Figure 8 Static monitoring of load cells installed in TC-P0 front for blast #235 and #236. Seismic events of MW1.2 and MW1.7 magnitude, respectively, were recorded

5.2 Seismic event MW1.8, conveyor tunnel P0 front

On 8 September 2022 at 07:47 hours, development blast #277 of the TC-P0 was fired. Induced by the blasting, three seismic events of local magnitude MW1.8 (crush type), MW1.0 (slip type) and MW1.6 (slip type) were recorded. The events radiated energy of 2.51*10^7 (J), 6.23*10^5 (J) and 4.71*10^6 (J), respectively, as shown in Figure 9. (Bahamondes et al. 2022b).

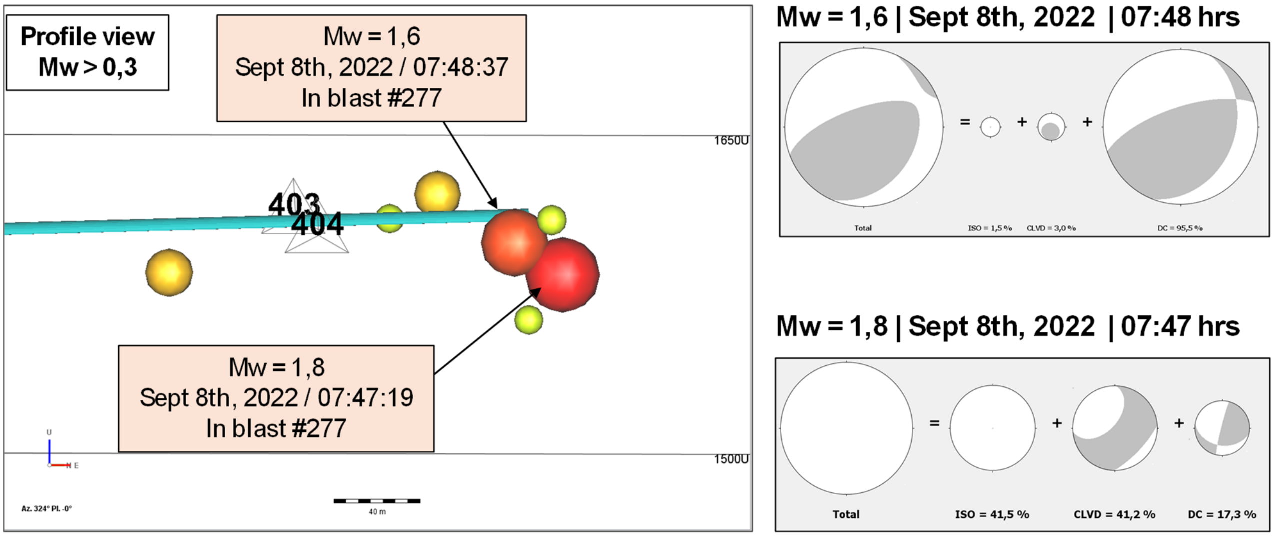


Figure 9 Profile view of seismic events MW > 0.3 recorded after blast #277. Focal mechanisms' decomposition for MW1.6 slip-type and MW1.8 crush-type seismic events

After the occurrence of the seismic events, damage observed in the development covered an extent of 100 m from the tunnel face and included shotcrete cracking, slight bulging, floor rise and deformed support system elements. It is important to mention that the damage was restricted to certain sectors of the tunnel and the rock mass was 100% contained by the installed support, as shown in Figure 10.

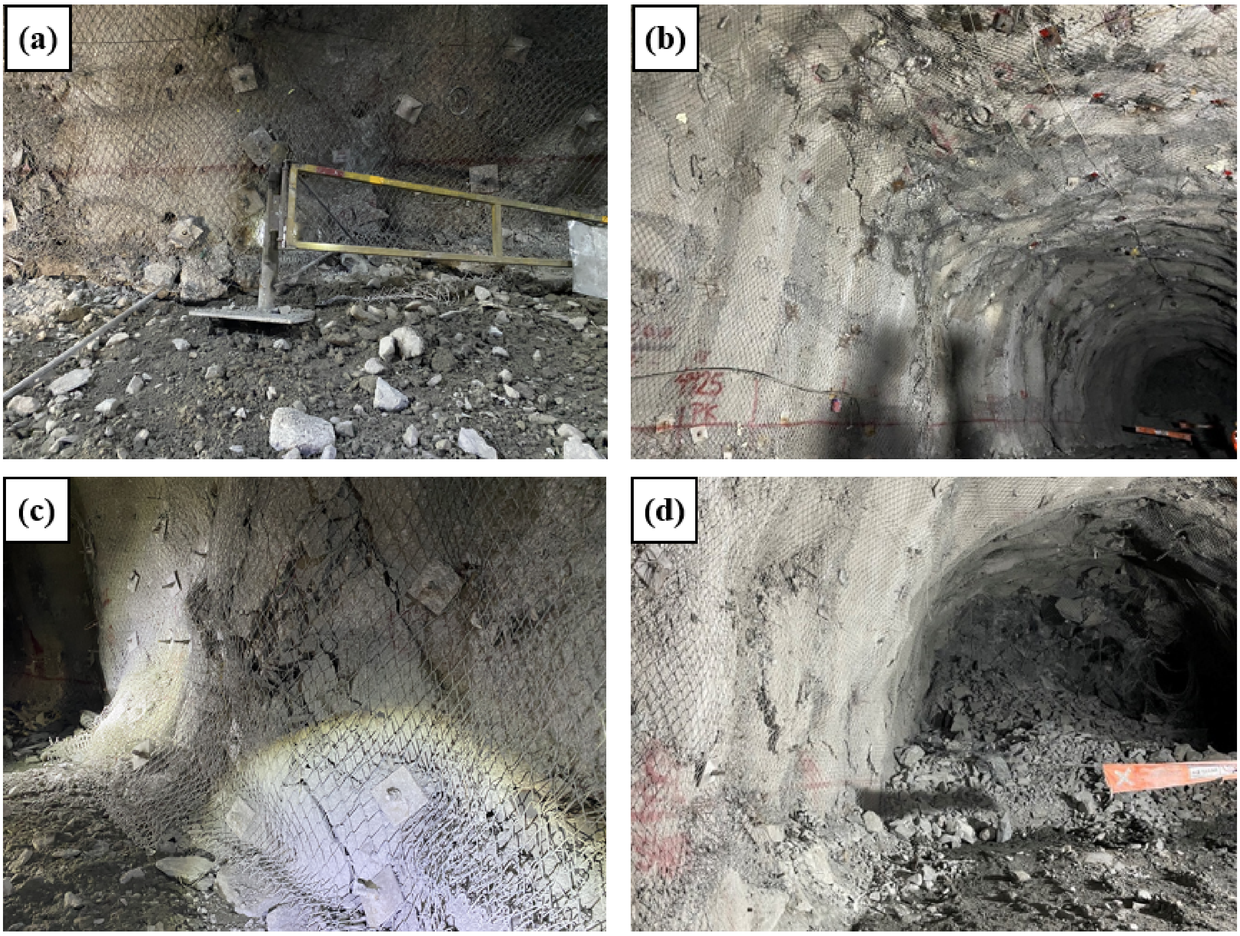
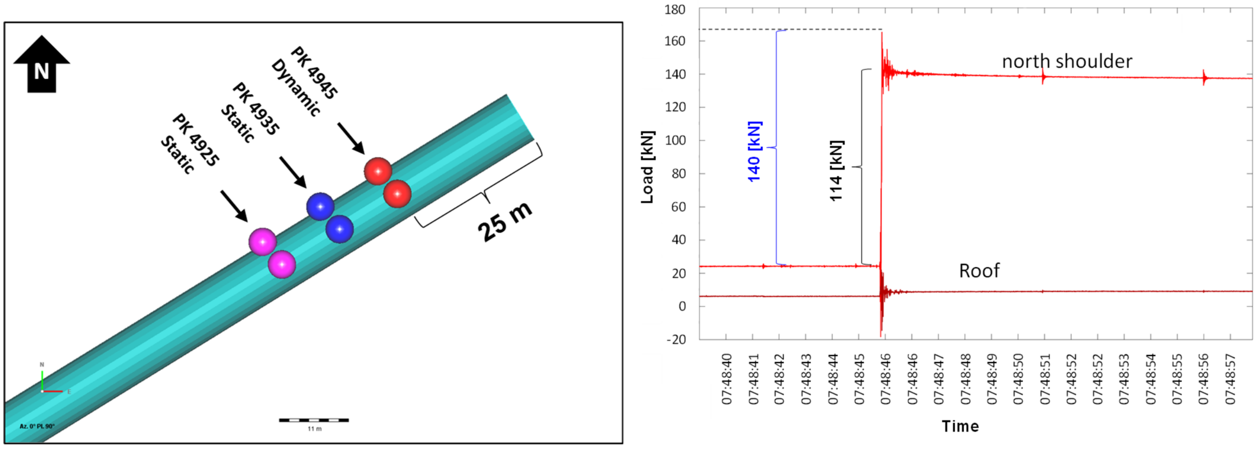


Figure 10 **Ground inspection after seismic events; (a) Floor rise; (b) Slight bulging of north shoulder; (c) Slight bulging of south wall; (d) North wall cracking**

During the execution of blast #277, six load cells were active: two of them with dynamic monitoring at a sampling rate of 2,400 Hz (pk 4945) and the remaining four in static monitoring with a sampling frequency of one every 10 minutes (pk 4935 and pk 4925, respectively). Figure 11 shows a schematic diagram of the location of the load cells.

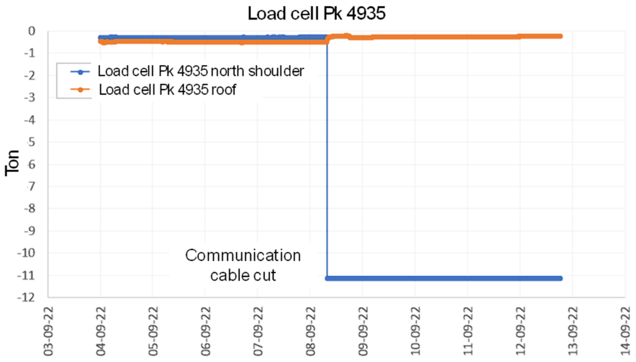


(a) (b)

Figure 11 **(a) Scheme of the locations of load cell installed in TC-P0; (b) Dynamic monitoring signal of load cells located in pk 4945**

Analysing the information of the load cells in dynamic mode (pk 4945) shows that the greatest variation is recorded in the cell located in the north shoulder, which reached a peak of 140 kN (approximately 14 t) and left a final load in the system of 114 kN (Figure 11).

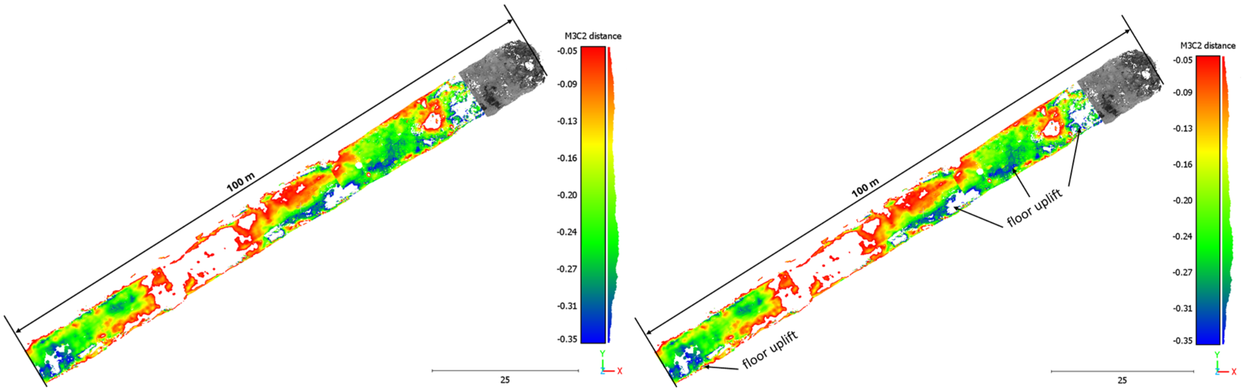
Load cells in static monitoring located at pk 4935 show no load variation in the roof sector, and in the north corner the cell suffers a cut in the communication cable. It is not known if this is a product of the blasting or a seismic event. The last pair of cells at pk 4925 shows a load variation only in the north corner, leaving a final load of approximately 18 t (Figure 12).



(a) (b)

Figure 12 Static monitoring data from load cells: (a) Pk 4935; (b) Pk 4925

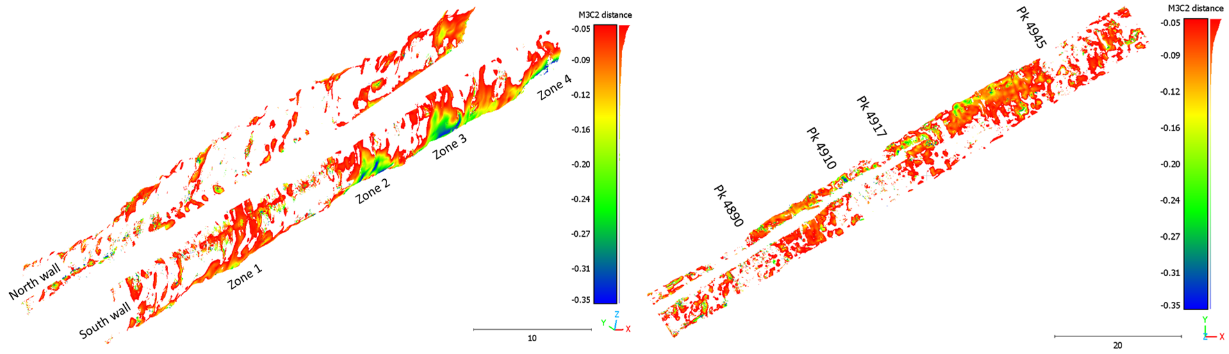
Using the M3C2 algorithm in Cloudcompare software, point clouds of #277 advance (after seismic events) were compared with the previous scans covering an analysis length of about 100 m back from the tunnel face. When analysing in detail by sectors there is a correlation between the observed floor uplift in field and the deformation analysis (Figure 13). The values of difference are negative and correspond to a convergence-type deformation.



(a) (b)

Figure 13 (a) Results from deformation analysis of a tunnel after seismic events; (b) Deformation evidence observed in analysis and its match with the ground inspection

In addition, deformation analysis of north and south tunnel walls shows specific zones where cracking and slight buckling were observed, and deformation was also observed in the roof (Figure 14).



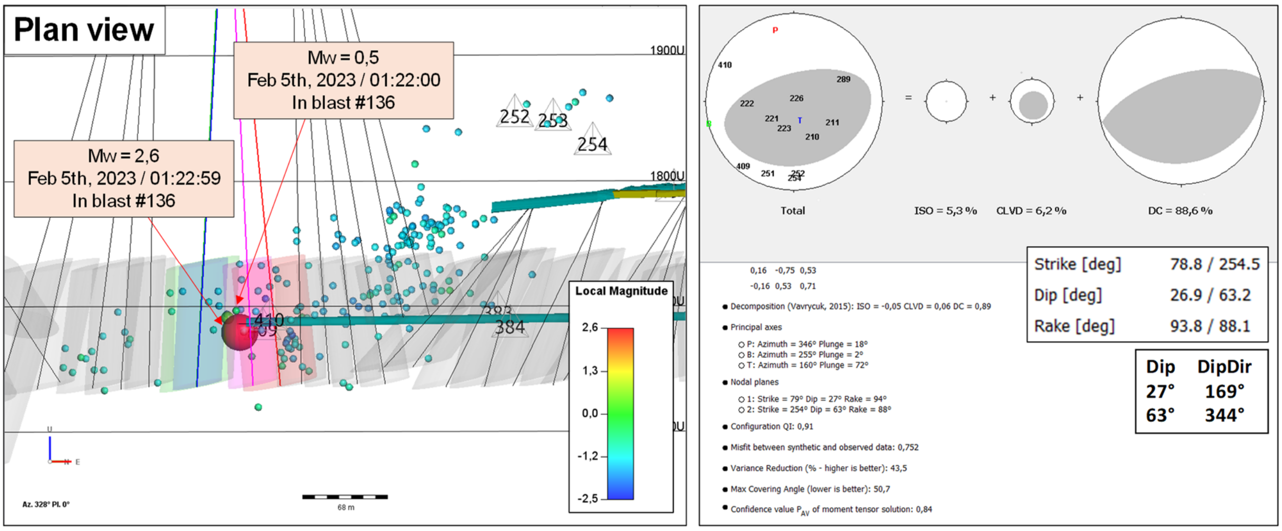
(a) (b)

Figure 14 **(a) Results from deformation analysis in the north and south walls; (b) Deformation analysis in the roof and corners**

Finally, deformation analysis between tunnel bends was also consistent with field observations and load cell records.

5.3 Seismic event MW2.6, conveyor tunnel OIM front

As a result of the advance blast #136 of CT OIM front (TC OIM), a large seismic event with magnitude MW2.6 (fault slip) and radiated energy of 2.8*10^8 (J) was recorded (Figure 15). The seismic event generated deformations in the tunnel contour over a distance of 100 m without ejection of the rock mass inside the tunnel (Figure 16) (Cordova et al. 2023).



0,16 -0,75 0,53
-0,16 0,53 0,71

- Decomposition (Vavrycuk, 2015): ISO = -0,05 CLVD = 0,06 DC = 0,89
- Principal axes
  - P: Azimuth = 346° Plunge = 18°
  - B: Azimuth = 255° Plunge = 2°
  - T: Azimuth = 160° Plunge = 72°
- Nodal planes
  - 1: Strike = 79° Dip = 27° Rake = 94°
  - 2: Strike = 254° Dip = 63° Rake = 88°
- Configuration QI: 0,91
- Misfit between synthetic and observed data: 0,752
- Variance Reduction (% - higher is better): 43,5
- Max Covering Angle (lower is better): 50,7
- Confidence value P_{AV} of moment tensor solution: 0,84

Strike [deg]	78.8 / 254.5
Dip [deg]	26.9 / 63.2
Rake [deg]	93.8 / 88.1

Dip	DipDir
27°	169°
63°	344°

(a) (b)

Figure 15 **(a) Seismic event location in section view; (b) Focal mechanism decomposition**

Figure 16 Photographic register from the ground inspection after a seismic event. Deformation is evident in the contour of the excavation

From the analysis of load cell data it was observed that the highest transient load recorded was 272 kN, while two other cells had values of 70 kN, with a permanent load change of 50, 5 and 20 kN, respectively, as shown in Figure 17.

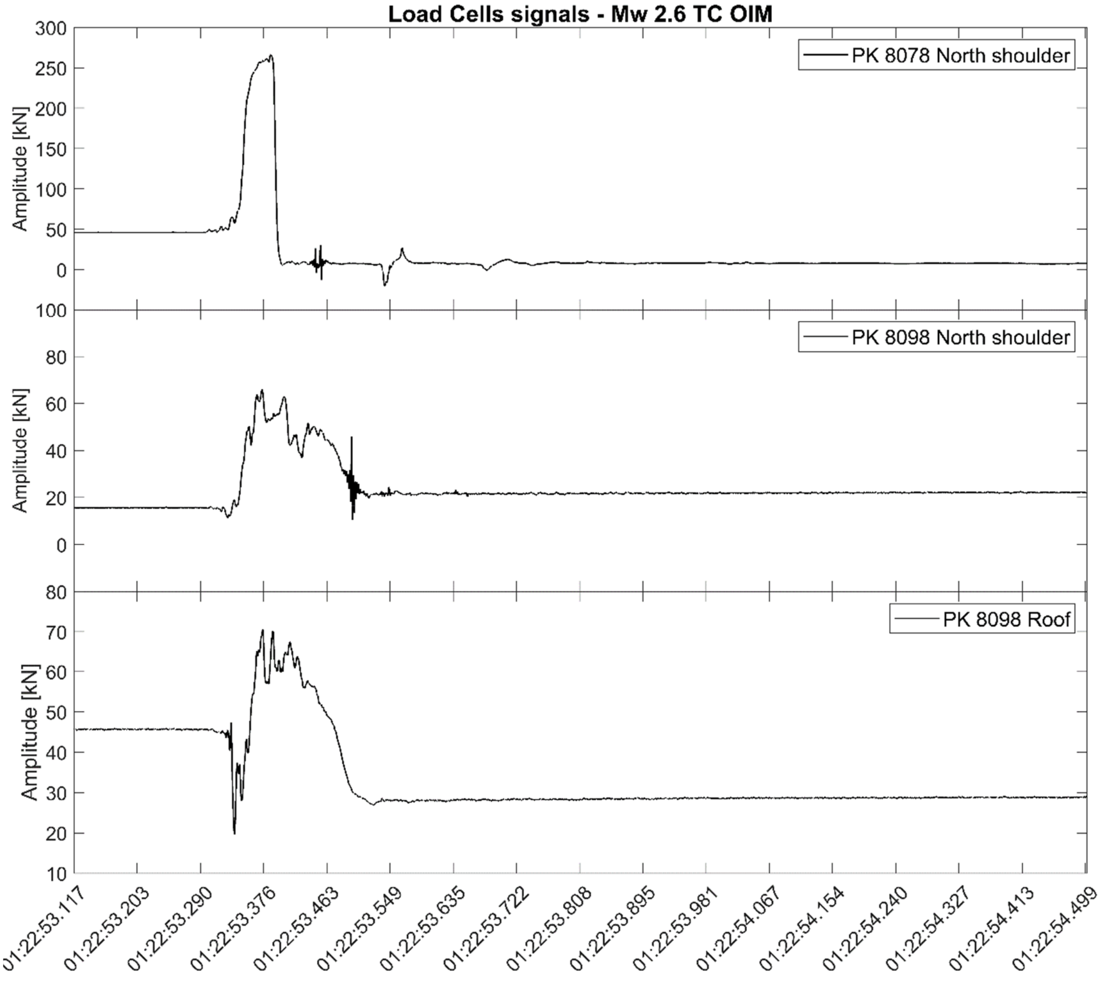


Figure 17 Dynamic monitoring signal from load cells installed in a tunnel

Figure 18 shows deformation analysis performed on two sectors of the tunnel. In this case a filter was applied to only show deformations over 20 cm.

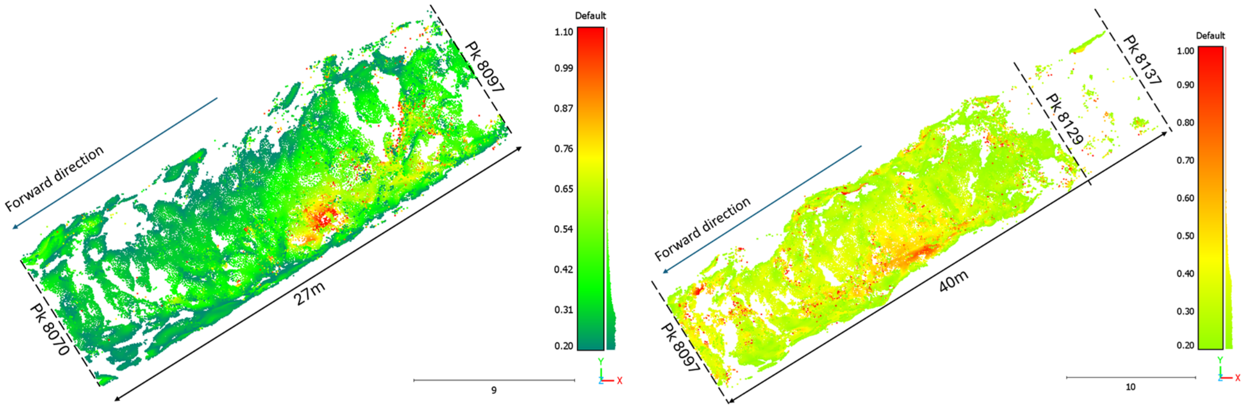
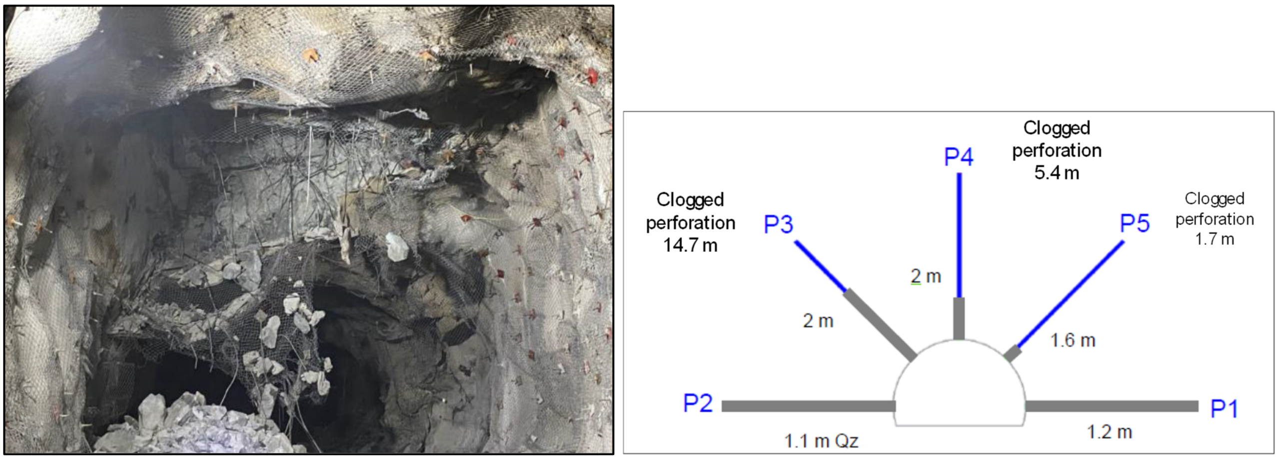


Figure 18 **Deformation analysis results from a laser scanner. Two sectors with deformation of over 20 cm are shown**

As a result of deformation recorded along the tunnel, five boreholes were drilled to introduce an inspection camera to determine the depth of the damage after the seismic event. Figure 19b shows the borehole orientation relative to the tunnel contour. The blue line represents the 25 m borehole, the grey line represents the depth reached when introducing the camera, and the numbers, in metres, represent a disturbed zone characterised by fractured rock. From the borehole camera logs it was possible to estimate, on average, a depth of failure of about 1.8 m in the north wall and 1.5 m in the south wall.



(a) (b)

Figure 19 **(a) Depth of damage observed during rehabilitation; (b) Drill orientation relative to the tunnel contour**

With this data and assumptions, combined with the record of higher load in cells, it is possible to estimate the value of energy as a function of deformation (Table 1). This tunnel has a support system with high energy absorption capacity, composed of a helical bar with A706-G80 steel, double cable bolts and two layers of rhomboidal mesh with a 63 mm opening. Knowing the capacities, maximum tolerances and dynamic laboratory tests of the reinforcing elements it was determined that, in the case of the cables, at 9 cm of deformation the support fails and at 5 cm almost all the energy has been dissipated. In the case of the helical bolts: at 5 cm, 25% of the energy has been dissipated; at 13 cm of deformation a little more than 50% has been consumed; and at 23 cm, the maximum displacement has been reached.

Table 1 (a) Energy variation as a function of displacement; (b) Bar displacement due to deformation

Force (N)	Displacement (m)	Energy (kJ)
272,100	0.00	0.0
	0.03	6.8
	0.05	13.6
	0.08	20.4
	0.10	27.2
	0.13	34.0
	0.15	40.8
	0.18	47.6
	0.20	54.4
	0.23	61.2
	0.25	68.0
	0.28	74.8
	0.30	81.6

(a)

Damage depth (cm)	Scanner cable	Scanner bolt A706
60	3	8
80	4	10
100	5	13
120	6	16
140	7	18
160	8	21
180	9	13
200	10	26
220	11	29
240	12	31
260	13	34
280	14	36
300	15	39

(b)

Based on the above it is possible to determine rehabilitation criteria for the tunnel, either by assuming the support capacity has been exceeded in areas with greater deformation and replacing it with new support according to the design or, in areas with less deformation, installing additional support to replace the dynamic capacity consumed by seismic events (Table 2).

Table 2 Recommended support rehabilitation criteria of the tunnel

Deformation rate (cm)	Bolt pattern 2 × 1	Bolt pattern 1 × 1	Cable pattern 2 × 1
5–15	Add		Add
15–23		Add	Add
>23		Replace	Replace

6 Conclusions and recommendations

6.1 Conclusions

- For a tunnel excavated within a rock mass with high stress, high anisotropy and fragile behaviour it is important to have a seismic monitoring system in place to capture the induced seismicity and then analyse it to determine the locations of these events and the predominant failure mechanisms.
- In addition, it is necessary to know the behaviour of the installed support system during and after a seismic event, and the applied dynamic stress.
- Integration of instruments such as load cells connected to dataloggers with high sampling rates (dynamic monitoring) have made it possible to observe deformations that, in some cases, may otherwise go unnoticed in the field, and which allowed the taking of preventive action to reinforce the installed support.

- It is interesting to see how, through dynamic monitoring, the impact of a seismic event on the reinforcement or support system can be evaluated with greater precision. It is also relevant to note that this type of monitoring shows differences in the response of the support system to different seismic failure mechanisms. The results observed through the load cells confirm that determining the failure mechanism is key to understanding its impact on the tunnel.
- Crush-type events are those that generate the greatest dynamic stress on the support system in relation to their magnitude, i.e. it is not necessary to have a large seismic event to have damage in the installed support system. Additionally, it is necessary to mention that since the seismic frequency rate is inversely proportional to the magnitude of the event, this type of seismic event has the greatest probability of generating complications in the construction process of tunnels.
- Additionally, monitoring using load cells (static or dynamic) allows understanding of the consumption of the support system capacity and how much is available after a seismic event.
- The integration of a laser scanner, ground inspections, deformation analysis and borehole camera inspections of the rock mass has allowed the specification of a rehabilitation criteria for the tunnel, either by assuming a total loss of support capacity in areas with greater deformation and replacing it with new reinforcing members according to the original design, or by installing additional support to replace the dynamic capacity consumed by the event.

6.2 Recommendations

- For tunnel development within a rock mass with high stress levels, high anisotropy and fragile behaviour it is important to keep seismic monitoring and geomechanical instrumentation systems operative, as well as to maintain a deformation database after every blast. In addition, the information generated must be followed up and analysed.
- It is also recommended to periodically track the installation and replacement of load cells and where they were installed to facilitate the analysis of information and understand the relationship between the information recorded and field inspections.
- As an improvement opportunity, work should be done to implement a system that visualises the data collected by the load cells remotely and online.

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