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Laboratory-scale dynamic test of load distribution elements. Validation at GMTC testing facility

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ABSTRACT

Ground support systems must provide safe and effective designs for underground excavations in high--stress conditions. These systems must be capable of withstand dynamic impacts and yielding during the loading process. In this context, dynamic testing of the reinforcement and load distribution elements of the ground support system are necessary.

Over the last decade, Geobrugg company has been working on improving ground support systems by testing them in a large-scale impact test facility located at Walenstadt, Switzerland. Kin the past few years, this innovative facility has been used to test various configurations of ground support systems. The results of these tests have improved the understanding of the behavior of ground support systems under dynamic loads. Inspired by these results, Geobrugg Andina Chile has built, calibrated (Hinojosa et al. 2023) and validated a facility for load distribution elements in Rancagua, Chile, at the GMTC (Geobrugg Mining Technology Center) laboratory. This test facility has the potential to be an invaluable tool to test, standardize, certify, improve, and contribute to the understanding of the behaviour of load distribution elements (and ground support systems in the future) under dynamic loads at laboratory-scale.

1 INTRODUCTION

Mining conditions are becoming increasingly difficult as access to ore deposits becomes more complex due to its deepness, and the high-stress environments present challenges to continued resource exploitation. One of the main issues is related to the occurrence of seismic events and the associated rockburst phenomenon, leading to operational and safety problems. The amount of energy released during seismic events requires mitigation by ground support systems that are capable to control large displacements without failure. These dynamic systems are composed of anchoring elements (e.g., rockbolts, cablebolts) able to absorb a large amount of energy and surface support (e.g., mesh, mesh plus shotcrete) that provide containment to the rock mass and load transmission. Recent work developed by Kaiser & Moss (2022) provides a comprehensive understanding on how these concepts are implemented to design effective support in high-stress environments.

The design of ground support systems requires research into the behaviour of each support element under dynamic loads. Previously, several tests have been carried out to individual bolts, cables, and mesh, but in practice, all components must fit and work together (Vallejos et al. 2023, Brändle et al. 2017, 2020, 2021; Brändle & Luis Fonseca 2019; Bucher et al. 2013; Cala et al. 2013; Muñoz et al. 2017; Roth et al. 2014). Thus, tests on ground support elements/ systems are relevant to assess and increase their performance and offer improved designs to mining industry. Some institutions in Canada, South Africa and Australia have been testing reinforcement and retaining elements under dynamic loads. However, the facilities that can test the combinations (reinforcement, retaining or ground support systems) of rockbolts, cablebolts, and mesh as a system are limited.

Over the years, large-scale tests have been conducted at the rockfall testing facility at Walenstadt, Switzerland, that have contributed to improving knowledge as well as trying different types of test configurations and sample configurations (Vallejos et al. 2023, Brändle et al. 2017, 2020, 2021; Brändle & Luis Fonseca 2019; Bucher et al. 2013; Cala et al. 2013; Muñoz et al. 2017; Roth et al. 2014). Recent work developed by Vallejos et al. (2023) provides a back-analysis on the behaviour of six ground support systems tested at Walenstadt, Switzerland.

Since 2018, Geobrugg and the Advanced Mining Technology Center at the University of Chile have been collaborating to improve the performance of ground support systems under dynamic loads (rockburst prone), considering full-scale tests, back-analysis, numerical modelling, and design.

Inspired by previous works, Geobrugg has built a new testing facility for load distribution elements (currently in its second stage of validation and contemplating a third stage of operation) at Rancagua, Chile. This paper presents the test set-up, measurement system, results, and analysis of a series of laboratory-scale dynamic tests carried out on load distribution (retaining) elements in 2023. Hereafter, the surface retaining elements will be referred to as load distribution elements. This change is due to the main contribution of these elements, i.e., load distribution to the anchoring elements, which is not recognised using the common terminology.

2 DYNAMIC LABORATORY TEST.

During the last 30 years, significant effort has been made to obtain and quantify the dynamic response of a complete ground support system to provide solutions for rockburst control in high-stress mining environments. Testing and measurement of dynamic response of isolated components that compose the ground support system, such as rockbolts, cablebolts or load distribution elements (mesh or mesh plus shotcrete), have been conducted by a few institutions including CanMet-MMSL, Western Australian School of Mines (WASM) and New Concept Mining (Crompton et al. 2018; Kaiser et al. 1996; Player et al. 2004). In addition, simplified load distribution elements (retaining) and ground support systems have been tested by projects such as SIMRAC/SRK or GRC (Cai & Kaiser 2018; Kaiser et al. 1996; Ortlepp 2001; Ortlepp & Stacey 1998, 1997) using the impact principle and the momentum transfer concept (WASM). Figure 1a, b and c illustrate the dynamic facilities of CanMet-MMSL, WASM and New Concept Mining, respectively. Figure 2a, b and c show the SIMRAC/SRK apparatus, the GRC apparatus and the Geobrugg test at Walenstadt, respectively.

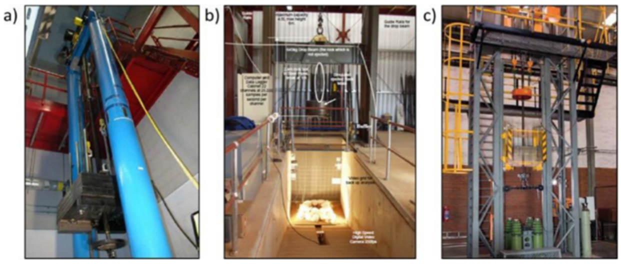


Figure 1 (a) CanMet-MMSL facility (Cai & Kaiser 2018); (b) WASM facility (Player et al. 2004); (c) New Concept Mining facility (Crompton et al. 2018).

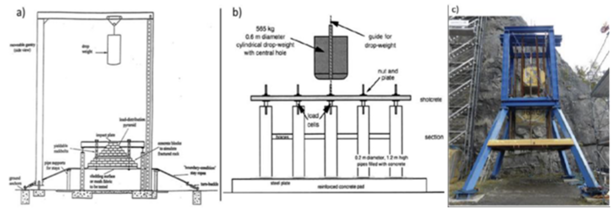


Figure 2 (a) SIMRAC/SRK apparatus (Ortlepp & Stacey 1997); (b) GRC apparatus (Kaiser et al. 1996); (c) Geobrugg test at Walenstadt (Brändle et al. 2020).

The dynamic testing of load distribution elements and ground support systems have been limited due to the difficulty in representing the in-situ conditions of a seismic event, quantifying the damage, measuring, and validating the response of each element and the interaction among them. Geobrugg has been performing real-scale dynamic tests on load distribution elements and ground support systems using the impact principle (drop weight test) since the research program started by Cala et al. (2013) through its facility at Walenstadt, Switzerland. The Walenstadt facility has been improved over the years to better represent and understand the damage process that occurs to a complete ground support system during a dynamic impact that represents the in-situ conditions of a seismic event (Vallejos et al. 2023, Brändle et al. 2017, 2020, 2021; Brändle & Luis Fonseca 2019; Bucher et al. 2013; Cala et al. 2013; Muñoz et al. 2017; Roth et al. 2014).

Inspired by the results obtained from the research program carried out at Walenstadt, Geobrugg has built a new test facility (GMTC) for load distribution elements at Rancagua, Chile, which has already completed its first phase of implementation (Hinojosa et al. 2023) and is currently in the validation phase. The facility consists of a loading mass that is released in free fall onto a square test sample of a load distribution element (mesh). A square rockbolt pattern (composed of four threadbars) is attached to the load distribution element, which serves as a boundary condition for the test sample.

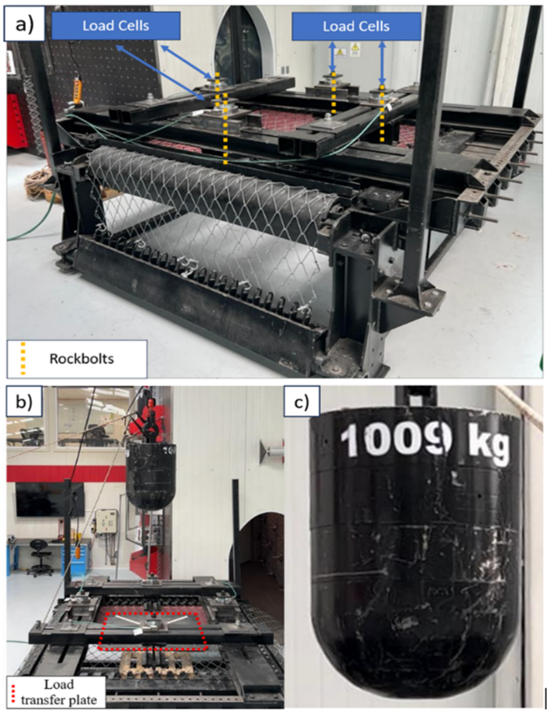


Figure 3 (a) Dynamic test facility at GMTC: isometric view; (b) front view; (c) loading mass.

2.1 Test arrangement.

The arrangement for performing and recording the dynamic tests consists of the following components:

- A loading mass (Figure 3c) of 1,009 kg released in free fall to a maximum height of 2 m. The mass leads to a nominal maximum input energy of 19.8 kJ.
- A steel impact plate (Figure 3b and shown later in Figure 4c) of 1 × 1 m (20 mm of thickness) located in the centre of the test sample (mesh) and between the test sample and the loading mass. In the test, the steel plate is directly impacted by the loading mass improving the load distribution on the sample.

2.2 Measuring system

The measuring system used for the tests include:

- Three high-speed cameras: two cameras (in perpendicular directions) pointing to the lower area (internal face) of the load distribution sample, and a third camera pointing to the whole test (upper area of the load distribution system and loading mass).
- One accelerometer was located at the top of the loading mass. Figure 4a shows the accelerometer.
- Eight load cells were used, one per rockbolt. Four located at the anchor (upper area) of the rockbolts and four located at the feet of the structure (one per leg). Figure 5 and Figure 6 illustrates the load cells used in the test.
- Reference tapes were in each rockbolt, whereas reference points were in the load distribution sample, and reference rulers were used to complement the measurement of the high-speed cameras. Figure 4c shows an example of the reference tapes located in each rockbolt, reference points located in the load distribution sample (each square represents an area of 1 cm^2), and a ruler located at the back of the apparatus for the test.

A coordinate reference system for the test located in the middle of the load distribution system (origin) to support the measurement of the dynamic displacement as is shown in Figure 7. Table 1 illustrates the properties of the measuring instruments.

Table 1 Properties of the measuring instruments

Measuring instrument	Properties
High-speed cameras	Recording frequency of 240 to 2143 fps
Accelerometer	2000g triaxial accelerometers with a frequency of 20 kHz
Load cells	750 kN force sensors with a frequency of 4.8 kHz
Reference tapes and rulers	Tapes with a square pattern of 1 cm^2 and rulers (cm)

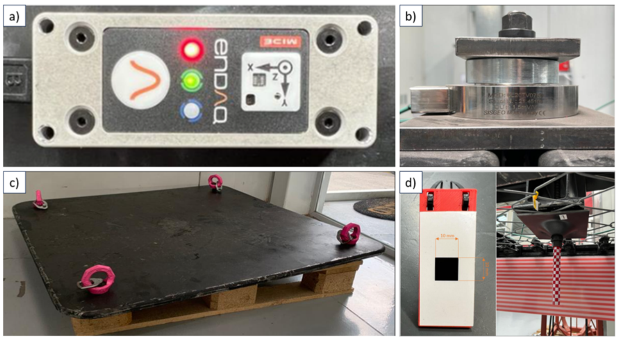


Figure 4 (a) Accelerometer located at the loading mass; (b) Load cells located at the anchor of rockbolt and at the feet of the structure; (c) Steel plate for load distribution; (d) Example of reference tapes located at rockbolts, reference points located in the load distribution element, and ruler located at the back of the apparatus.

Figure 5 shows the location of the load cells in the structure, where load cells 1, 2, 3 and 4 correspond to the load cells located at the top (anchor of the rockbolts) and load cells 5, 6, 7 and 8 are the load cells located at the feet of the structure (one per leg).

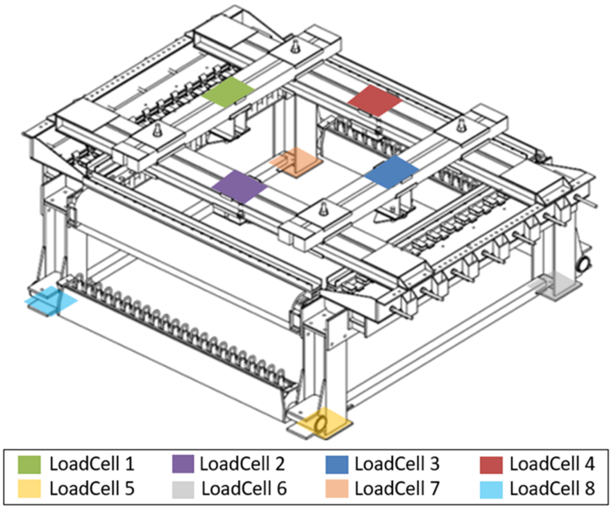


Figure 5 Distribution of the eight load cells in the structure.

2.3 Ground support system.

The test setup was built to be as simple as possible to evaluate the performance of the load distribution elements, considering:

- A load distribution element (sample to be tested) with a test area of 2 × 1.8 m is composed of a Geobrugg chain link mesh made of high-tensile steel wire with a diameter of 4 mm (commonly known as MINAX G80/4). Figure 6 illustrates a scheme of the MINAX G80/4 high-tensile mesh and Table 2 shows its properties.
- A reinforcement system composed by four threadbars (rockbolts) with a diameter of 22 mm, a length of 0.6 m and made of A630 steel grade (ultimate strength 630 MPa; yielding strength 420 MPa). The rockbolts were in a square pattern of 1 × 1m. Each rockbolt was attached to the retainment system using a plate (200 × 200 × 6 mm) and a nut. Note that the main reason to include this rockbolt pattern is to pin the mesh as it is typically installed in situ. Figure 7 illustrates the test configuration with each rockbolt identified (ID number) from a lower view of the load distribution system.

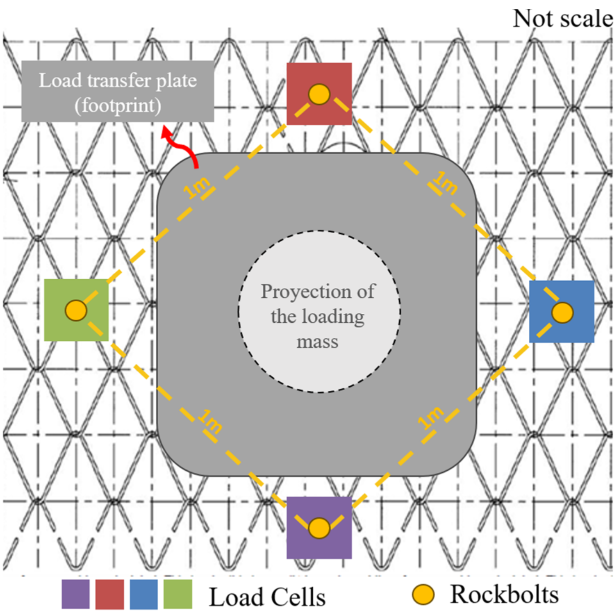


Figure 6 **Schematic diagram of the test apparatus with the distribution of the load cells and the test sample (mesh).**

Table 2 **Diamond-shaped high-tensile mesh (Geobrugg MINAX G80/4) properties.**

Properties	MINAX G80/4
Mesh width (Di)	80 mm
Diagonal (x, y)	102 x 107 mm
Wire diameter (d)	4 mm
Wire strength	1770 MPa
Tensile resistance of a wire	22 kN
Tensile strength of mesh longitudinal	190 kN /m
Weight	2.6 kg/m²

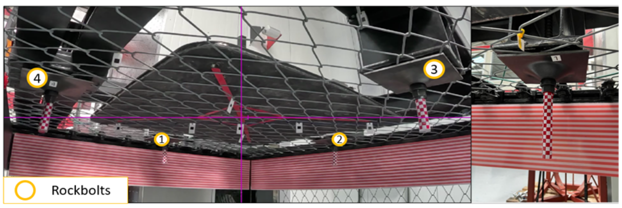


Figure 7 **Lower view of the test configuration with each rockbolt identified (ID number) and the coordinate reference system (lines in magenta).**

3 TEST RESULTS

The behaviour of the test samples (ground support systems) during the tests was recorded and analyzed using the information collected by the measurement system detailed in Section 2.3.

In the tests performed, the ground support systems brought the impact loading mass to a state of equilibrium in all tests; however, the load distribution element (element of interest) occasionally failed (local rupture). It was common for the impact of the loading mass to cause one of the rockbolt plates to shear the load distribution element (mesh), deforming it and causing it to fail.

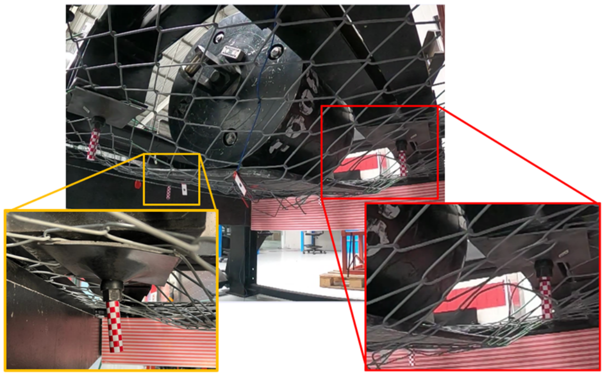


Figure 8 **Final dynamic state of the load distribution system tested with damaged area. Test Nº11 (zoom in to edge of Rockbolt 2 and deformation of rockbolt plates).**

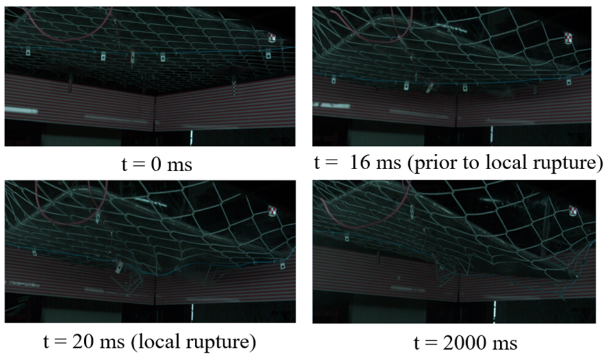


Figure 9 **Dynamic loading process of the test recorded by the high-speed cameras as a function of time. Test Nº24.**

To date, a total of 24 dynamic tests have been conducted, with the loading mass being dropped onto the test samples from various heights.

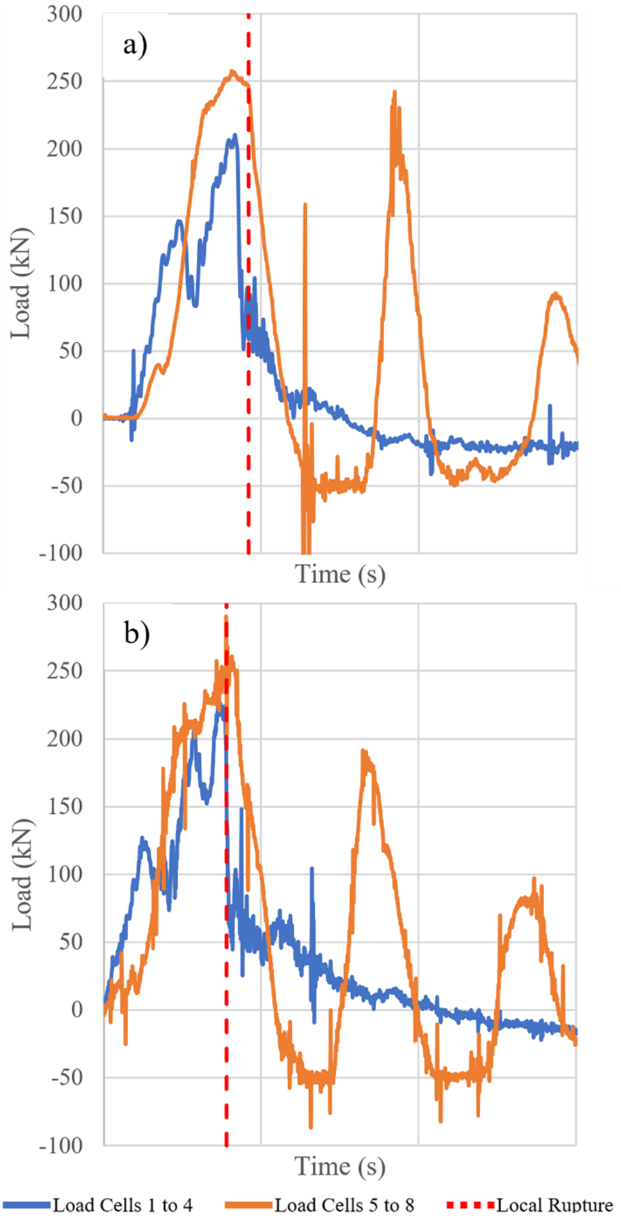


Figure 10 Load-time curves for the sum of the loads recorded by the cells located at the anchor of the rockbolts (blue) and at the legs of the structure (orange) for tests N°23 (a) and N°24 (b).

The results of 6 tests performed during 2023 (calibration stage) are presented below, which are selected according to the following criteria:

- Correct operation of the load cells.
- Correct operation of the high-speed cameras.
- Tests on MINAX G80/4 mesh.

Bring the load distribution system to the limit (local rupture - failure). The Figure 10 presents two examples (Test n°23 and n°24) of the recorded responses of the load cells (rockbolts and legs of the structure). In this case, the results of the load-time curves obtained by summing the load cell records at the anchors of the rockbolts and at the legs of the structure are presented. From this figure, it can be observed that the cells located at the anchor of the rockbolts present load before the cells located at the legs. Additionally, it is observed that the sum of the loads of the cells located at the anchor of the rockbolts is like the sum of the loads of the cells located at the legs of the structure. The load recorded by the cells located at the legs of the structure is slightly higher than the loads recorded at the bottom of the bolts, this is due to the weight of the structure, which also generates the oscillations observed after the local rupture of the test sample (mesh). The similarity of the curves confirms that the system is closed, and it is possible to use the cells at the anchor of the rockbolts to estimate the dynamic load applied on the load distribution element (mesh).

3.1 Analysis

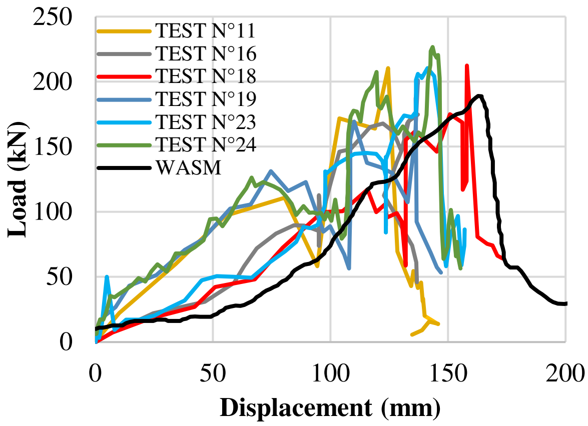
From Figure 11a and b, looks that the load-displacement and energy-displacement responses of the tests on MINAX G80/4 are similar to those conducted at WASM (Villaescusa et al., 2023; WASM Dynamic test report number 57, 2008).), respectively.

It should be noted that the differences in response observed between both installations (GMTC and WASM) are primarily attributed to:

- The impact principle (drop weight test) used in the GMTC facility compared to the momentum transfer principle of the WASM facility.
- The stiffness of the load application in the GMTC facility (stiff load – steel block) compared to the less stiff load (bag with steel balls) of the WASM facility, which adapts to the mesh during impact.
- Boundary conditions used to support the load distribution element (mesh); in the GMTC facility, a combination of braces with rockbolts and a load transfer plate is employed. Whereas in WASM facility only braces at the boundary of the sample are used.

- The initial tension applied to the load distribution element before conducting the test. In GMTC facility, the test sample is tensioned prior to the test. In the WASM facility, pre-tension is obtained by placing the loading mass over the test sample from the beginning, which also deforms the test sample prior to the test (Figure 12).

Based on these differences, the comparison of the WASM response presented in Figure 11 is for reference only.



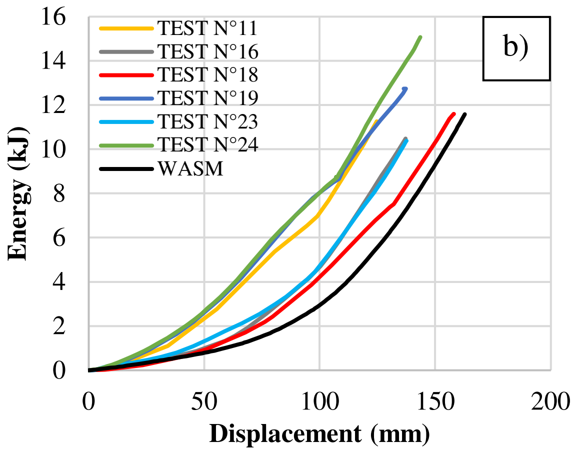


Figure 11 Responses from tests. a) Load-displacement (WASM response obtained from WASM dynamic test report number 57, b) Energy-displacement. (WASM response obtained from Villaescusa et al., 2023).

As can be seen in Figure 11b, test N°24 shows a higher energy dissipation than the previous tests, this is mainly due to the fact that in this particular test, the bracing of the load distribution element with the structure was partial (to analyze its effect), causing the load distribution element to slide and allowing it to dissipate more energy.

After analyzing all the tests carried out, looks that both the load-displacement and energy-displacement results are similar for the six tests, with only a small variation due to the initial tension applied to the load distribution element being tested. The load and energy values obtained are representative of the mesh analyzed (MINAX G80/4) and like those found in the literature. Therefore, it can be concluded that the test is repeatable.

Figure 12 Arrangement at WASM, Chain link mesh (Villaescusa, 2009).

As can be seen from the load-displacement responses of the tests in the previous section, when the displacement approaches 80 [mm], noise is generated before the peak load is reached. This is attributed to the use of a load transfer plate in the tests (deformation of the load transfer plate). By removing this load Transfer plate and using a less stiff loading mass that directly impacts the mesh, this "noise" is not generated, but the results of this type of test fall outside the scope of this publication.

4 CONCLUSIONS

Dynamic tests at laboratory scale contribute to the knowledge, standardization, and certification of different configurations of ground support systems. The test setup on this occasion allowed the authors to study the damage process in a load distribution element in a dynamic impact recreated in laboratory scale conditions, and to validate the test due to the consistency of the results and their repeatability.

The results of the test performed quantified the potential energy absorption capacity of the load distribution element tested (MINAX G80/4) under dynamic load (focus of the test). In most of the tests performed, the load distribution element was able to absorb almost all the total input energy, bringing the loading mass to an equilibrium state, deforming but failing locally around some steel plate in the process (puncturing). In this sense, the boundary condition given by the rockbolts (plates) led to the shearing of the load distribution element (mesh). The reinforcement system absorbed a minimal part of the input energy, without plastic deformation (elastic range without failure).

Considering the results, these tests allow to measure the capacity of the load distribution elements in terms of load, displacement, and dissipated energy. The differences observed in the responses of both tests (WASM and GMTC) are mainly associated with the stiffness and boundary conditions of the arrangements to be tested, including the interaction with rockbolts and plates in the GMTC test. In addition, the measurement system was integrated with appropriate tools to measure the load capacity, displacement and energy absorbed in the processes. In this second stage of implementation, following the work done by Hinojosa et al. (2023) (first stage of calibration), the dynamic test belonging to GMTC is validated, as presented in this paper.

Therefore, an analysis of the observed behaviour and response of the dynamic loading process for load distribution elements is presented. The tests revealed that the current dynamic testing facility at Rancagua (Chile), henceforth referred to as the GMTC facility, is validated and has the potential to be an invaluable tool to test, standardise, certify, improve, and contribute to the understanding of the behaviour of load distribution elements (and ground support systems in the future) under dynamic loads at laboratory scale. This knowledge also contributes to the monitoring of seismic events and rockburst phenomena in excavations under high stress conditions. In this context, more detailed analysis is being developed to gain a better understanding of load distribution elements and ground support systems.

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