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From full-scale impact testing to practical design of dynamic ground support systems

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Abstract

Rock damage and rockburst-related events continue to pose significant hazards in underground mining and tunnelling operations. To mitigate these risks, ground support systems must be capable of absorbing and dissipating high levels of dynamic energy while maintaining post-impact integrity. Surface support elements such as high-tensile steel meshes, in combination with rockbolts, are critical components in controlling rock ejection and ensuring safe working conditions. This paper presents results from an extended full-scale dynamic testing program conducted in Walenstadt, Switzerland, aimed at enhancing the understanding and design of dynamically loaded ground support systems. Following an initial series of impact tests, additional experiments were performed to further investigate the behaviour of selected mesh-bolt configurations under varying impact energies. A purpose-built test rig enabled the application of controlled, full-scale dynamic impacts to different support systems, with systematic variations in energy input while maintaining identical system layouts. The dynamic response was monitored using load cells, accelerometers and high-speed video analysis, allowing detailed evaluation of load distribution, deformation mechanisms and energy dissipation at both element and system level. A key objective of the extended test series was to quantify the specific energy dissipation capacity of individual support elements when acting within an integrated system and to determine the spatial distribution of absorbed energy, expressed in kJ/m², across the supported area. By progressively increasing impact energy, residual capacities and post-impact safety margins of the systems were identified. Based on these findings, a system-based ground support design concept was developed, linking test-derived performance parameters with practical design criteria. The results highlight the necessity of considering ground support as an integrated system rather than as isolated components when subjected to dynamic loading. The proposed design concept, supported by full-scale experimental data, provides a practical framework for selecting and designing surface support systems with improved energy absorption and robustness, contributing to safer and more reliable underground mining operations.

Keywords: *dynamic ground support, full-scale testing, energy dissipation, load transfer, ground support scheme design*

1 Introduction

Underground mines are progressively moving to greater depth to access remaining resources, which increases the geotechnical challenges associated with highly stressed excavations. Seismic events and the associated dynamic loading of the rock mass surrounding these excavations are a major hazard, and robust ground support is a key factor for safe and economical mining at depth. Ground support schemes consist of rock reinforcement elements, such as bolts and cable bolts, and surface support, such as mesh and shotcrete. To withstand dynamic loading without excessive deformation or damage, all of these components must work together as a system, without a weak link between them.

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Full-scale testing has been carried out at several test sites worldwide to assess the dynamic performance of ground support. However, most of this testing has been performed on individual components – bolts, mesh or shotcrete – and only rarely on parts of complete ground support schemes. Where full schemes were tested, the loading typically concentrated on either the mesh or the bolts rather than realistically loading a larger in situ area with multiple bolts and the associated surface support (Villaescusa et al. 2023). This limitation has persisted in more recent full-scale test programmes (Brändle et al. 2022; Vallejos 2022; Elorietta et al. 2022; Cuello et al. 2024; Durham et al. 2024), and it also applies to back-analysis and numerical modelling, where it has not yet been possible to systematically evaluate the load and energy distribution within a ground support scheme during dynamic loading.

An earlier test arrangement at the Walenstadt rockfall test site in Switzerland, with 5 reinforcement elements and 2 layers of mesh and shotcrete, was only able to load either the bolts or the surface support, but not the full scheme at once (Bucher et al. 2013). Subsequent development work achieved the simultaneous yielding of up to 4 reinforcement elements (Bucher 2015), but a repeatable method for loading a full, in situ scale ground support scheme with multiple reinforcement elements and attached surface support to the point of rupture remained an open research need.

This research addressed that need by designing, building and commissioning a full-scale test site, the Geobrugg test facility, capable of testing a ground support scheme with nine reinforcement elements and a 3.8 × 3.8 m surface support system at input energies exceeding 500 kJ. An initial series of tests was carried out to commission the facility and develop a repeatable load transfer mechanism; an extended series of additional full-scale tests was then performed on selected mesh-bolt configurations under systematically varied impact energies, from which the spatial distribution of dissipated energy within each scheme was determined (Roth 2025).

This paper summarises the test facility and method, presents the key findings on load transfer and energy distribution from across the full test program, and – as its main contribution – distils these full-scale results into a practical, step-by-step method for designing ground support schemes subjected to dynamic loading. Section 2 describes the Geobrugg facility and test method. Section 3 summarises the full-scale test programme. Section 4 presents the load transfer and energy distribution results for reinforcement elements and surface support. Section 5 develops the practical design method and illustrates its use with data from the tested schemes. Section 6 concludes the paper.

2 The Geobrugg full-scale dynamic test facility

2.1 Background and test method selection

The Geobrugg test facility was built at the Walenstadt rockfall test site in Eastern Switzerland, which has been operational since 1999 for the testing of flexible rockfall barriers (Gerber 2001). The site is equipped with a 25 t crane that can release a test block from up to 50 m above ground, providing an existing capability that was adapted for ground support testing. The facility is owned by Geobrugg AG, technically supervised by the Western Australian School of Mines (WASM), and instrumented by the independent Dynamic Test Center of the Bern University of Applied Sciences.

The dynamic test method was selected as impact on a simulated rock mass, rather than rapid hydraulic loading, direct impact, momentum transfer or in situ blasting. This method has no practical limit on input energy, and the simulated rock mass distributes the impact to multiple reinforcement elements at once, which is essential for loading a realistic multi-bolt scheme rather than a single component. Cement encapsulation was used throughout to remove the additional variability associated with resin encapsulation. In previous test programs elsewhere, higher energies were achieved with multiple successive drops, but this has been shown to overestimate the energy dissipation capacity of the ground support (Masoudi et al. 2018). The Geobrugg facility was therefore designed to deliver the full required input energy in a single drop.

2.2 Test apparatus and instrumentation

The test setup releases a 9,380 kg test block from a height of up to 6.6 m, giving a maximum input energy of more than 600 kJ and a maximum impact velocity of 11.4 m/s. The block falls with a centre hole along the centre reinforcement element onto the simulated rock mass (cement aggregate fill [CAF] with a thickness of 600 mm), which sits above a surface support system of 3.8 × 3.8 m attached to the collars of nine reinforcement elements arranged in a split-pipe configuration (Player 2012) at approximately one bolt per square metre. Because the impact is applied at the centre of the scheme first, the loading and deformation propagate outward from the centre reinforcement element, through the 4 intermediate ('Dice-5') elements, to the 4 corner elements – reproducing, at full-scale, the way a scheme responds to a localised seismic source in situ. Throughout this paper, dynamic displacement refers to the maximum outward movement of each reinforcement element collar, or of the surface support panel, determined from high-speed video tracking; dissipated energy for each component is calculated as the integral of its force–displacement curve, and the total dissipated energy of a scheme is the sum of this quantity over all 9 reinforcement elements and the surface support panel.

Figure 1 shows the Geobrugg facility with its main components: the falling test block with its centre hole, the simulated rock mass, the nine reinforcement elements anchored in the steel frame below.



Figure 1 Test setup with the simulated rock mass cemented aggregate fill of 600 mm, 9 reinforcing elements in split tubes and drop weight (Geobrugg AG 2024)

Shotcrete surface support was applied at a conservative flat geometry and 100 mm thickness, bonded to the simulated rock mass as it would be when sprayed onto an exposed rock face; a curved surface, as normally installed underground, would add capacity through arching that is deliberately excluded here. The reinforcing mesh could be positioned at different depths within the shotcrete layer – centred, as a fill-in layer, on the outer face, or as multiple layers – to examine its effect on load transfer and shotcrete ejection. The facility is fully instrumented with load cells on each reinforcement element and at the surface support boundaries, accelerometers on the test block, high-speed cameras and a laser scanner, enabling the dynamic force, displacement and energy dissipation of every component to be reconstructed from each test.

3 Full-scale test program

Between September 2021 and August 2024, 26 full-scale tests were carried out at the Geobrugg facility. An initial series of 10 tests, completed by August 2022, commissioned the apparatus and instrumentation and developed a repeatable load transfer mechanism between the reinforcement elements and the surface support, using different thicknesses of simulated rock mass. An extended series of 16 additional tests, completed by August 2024, further investigated selected mesh-bolt configurations under systematically varied impact energies, all with fully cement-encapsulated reinforcement elements. Of these 16 tests, 12 examined complete ground support schemes, comprising reinforcement elements and an attached surface support system, and are summarised in Table 1. The remaining 4 tests isolated individual components – 3 with the simulated rock mass only, and one with the surface support only – and are not part of the scheme-level dataset used in Sections 4 and 5.

Table 1 Ground support schemes tested during the extended 2022–2024 full-scale test program (Roth 2025)

Reinforcement elements	Surface support	No. of tests	Typical input energy
Fully coupled 20 mm threaded bars	Woven wire mesh reinforced shotcrete	2	540–550 kJ
Partially decoupled 20 mm threaded bars	Welded wire mesh reinforced shotcrete	2	450–530 kJ
Partially decoupled 20 mm threaded bars	Woven wire mesh reinforced shotcrete	7	440–590 kJ
Fully coupled cable bolts	Woven wire mesh reinforced shotcrete	1	540 kJ

By progressively increasing the impact energy across repeat tests on the same scheme configuration, the residual capacity and post-impact safety margin of each system could also be assessed. In total, 234 individual reinforcement elements and 234 m^2 areas of surface support were instrumented and analysed, providing a substantial full-scale dataset on the dynamic performance of typical ground support schemes and the basis for the design method developed in Sections 4 and 5.

4 Load transfer and energy distribution in ground support schemes

4.1 Energy dissipation by the simulated rock mass

Because the test method relies on impact onto a simulated rock mass, the proportion of input energy dissipated by that rock mass has a direct bearing on the energy actually delivered to the ground support scheme, and on the repeatability of the tests. Across 11 of the 12 complete-scheme tests (the single fully coupled cable bolt scheme, which combined a centre cable bolt with threaded bar Dice-5 and corner elements, was excluded from this particular analysis as its mixed reinforcement layout is not directly comparable to the other 3 configurations), the cemented aggregate fill used as the simulated rock mass dissipated between 61 and 72% of the input energy, with an average of 66% and a standard deviation of 3%. This is notably higher than the 50% assumed by Ortlepp & Stacey (1997), whose test apparatus simulated an already fractured rock mass using a layered brick assembly, compared with the CAF used in this study, which behaves as a stiffer, more continuous mass. A stiffer simulated rock mass is expected to dissipate proportionally more of the impact energy through its own compaction and internal fracturing before load reaches the ground support scheme, so the higher ratio measured here is considered a repeatable characteristic of the CAF used rather than an anomaly. Because underground rock mass conditions range from intact to highly fractured, neither test arrangement should be taken as universally representative; the CAF ratio reported here is specific to this test method and facility and is applied consistently when interpreting the full-scale scheme results in this paper.

4.2 Load transfer within reinforcement elements

With more than 200 reinforcement elements tested, a clear and repeatable load transfer pattern was observed: the centre element loads first, followed by the 4 Dice-5 elements, followed by the 4 corner elements. This pattern held both for ground support schemes with partially decoupled threaded bars, where the elements yield without failing, and for schemes with fully coupled threaded bars, where multiple elements rupture in sequence; even after 5 elements had ruptured, the corner bolts continued to carry load and dissipate energy, demonstrating the redundancy that a correctly designed multi-bolt scheme provides. Figure 2 shows a representative example of this load transfer pattern from one of the tests.



Figure 2 Test result with ruptured centre bolt (red), yielded Dice-5 bolts (blue) and slightly yielded corner bolts (green) (reproduced from Roth 2025, Figure 11.1)

The energy dissipation capacity of the reinforcement elements across all tests is summarised in the design chart in Figure 3.

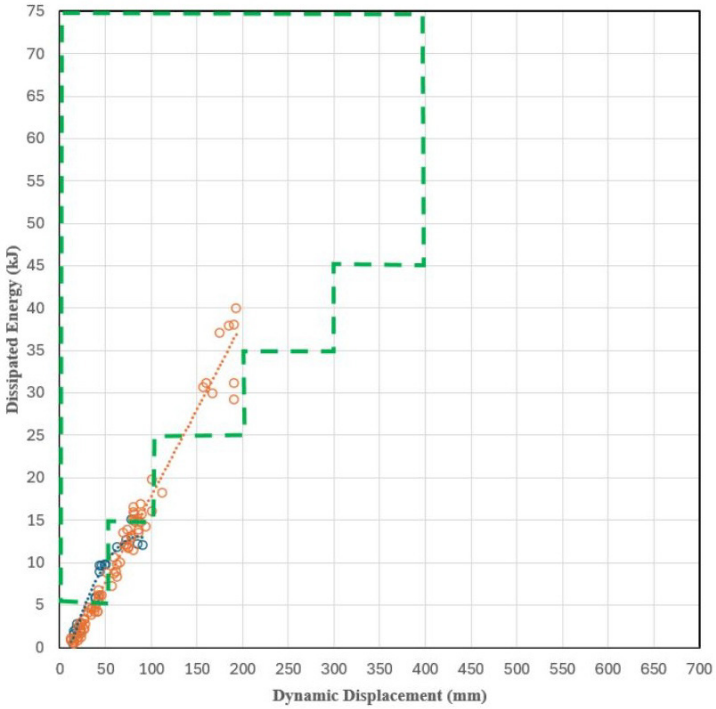


Figure 3 Design chart of typical reinforcement elements with fully coupled 20 mm threaded bars (blue) and partially decoupled 20 mm threaded bars (orange) (reproduced from Roth 2025, Figure 10.10)

Figure 3 compiles the dissipated energy and dynamic displacement of the threaded bars from all tests. Fully coupled 20 mm threaded bars rupture after dissipating only 10–15 kJ within about 100 mm of displacement. Partially decoupled 20 mm threaded bars, with a 1.0 m decoupling length, follow the same approximately linear energy–displacement relationship but reach 30–40 kJ before rupturing, at displacements of 150–200 mm – 2–3 times the capacity of the fully coupled configuration. These full-scale results are consistent with the existing WASM component-testing database (Villaescusa et al. 2023).

A comparison with the static characteristic of the same 20 mm threaded bar (yield load 190–200 kN, tensile strength 220–230 kN, static yield elongation of 60 mm over a 1.0 m sample, static energy dissipation of 12.5 kJ) shows that the dynamic force is only slightly higher than the static value, consistent with the modest dynamic increase factor (of the order of 1.05–1.15) reported for reinforcing steel bars at comparable strain rates (Ansell 2006). The much larger difference is in the yielding elongation: threaded bars tested dynamically with a 1.0 m decoupled length reached elongations exceeding 150 mm, with the decoupled length itself extending to 1.5–1.7 m after loading – at least 50% more yielding than under static loading. This additional yielding capacity, rather than an increase in yield force or material strength, is the main source of the higher energy dissipation observed under dynamic loading.

4.3 Load transfer within surface support systems

The behaviour of the surface support was found to be decisive for how load transfers across the full scheme. High-strength woven wire mesh reinforced shotcrete deforms over a large area and continues to transfer load outward even after the centre of the panel has been overloaded and damaged. Welded wire mesh reinforced shotcrete, in contrast, fails along the rectangular geometry of the mesh and is much less able to redistribute load to the surrounding area. The surface support panel in every test consisted of a single 3.8 × 3.8 m sheet of mesh matching the size of the test frame, with no overlaps between adjacent sheets; the additional load transfer capacity provided by overlapping mesh sheets, as used underground, is examined separately at component scale by Brändle & Bucher (2023). The resulting design chart for typical surface support systems is presented in Figure 4.

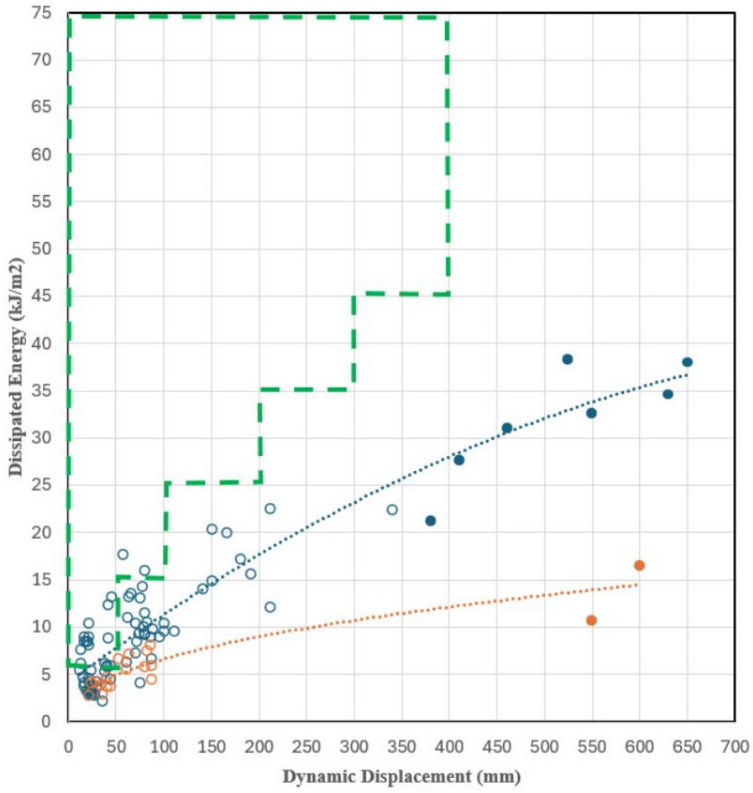


Figure 4 Design chart of typical surface support with high-strength woven wire mesh (blue) and welded wire mesh (orange) reinforced shotcrete (reproduced from Roth 2025, Figure 10.13)

At equal input energy, the total force recorded across the nine reinforcement elements was similar (around 2,000 kN) irrespective of which surface support type was installed, indicating that the reinforcement response is governed mainly by its own characteristic rather than by the surface support. The total force at the surface support boundaries, however, was roughly half as large with the woven wire mesh as with the welded wire mesh, because the woven mesh deforms more and dissipates more energy internally rather than transmitting it directly to the boundary.

Figure 4 compiles the energy–displacement data for both surface support types across all tests. The woven wire mesh reinforced shotcrete dissipates 20–25 kJ at displacements approaching 350 mm without rupturing, while the welded wire mesh reinforced shotcrete ruptures after only 5–10 kJ at around 100 mm of displacement. Neither surface support system on its own reaches typical design energy demands, confirming that a capable reinforcement system is indispensable in any ground support scheme intended for dynamic loading – the surface support alone cannot provide the required capacity.

5 From test results to practical design

5.1 Combined performance of ground support schemes

Because the reinforcement elements and surface support do not behave independently once assembled into a scheme, their capacities cannot simply be added together. The combined, full-scale behaviour of the scheme governs its dynamic performance, and the specific energy dissipation of the scheme, expressed per square metre of supported area, is the key design parameter. Figure 5 compiles the energy–displacement data for the 3 ground support scheme types tested, using data points from the centre, Dice-5 and corner areas of each test to trace the trajectory of the scheme as it deforms further under load.

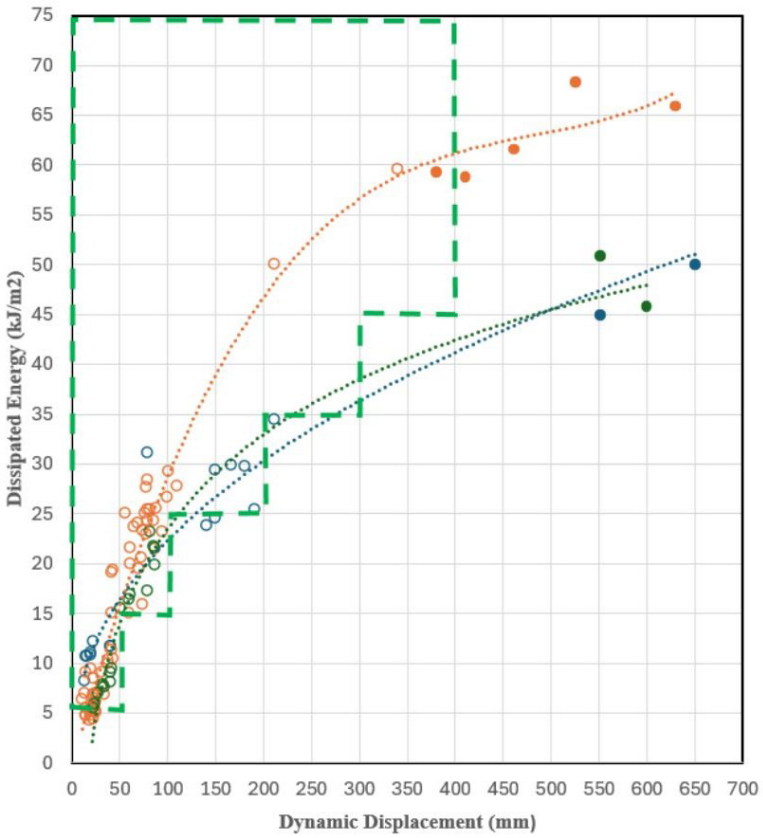


Figure 5 Design chart of typical ground support schemes with partially decoupled threaded bars and woven wire mesh (orange), partially decoupled threaded bars and welded wire mesh (green), and fully coupled threaded bars and woven wire mesh (blue) (reproduced from Roth 2025, Figure 10.20)

The scheme with fully coupled threaded bars and woven wire mesh reinforced shotcrete dissipates only 5–15 kJ/m² within about 50 mm of displacement. Despite the strong surface support, the reinforcement ruptures too early to add meaningful capacity to the scheme. The scheme with partially decoupled bars and welded wire mesh reinforced shotcrete reaches 15–20 kJ/m² within about 100 mm, but here it is the surface support that limits performance. Fully coupled threaded bars combined with woven wire mesh reinforced shotcrete show markedly lower energy dissipation and deformation capacity than either partially decoupled configuration, as the reinforcement ruptures early; no fibre reinforcement was used in the shotcrete of any of the three schemes shown in Figure 5, only mesh, consistent with Table 1. Only the combination of partially decoupled threaded bars and high-strength woven wire mesh reinforced shotcrete dissipates energy well within the design region, reaching 45–55 kJ/m² over approximately 300 mm of displacement without rupture. This does not imply that welded wire mesh or fully coupled bars are unsuitable in general: at lower dynamic energy demands, corresponding to less severe seismic hazard, either configuration may provide adequate capacity, and the appropriate scheme should always be selected to match the site-specific demand rather than assumed from these high-energy test results alone.

5.2 Proposed design procedure

Based on these full-scale results and on the established fundamentals of dynamic ground support design, a 5-step design procedure is proposed for translating a site-specific demand into a ground support scheme selection, illustrated in Figure 6.

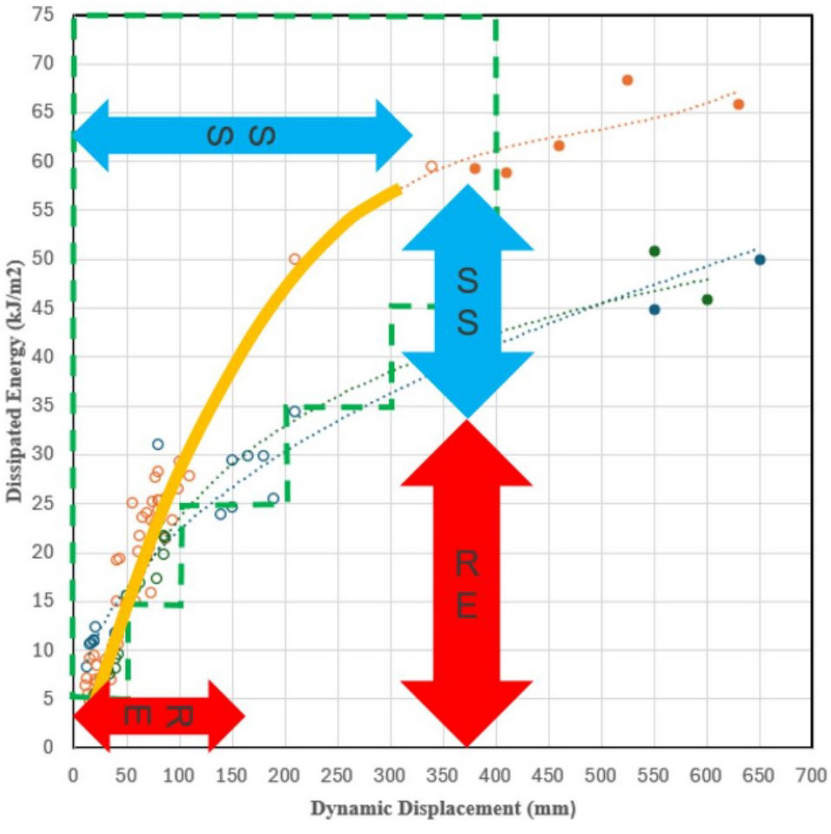


Figure 6 Proposed method for designing ground support schemes with reinforcement elements (RE) and surface support (SS) (reproduced from Roth 2025, Figure 11.3)

The 5 steps would include the following:

- Define the dynamic energy demand, in kJ/m², and the acceptable dynamic deformation for the excavation.
- Apply a safety margin to the demand (e.g. an additional 10 kJ) to obtain a target design point.

- Select reinforcement elements able to dissipate at least 60–65% of the total energy demand within half of the acceptable deformation.
- Select a surface support system able to dissipate at least 35–40% of the total energy demand while deforming over the full acceptable deformation range.
- Check that the combined energy–displacement trajectory of the selected scheme remains within the design region on charts such as Figure 5.

As a baseline reinforcement density, one reinforcement element per square metre is recommended to avoid both excessive overall deformation and a shortfall in energy dissipation capacity. In a worked example, a demand of 50 kJ/m² within 300 mm of acceptable dynamic displacement is met by selecting a reinforcement element able to dissipate around 30 kJ within 150 mm (at one bolt per square metre), with the surface support providing the residual 20 kJ/m² within the full 300 mm of allowable deformation – a combination consistent with the partially decoupled bar and woven wire mesh scheme identified in Section 5.1.

It should be noted that the dynamic deformation of a ground support scheme is, strictly, an output of the interaction between the imposed demand and the stress–strain response of the installed elements, rather than a free design input (Kaiser & Moss 2022). In the procedure above, the acceptable dynamic deformation is used as a practical upper bound on the convergence or damage the excavation can tolerate before it is no longer serviceable or safe to access, consistent with a deformation-based design philosophy. It constrains which reinforcement and surface support combinations are considered, rather than dictating how much the scheme will actually deform under a given demand. The Factor of Safety or dynamic acceptance criterion applied to the demand should be determined on a case-by-case basis, informed by a site-specific seismic risk assessment or company ground control guidelines, rather than assumed generically. It should also be noted that the reinforcement densities and capacities discussed above are specific to the one bolt per square metre spacing tested; wider bolt spacings will result in lower system capacities than those reported here.

5.3 Building a database for post-event assessment

Beyond initial design, the full-scale dataset also supports the assessment of residual scheme capacity after an actual dynamic event, by comparing the observed deformation and damage of an in situ scheme with reference data from tests at a similar dynamic displacement. Table 2 illustrates this using 4 tests on the same scheme configuration – partially decoupled 20 mm threaded bars with high-strength woven wire mesh reinforced shotcrete – at increasing levels of dynamic displacement, obtained by progressively increasing the impact energy across the extended test series.

Table 2 Energy dissipation by reinforcement and surface support at increasing dynamic displacement for the partially decoupled bar/woven wire mesh scheme (Roth 2025)

Test	Dynamic displacement (mm)	Total dissipated energy (kJ/m²)	By reinforcement (kJ/m²)	By surface support (kJ/m²)
22	210	50	38	12
11	340	60	37	23
20	410	59	31	28
23	460	62	31	31

As dynamic displacement increases across these 4 tests, the share of the total energy dissipated by the surface support increases relative to the reinforcement, which reaches a comparatively stable share once yielding. This kind of relationship, once established for a given scheme from full-scale testing, gives practitioners a practical way to estimate the residual energy dissipation capacity and post-impact safety margin of an installed scheme from a post-event deformation survey, without requiring further physical testing on each occasion.

5.4 Shotcrete ejection as a secondary hazard

Shotcrete that is not adequately contained by wire mesh can itself become a projectile hazard under dynamic loading (Stacey 2016). Ejection velocities back-calculated from the test programme were in the range of 5–7 m/s; because the impact test method tends to exaggerate ejection through the tensile wave reflected by the stationary simulated rock mass, these values should be treated as a conservative upper bound rather than a direct in situ prediction. Mesh position within the shotcrete layer had a clear effect: ejection was greatest when the mesh was centred within the shotcrete (Figure 7), reduced when the mesh was placed toward the outer face (fill-in position) (Figure 8), and further reduced with a second mesh layer on the outer surface (Figure 9). The addition of fibres to the shotcrete also reduced ejection, by causing the shotcrete to break into larger fragments during dynamic loading.



Figure 7 Shotcrete ejection when mesh installed in centre of shotcrete layer (reproduced from Roth 2025, Figure 10.17)



Figure 8 Shotcrete ejection when mesh installed on outer part of shotcrete, fill-in position (reproduced from Roth 2025, Figure 10.18)



Figure 9 Shotcrete ejection when mesh installed on top of shotcrete layer (reproduced from Roth 2025, Figure 10.19)

6 Conclusion

The Geobrugg test facility in Walenstadt, Switzerland, was designed, built and commissioned to test full-scale ground support schemes – 9 reinforcement elements together with an attached 3.8 × 3.8 m surface support system – to the point of rupture, with a maximum single-drop input energy exceeding 600 kJ. The 12 tests on typical ground support schemes reported in this paper (Table 1) were carried out at energies of up to 590 kJ. Across an initial commissioning series and an extended series of 16 tests on typical ground support schemes under systematically varied impact energies, the simulated rock mass was found to dissipate an average of 66% of the input energy, and the reinforcement and surface support were shown to respond as a coupled system rather than as independently additive components.

Of the 3 ground support scheme types tested at full-scale, the combination of partially decoupled threaded bars with high-strength woven wire mesh reinforced shotcrete achieved the highest energy dissipation and deformation capacity of those tested, dissipating 45–55 kJ/m² over about 300 mm of displacement without rupture, while fully coupled threaded bars and welded wire mesh reinforced shotcrete were each in turn found to be the limiting component in the other two scheme combinations. As discussed in Section 5.1, this reflects the demand levels used in this test programme (440–590 kJ) and should not be read as a general recommendation independent of the site-specific dynamic demand.

These full-scale results have been distilled into a 5-step, system-based design procedure that allows practitioners to move directly from a site-specific dynamic demand and allowable deformation to the selection of reinforcement and surface support, using energy and deformation shares of 60–65% and 35–40% respectively as design targets, and a baseline reinforcement density of one element per square metre. The resulting dataset also provides a basis for assessing the residual capacity and post-impact safety margin of an installed scheme following an actual dynamic event, by comparison with reference deformation and energy data from full-scale testing.

This initial database of 26 full-scale tests should continue to grow with further testing including cable bolts, alternative encapsulation materials, and the capacities of overlaps and connections between adjacent surface support panels. Physical full-scale testing of this kind remains an essential complement to numerical modelling as the depth, and therefore the dynamic demand, of underground mining continues to increase.

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