AN EXAMINATION OF DYNAMIC TEST FACILITIES

John Player, Prof Ernesto Villaescusa, Dr Alan Thompson

ABSTRACT

A critical examination of a number of testing facilities that have been used by the mining industry for the assessment of the dynamic capacity of reinforcing and support elements has been undertaken. Numerous international dynamic testing facilities have been developed for testing elements and structures for these applications. The facilities use various loading mechanisms, boundary conditions or test procedures, and are generally designed to examine specific conditions and / or elements. However, not all facilities have the capability to calculate and assess, energy and force displacement curves from the loading.

INTRODUCTION

The ability to dynamically test an element of a structure is important in both mining and civil applications: multi-storey building designs for earthquake loading, structural components for car crashes, steel panels for explosion resistance, composite materials for controlling missile penetration, rock bolts for energy absorption, and surface liners for the containment of broken rock from dynamic rock failure (rockburst).

A number of test facilities for mining applications existed in South Africa and Canada prior to 2002. At this time there was no test facility in Australia capable of dynamically loading and assessing the behaviour of reinforcement systems, support system and ground support schemes. An increasing frequency of dynamic rock failures and ground support problems in Western Australia during the 1990s, (Li et al., 1999), provided the impetus for the development of a testing facility at the Western Australian School of Mines (WASM).

The WASM Dynamic test facility differs from other mining dynamic test facilities in that it does not use the direct impact of a free moving mass onto a stationary scheme / system / element. Rather the scheme / system that requires testing is moving and impacts against an energy distribution device or stationary body. Facilities that use a moving test body tend to be large but there exist numerous civil engineering and military applications. These facilities are used to provide body and element information on the performance of a full-scale systems. Some examples are, studies of a car crashing against a barrier, or a loaded train wagon into another wagon.

Rates of Loading

There are various methods used to create different rates of load application to structures and elements of structures. They are summarised in the following sections:

- Static / pseudo – static
- Transient / vibration / cyclic
- Rapid

- Dynamic impact
- Multiple loading cycles

Static/pseudo-static loading

Static/pseudo static loading is most commonly used to measure the response of materials. Within this category of loading, there are three types of tests:

- Pseudo-static tests in which tensile or compressional loading is slowly increased.

  The deformational response is assumed to occur immediately and is measured simultaneously with the applied force to produce a force-displacement or stress-strain characteristic response.

- Creep tests in which the element is subjected to constant force and the deformation measured at various times after application of the force.

  The deformation increases with time and results in a displacement-time characteristic for the particular applied force. Materials that are susceptible to creep will generally exhibit higher rates of creep at high loads. Failure may occur at force levels much lower than the strength measured in psuedo-static tests.

- Load relaxation tests in which the element is stretched or compressed and maintained in the deformed position while the force is monitored with time.

  For susceptible materials, the force decreases with time. The rate of force decrease is related to the creep rate of the material. The load relaxation test is generally preferred to a creep test as it does not necessarily require the use of a universal testing machine.

Transient/Vibration/Cyclic

These types of loadings involve application of force that varies with time during which the displacement response is measured. Examples of transient/vibration/cyclic loading methods are:

- excitation of a structure on a shaker table,
- out of balance loading within a large structure (e.g. Iskhakov and Ribakov, 2000),
- vibration loading of a structure mounted on the ground (e.g. Lu et al., 2000),
- vibrational loading of a structure / element underground from an explosive detonation (e.g. Ansell, 1999, and Milev et al., 2001).

The purpose of the first three types of tests is usually to determine the unstable, resonant frequency response of the structure.

Rapid Loading

Rapid loading can be produced by a volumetric increase of expanding gases to load an element or structure (e.g. Smart and Schleyer, 2000).

This may produce a constant velocity with unknown input energy.

Dynamic Impact

An impulsive force may be produced by the impact of a body with known momentum with another body (generally stationary). For example:

- direct impact of a mass onto an element, (e.g. Hansen et al. 2003, and Kaiser et al. 1996).
- impact of the structure / element onto a fixed element, (e.g Ansell 2000).
- impact of the structure / element onto a moveable element, eg military collision testing of loaded train wagons (Whitesands Test facility).
- impact of a mass on to a load transfer mechanism or energy dissipation element (e.g. Ishikawa et al. 2000 and Player et al. 2004)

Direct impact appears to be the most common loading method for civil, mining and military applications (excluding the modelling of earthquake loads on structures). Some methods of direct impact are :

- a free falling mass (e.g. Masuya et al. 2000).
- a guided mass (e.g. Kishi et al. 2000).
- a fired mass (missile / bullet penetration) (Whitesands Test Facility).
- impact from a mass directly onto the test structure / element (e.g. Ando et al. 2000) and in particular shotcrete panel tests (e.g. Kaiser et al. 1996).
- impact from a mass onto a surface that spreads the load from the moving mass to the test structure / element (e.g. Ishikawa et al. 2000, GAP221 Report, 1997 and GAP423 Report, 1998).
- the structure or element to be tested is moving and impacts a movable or non-movable element, e.g. commercial and military vehicle crash simulations.

Multiple Loading Cycles

It is accepted that many materials may fail when subjected to multiple loadings. It is expected that ground support systems in seismically active mines will be subject to multiple events. However, by only testing an element or system with small multiple loads will provide an incorrect capacity of the element or system to a single critical loading event, Player et al 2008(a). To understand the critical loading conditions for a reinforcement system, that system must fail on the first load. Facilities that rely on multiple loads, fail to acknowledge that material properties change with increased strain rate, plastic deformation or that dynamic friction can reduce with velocity. Multiple loading to failure also ignores that the embedment conditions, including the probable increase of the debonded length at a simulated discontinuity will change following each successive load and hence modify the performance of the system being tested.

Dynamic Loads in Underground Mining

One purpose of rock support and reinforcement is to maintain excavations safe and open for their intended lifespan. The effectiveness of a chosen reinforcement strategy affects the safety of personnel and equipment and impacts on the economics of ore extraction.

The type of support and reinforcement required depends on several factors. These include, strength of the rock mass, geometry of the excavation, stress state present in the rock, blasting practices, weathering and corrosion processes.

Mines that are prone to dynamic failure must design an appropriate ground support scheme maybe the main measure to mitigate the effects of seismic activity and subsequent rockmass damage. Consequently, there exists a need to develop an understanding of the energy absorption capacities of reinforcement systems, support systems and ground support schemes to dynamic failures.

Design of reinforcement and support cannot be performed with a high degree of certainty for seismic and dynamic loadings as the forces and displacements required to be sustained by the reinforcement and support systems have not been established. Some suggested values of the parametres required for design are now presented and discussed.

Seismic systems have been used for at least the last 15 years to measure the seismicity in mines. There is a large amount of data on seismic event traces but very little, if any, information related to the velocities of rock mass ejection associated with violent failures, and the forces and displacement induced in reinforcement and support systems. Generally, the assessment of reinforcement and support systems is based on the size of the seismic event and its relative proximity to observed damage. Some of the suggestions made by various workers in the area of mine seismicity and ground support are:

Wagner (1982), discussed a static force capacity to withstand nearby seismic events with an allowance of 300mm for drive closure. Roberts and Brummer (1988), consider seismic loading from a low frequency wave and developed this work further. Jager et al. (1990), published damage mechanisms and the requirements for yielding rock bolts to control dynamic violent failures; this followed the development of the cone bolt. The experience-based requirement was “to control reasonably severe rockburst deformations, tendons must have the capacity to absorb at least 25kJ of energy during the rockburst”. This was the requirement for the rock bolt; the surface support is additional.

GAP709 (2002) undertook extensive measurement of skin velocities from seismic events on excavations in South African gold mines, Peak Particle Velocity (PPV) of 3.0m/s were recorded with peaks of upto 3.5m/s predicted for the operations assessed. Events were correlated to the original source recorded by the seismic monitoring system at the mine.

Typically practitioners have made the ejection velocity of a block of the rock proportional to the PPV of the seismic wave. This has been done because the PPV is easy to measure. But why is the PPV of a free moving wave in a rock mass supposed to have to some relationship to how a reinforced block of rock behaves when it is ejected from an excavation? Mechanically this cannot be correct, but it is used because the PPV is apparently an easy relationship to calculate.

The relationship is examined either in the near field or the far field.

Far Field Excitation Velocity

Kaiser et al. (1996), Kaiser and Malony (1996) and Stacey and Ortlepp (2002) developed ground support scheme criteria for seismic events. The criteria are based upon;

- ground excitation velocity from far field Peak Particle Velocity (PPV) decay equations for seismic events,
- an assumption for the amplification of the PPV of the wave when it encounters an excavation,
- and an assumption on the volume of ground to be ejected.

Each group of authors used different decay equations for the calculation of PPV, different amplification factors at the excavation surface, and developed their own dynamic test facilities to assess energy absorption capacity for reinforcement and support elements (without calculating dynamic force-displacement curves) and hence arrived at different ground support requirements for similar dynamic events.

Kaiser and Malony (1996) application of scaling laws specifically state that they are not applicable in the near field, and their 90% confidence limit is only applicable upto a maximum velocity of 1m/s and the 50% confidence limit is only applicable to 0.3m/s. Such velocities are not sufficient to cause critical loading of reinforcement systems tested by the authors.

GAP709 reporting on blasting induced damage to simulate violent failure cite 800mm/s as a threshold from low intensity to high intensity. This is supported by Yi (1996) where he states "support design principles for static loading should be applied to low intensity rockburst condition", this is because standard mine induced far field seismic event do not have the energy to damage well supported excavations.

Near Field Excitation Velocity

Kaiser et al. (1996) from work by Aki and Richards (1980), state that the far field PPV relations do not hold within two times the source radius. The source radius is defined by Equation 1 from Scholz (1990).

$$r_0^3 = \frac{7M_o}{16\Delta\sigma} \qquad (1)$$

Where

r_o is the source radius,
M_o is the Moment in Nm and
$\Delta\sigma$ is the static stress drop in MPa

Ortlepp (1992) provides six different mechanisms for violent rock failure. Four of the mechanism use excitation of the rock mass around a tunnel by a wave from a seismic event. They are laminar buckling, ejection, inertial displacement and arch collapse. Two mechanisms are also given which are the results of the induced stress about an excavation, strain burst and implosion. In these latter two cases the seismic event and failure occur at or about the excavation surface, and would definitely be within the source radius. The first four cases may or may not occur within the source radius.

Big Bell Gold Mine (in Western Australia) seismic data set has approximately 20,000 quality monitored seismic events over a three year period. In this data set were 11 violent failures where the seismic trace was also obtained. Nine other violent rock failures occurred at the mine but the waveform and source parametres were masked by a production blast or occurred prior to the installation of the seismic system.

Of the eleven monitored dynamic rock failure events, ten had bulking and damage to the reinforcement systems within two times the source radius (Eq1), two events also had the shake down of rock from unsupported walls at more than twice the source radius, and one only had shake down from an unsupported wall of the closest development at more than twice the source radius.

These observations correspond with work published by Jager (1992) where he quotes McGarr from work in South African gold mines. "After plotting the distance of the hypocenter of 80 seismic events, which caused rockburst damage, from the area of damage and then calculating the source dimensions of the event, the author came to the conclusion that the majority of the severe rockbursts occur in the source region or near field." The actual formulae used to develop the peak ground velocity against cumulative damage were not given in the paper.

Gibowicz (1990) states from his personal experience, the estimated size and geometry of underground damage caused by dynamic failures were considerably smaller than that predicted by the Brune model for source radius.

Albrecht and Potvin (2005), Heal (2005) and Talebi (2005) all refer to McGarr (1991) paper for near field velocity equations for PPV but all provide different solutions. It is evident that a degree of interpretation has been applied.

These observations imply a more accurate understanding is required within or very near the seismic source radius of the following items:

- whether PPV is the best way to assess ground motion within the source or very near to the source,
- strain wave / displacement wave loading of the rockmass from the seismic source,
- whether a difference exists between seismic waveforms and loading mechanisms from a very large far field event compared with a moderate very near field event when they encounter an excavation,
- consideration is given that a departure from similarity occurs for seismic events having magnitude less than four. Consequently scaling relationships become of limited value, Gibowicz (1990).

Energy Release

A couple of questions are proposed regarding seismic energy release and rockmass response:

Question: Is a magnitude scale an adequate description of an event particularly when there are a number of published formulas for the calculation of the same scale?

Answer: Magnitude scales were highly relevant prior to the use of digital recording of seismic waves. Digital recording now enables data capture across the full wave frequency. Magnitude scales were developed for specific geographic regions, some have upper and lower limits of application and others can only be applied in one direction.

Question: How is the released excess seismic energy absorbed by the ground support scheme?

Answer: This will depend on the load transfer mechanisms from the rock to the reinforcing and support elements and the dynamic force-displacement curves of the elements.

Question: How are the dynamic forces transferred between the support and reinforcing elements?

Answer: This is not sufficiently understood.

The Western Australian School of Mines (WASM) dynamic test facility has been designed to provide answers to the last two questions. The assessment of dynamic force-displacement curves and the development of an energy absorption calculation methodology sets the WASM test facility apart from other mining dynamic test facilities. The facility is fully detailed by Player et al. (2004) and Thompson et al. (2004).

Terminology

The following terminology are used within this paper :

Reinforcement System

Comprises the reinforcing element (the bolt), an internal fixture (grout, mechanical or friction coupling), and an external fixture (face restraint). Examples are rock bolts and cable bolts.

Support System

One or a combination of surface fixtures generally linked to the reinforcement system (e.g. w-straps, weld or chain link mesh, and shotcrete or fibrecrete).

Ground Support Scheme

A combination of the reinforcement system and support system.

Critical Loading

The loading conditions that result in failure of the tested reinforcement system on the first load. It will be influenced collar mass, impact velocity, embedment conditions and surface hardware. The reinforcement system response to critical loading will be quantified by energy absorbed, displacement at the simulated discontinuity, velocity and deceleration of the mass.

Seismic Event

The release of built-up strain energy in the rockmass. This occurs as a result of stress change due to the formation of excavations. A fall of ground or yielding of a ground support scheme may or may not occur. The energy travels in the rock mass as a wave with frequency and amplitude and is complex in shape.

Dynamic Rock Failure (Rockburst)

A section of the rock mass detached when energy waves travelling through the rockmass encounter an excavation boundary. The wave excites the rock to be ejected, the rock mass that remains behind afterwards, and the ground support scheme, before some complex ejection process occurs. The ejected rock already has a velocity and does not accelerate further. The actions of the ground support scheme is to reduce and stop the displacement of the rock, provided it has sufficient capacity or length. Basically, either a fall of ground occurs or the ground support system displaces and maintains the ejected rock.

Mining Dynamic Test Facility

A Mining Dynamic Test Facility is specifically designed to test rock reinforcement or support elements and / or ground support schemes in a repeatable manner. The mode of loading maybe in tension, shear or a combination of the two.

Blast induced loading of ground support schemes (either on the surface or underground) does not fit this definition because of the difficulties in repeatability and variability within the rock mass at underground sites. Furthermore, blasting waves propagate through the rockmass and become highly complex when reaching the free surface, thereby making analysis of the ground support highly complicated.

Facilities that are solely configured to test ‘props’, in compressive loading from the hangingwall, are not considered in this paper.

Hadjigeorgiou and Potvin (2007) have extensively reviewed simulated dynamic failure via blasting both underground and on the surface and provided a shorter review on dynamic test facilities.

DYNAMIC TEST FACILITIES – MINING APPLICATIONS

Dynamic force-displacement curves should be used for the calculation of the energy absorbed or lost in the test structure / element and facility. This follows the established practice for assessing force-displacement curves and load transfer in quality, quasi-static performance testing of ground support elements, Windsor and Thompson (1993). Physical material properties are rarely constant across all strain rates, hence critical displacement, velocities and accelerations should be reported from a testing facility.

This review will not attempt conclude whether testing facilities have a correct methodology or not. However, a lack of published energy balance equations from existing test facilities is evident.

The facilities examined in terms of their advantages and limitations are:

- CSIR Terratek
- CSIR Impact Testing
- Geomechanics Research Centre Impact Testing (Laurentian University),
- Noranda Technology Centre Impact Testing (now called CANMET-Mining and Mineral Sciences Laboratories following moving of the rig in 2004)
- Ansell Impact Test (Sweden)
- Western Australia School of Mines (WASM) Momentum Transfer

The purpose of dynamic testing is to understand how a structure or an element behaves under rapid loading conditions. This is typically undertaken by building either a full scale or scaled model of the structure or element to be tested. Particular attention should be paid to load transfer to the element or structure, the design of instrumentation points and the methodology for calculating or measuring energy, force, displacement, velocity and acceleration.

The categories that differentiate the reviewed civil, military and mining test facilities are:

- the scale of test (energy input, scaling of test elements).
- unit being tested (an element of a structure, or the complete structure).
- application of energy (vibrational loading, direct impact, shock wave / compressed gas).
- instrumentation utilised for calculating energy.
- repeatability of the test and procedure.
- associated development of a computer model to compare expected responses to physical response, (e.g. Thompson et al. 2004, Kishi et al. 2000, Ishikawa et al. 2000).

CSIR TERRATEK

The Terratek unit, shown in Figure 1, was built in the USA in 1978. It was based at the CSIR mining centre in Johannesburg until its closure in 2007. The unit was capable of dynamic operation either up or down, loading bolts in tension or shear, or props in compression at a predetermined velocity. Configured for bolts the unit assessed the reinforcing element and anchor mechanism of the ground reinforcement system. The surface hardware that would be attached to the bolt could not be included.

The Terratek's capacity for a rapid displacement of 200mm with a set velocity between 1.2m/s and 3m/s. The velocity was determined by the amount of restriction from high to low pressure cylinders. The low pressure side was set at 40 tonnes and the high pressure was set at 160 tonnes. The achievement of the set velocity was best represented by a bell shaped curve. For the 3m/s set parameter the head of the jack needed to move 90mm to reach the required velocity of 3m/s.

The importance of the facility is the volume of testing that had been done, and how this information has been related to performance underground.

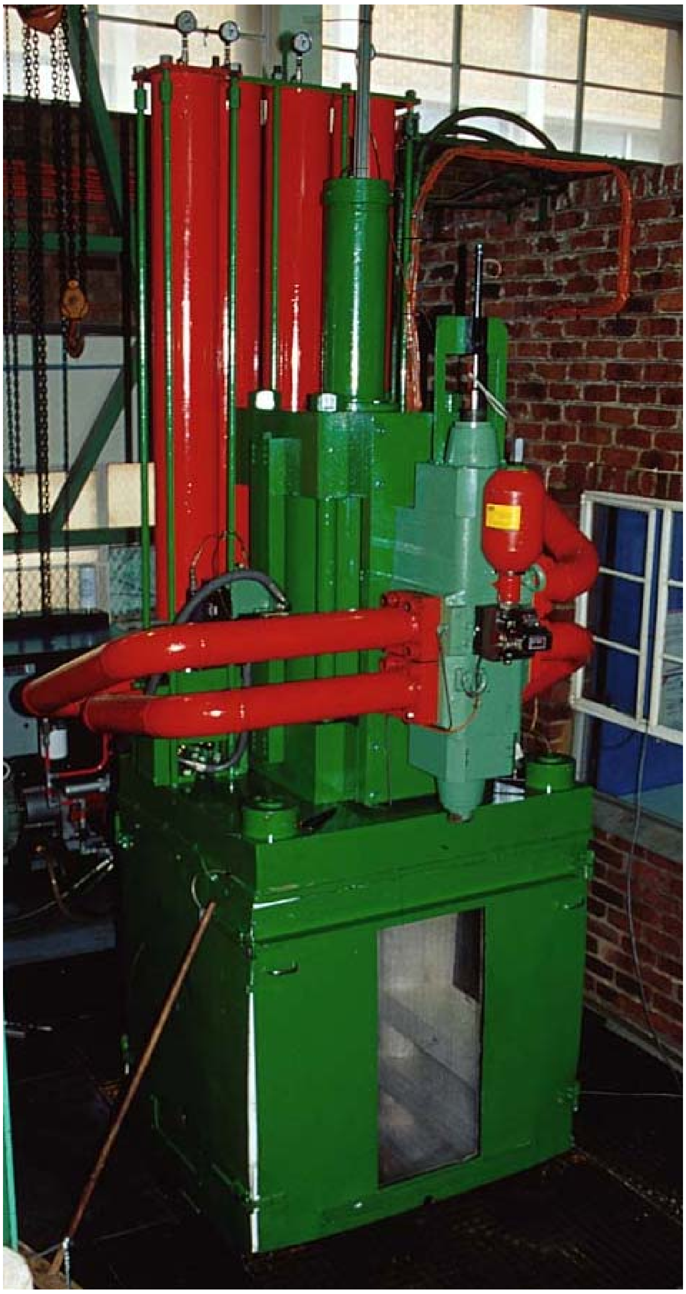


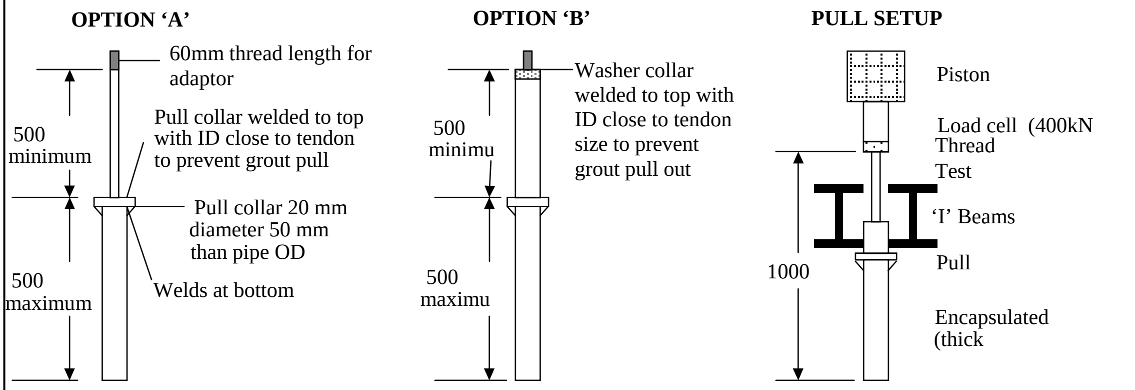
Figure 1: Terratek hydraulic dynamic test facility

The Terratek was also capable of slow displacement pulling a bolt at 30mm / minute or 15mm / minute. The unit had a maximum piston displacement of 600mm, with 500mm displacement set as the standard test criteria. The sample dimension and configuration for the Terratek testing apparatus are shown in Figure 2 (as provided by the CSIR).

TERRATEK SLOW AND DYNAMIC PULL TEST SAMPLE DIMENSIONS

These length dimensions are based on the piston being at the bottom of its stroke (i.e. it can withdraw up to the full stroke maximum of 600mm)

The pull collar attached to the encapsulation tube rests beneath twin I beams that locate in the machine frame. Withdrawinghte piston puill the tendon relative to the encapsulation tube



OPTIONS A & B

The bond length can range in length by up to an additional 500 mm.

The usual tube wall thickness is 5 to 6mm, if however the yield mechanism relies heavily on the confinement supplied by the rock mass much thicker wall tube is required to prevent tube distortion influencing the test results by supplying insufficient confinement.

NOTE

The 500mm length of tendon above the top of the pull collar is a minimum figure that is required to be able to reach the load cell adaptor when the piston rod is in its fully extracted position. Lenghts inexcess of 500mm are not a major problems, but it results in a loss of stroke length.

The 500mm distance from the top of the pull collar is a maximum dimension limited by the available clearance below the I-beams.

Figure 2: Terratek bolt sample lengths (provided by CSIR)

Advantages of the Terratek

The Terratek was the only hydraulic dynamic test facility reviewed and is considerably older than the other facilities. The unit was particularly useful to the South Africa deep gold mines in the testing of stope support props. This was done without significant upgrades during its life. The unit's main advantages were:

- cheap test costs,
- the fastest cycle time of any facility – upto 15 tests per day on support props
- the only facility capable of applying dynamic load in compression, tension or in shear by reconfiguring the setup,
- it could also perform quasi-static tests,

The facility could have been improved by:

- the ability to perform double embedment length tests.
- an instrumentation upgrade and improved analysis methodology applied with signal filtering, to allow more accurate calculation of energy absorption to enhance the value of the tests.

Disadvantages of the Terratek

The limitations of the Terratek are assessed as:

- applied velocity is independent of the load transfer capability of the reinforcing element being tested. Consequently, the force applied to a rock bolt element is not related to the input energy from the hydraulics of the Terratek.
- the force applied to the element at the selected test velocity may exceed the force that a dynamic failure could apply to the element.
- the method by which load is applied does not account for energy absorbed by the reinforcement system, which if effective, reduces the velocity of the ejected rock by causing deceleration and at the same time doing work.
- the unit can only test the rock bolt elements and its anchor mechanisms and not a complete system.
- Instrumentation occurs at the collar of a reinforcement system. Sampling occurs from a load cell attached to the pulling collar. Readings for displacement, piston velocity, and force are taken at a rate of 1000 samples per second for the rapid test, there is no filtering of the data. The data is graphically presented, although electronic data is also available.

A typical force-time response for a yielding reinforcement element obtained in the test facility is shown in Figure 3. It is not clear how manufacturers and site engineers can interpret the data when presented in this form. Of some concern was whether measuring the force applied at the "collar" of the bolt was representative of the resisting force at the anchor. To investigate the potential cause for the fluctuations, a computer program was developed to simulate the Terratek testing method. The software was used to simulate the yielding reinforcement element and the results are given in Figure 4. The similarities in the forms of the collar force-time responses suggest that the simulation software produces results that are representative of this test facility. If this is the case, then it is pertinent to examine the force-time and force-displacement responses predicted for the yielding anchor shown in Figure 5 and Figure 6, respectively. These predictions suggest that the force at the anchor in a test could be expected to be almost constant while the collar force fluctuates widely above and below this constant force.

It is worth noting that for about 20 years no questions have been raised or comments have been offered as explanation of the widely varying collar forces produced by the Terratek and no "filtering" of data has ever been attempted. This does not imply that the Terratek results are invalid as the computer analysis at WASM confirms that the mean force will be representative of the actual anchor force.

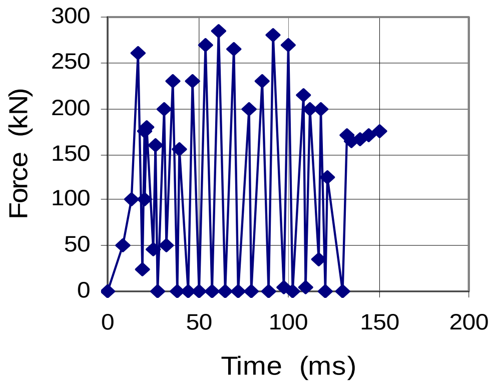


Figure 3: Example of a force-time response curve obtained using the Terratek.

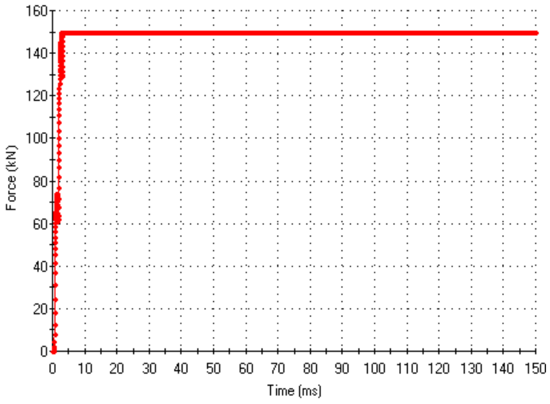


Figure 5: Computer simulation of the force-time response for the yielding reinforcement element anchor.

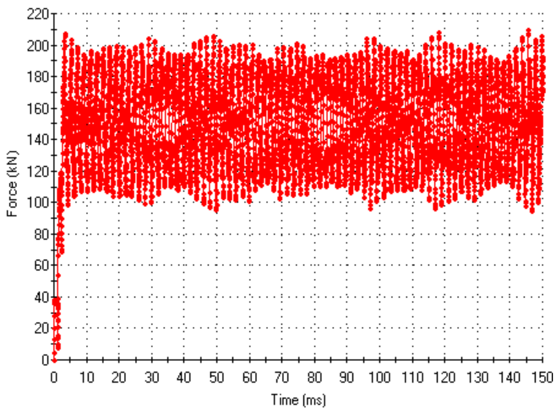


Figure 4: Computer simulation of the Terratek test for the yielding reinforcement element.

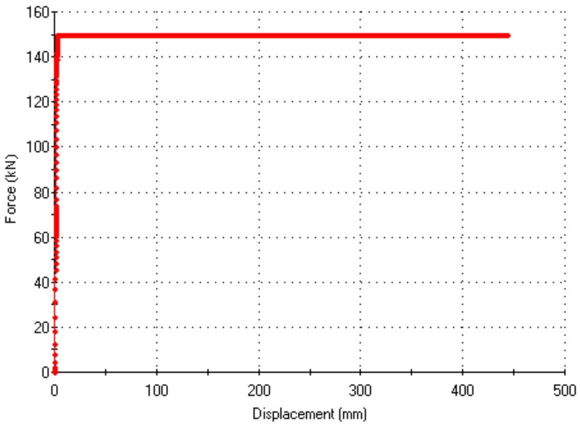


Figure 6: Computer simulation of the force-displacement response for the yielding reinforcement element anchor.

CSIR DROP TEST FACILITIES

In 1997 and 1998 Steffan Robertson and Kirsten Consultants (SRK) developed two drop test rigs for the testing of ground support and reinforcement elements. Facilities were built using funding from the Safety in Mines Research Advisory Committee (SIMRAC) and Reported in the Gold and Platinum (GAP) Research Projects 221 and 423. These facilities used the principle of a moving mass impacting a stationary test structure or element. The drop test rigs are based in Johannesburg at the CSIR, however they are currently decommissioned.

- GAP221 Project developed the first rig for testing support system tests. It was later upgraded to include some level of instrumentation and to undertake ground support scheme tests. The facility and the results are described in GAP221 Project Report (1997), Ortlepp and Stacey (1997), Ortlepp and Stacey (1998), Ortlepp et al. (1999) and, Ortlepp and Swart (2002).
- The second facility was specifically designed for testing reinforcing elements and is described in detail in GAP423 Project Report (1998), Stacey and Ortlepp (1999) and, Stacey and Ortlepp (2002).

A brief description of a new facility and methodology was provided by Ortlepp et al (2005). However, insufficient details do not allow constructive comments on its advantages and limitations.

Reinforcing Element Testing from Impact Drop Test CSIR

The facility constructed for the GAP423 project is shown in Figure 7. This figure was sourced from Stacey and Ortlepp (1999) (additional comments are annotated). The facility had the capability to test reinforcement elements and anchorage mechanisms, but testing did not always include appropriate surface hardware that would have been included in a reinforcing system. The facility functioned by using a free falling mass to impact a stationary “swing beam”. The impact force was translated from the swing beam to the outside of a thick wall pipe (that simulates borehole confinement) and the head of the bolt being tested. Information on the facility was primarily sourced from the GAP Report 423 (1998), because it provided the most details on the construction of the facility, test results and analysis process. The database consists of 58 samples tested and published of which, twelve of the bolts failed on the first impact.

The facility was modified after the initial test program, as it was considered too soft with significant energy absorption by the facility, thus reducing the energy transferred to the bolt. Stiffening of the cross beams was reported to increase the level of energy imposed upon the bolt.

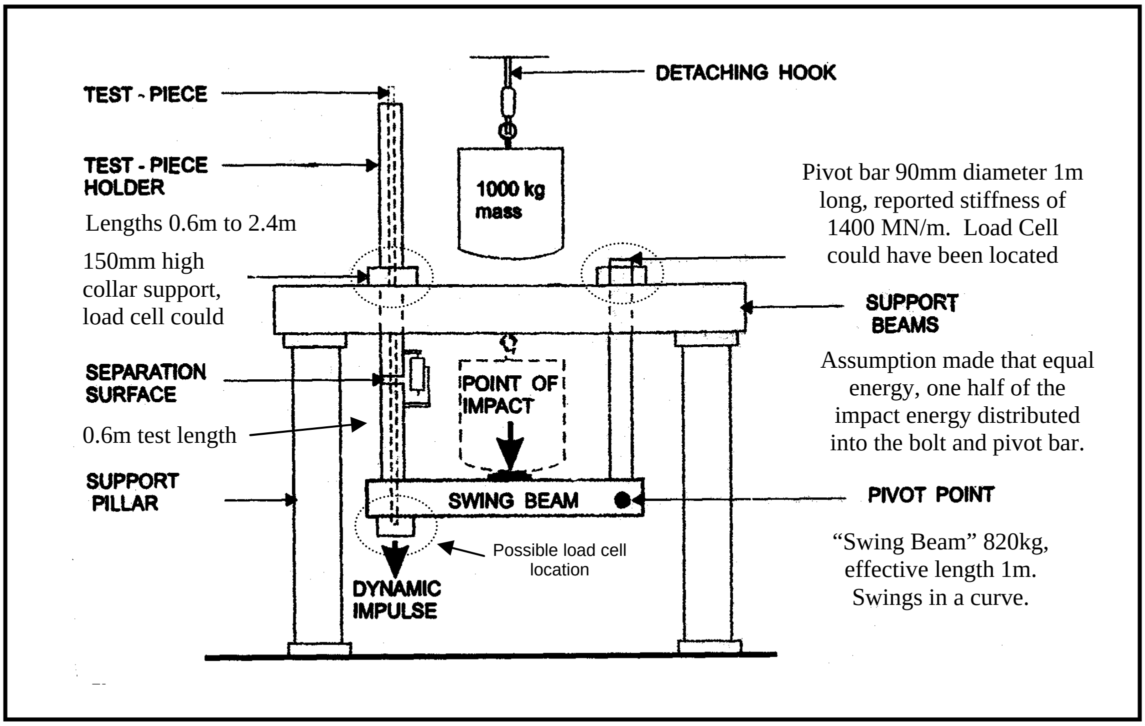


Figure 7: Mass drop onto swing beam to load the reinforcement element

Advantages in the facility

The facility had the following positives:

- appropriate use of thick walls pipes to simulate rock mass confinement by a borehole. Rock bolt elements were installed into 63OD with 40ID or 93OD with 64ID steel pipes.

- the steel pipes were held in place by 150mm long clamps mounted in machined groves into the pipes above the frame and below the swing beam.
- the load was applied to the outside of the pipe and would be a reasonable representation of the load applied by ejected rock to the borehole, but not the surface hardware.
- the testing facility appeared comparatively cheap to construct.
- a reasonably testing rate should be possible as the tests are relative easy to setup,
- tests can be undertaken in double embedment configuration.

Limitations of the facility

The major limitations of the facility was the process by which load was transferred within the facility and the relative stiffness of the components other, although less significant limitations are:

- minimal instrumentation and basic calculation methodology used to assess the energy absorption capacity of the rock bolts.
- no load cells were used to measure the load split between the pivot bar and test bolt, but they could have been located at the locations shown in Figure 7 to record the anchor and collar forces
- the swing beam did not directly load the surface restraint component of a reinforcement system.

Stiffness and energy split methodology

The GAP423 Report (1998) makes the assumption of an equal energy split into the test bolt and pivot bar, equated to half the kinetic energy of the drop mass at the instant of impact. Load cells would have made it possible to calculate the actual load transfer

Testing the assumption of equivalent stiffess between the pivot bar and test sample was done at the facility by replacing the pivot bar (with a calculated stiffness of 1400MN/m) with the same bolt as that in the sample location. As both bolts were the same, then it would be expected to have the same stiffness, and hence behave similarly under the impact load.

However, the pivot bar and the sample bolt can only have equal stiffness if the stiffness of the sample is calculated over a short separation length, and that is compared to the complete free length of the pivot bar stiffness (K) given by Equation 2

$$K = \frac{AE}{L} \quad (2)$$

where E = elastic modulus of the pivot bar material

A= area of the pivot bar

L = free length of the bar

For example, if E for steel is 206GPa, A of the cylinder bar = 6360mm^2 (90mm diametre pipe) and L= 1.0m (from the pivot or load point to the anchor point), then K = 1310MN/m for the pivot bar.

For a 20mm rock bolt and E=206GPa, then it has the same instantaneous stiffness only when L = 46mm. This assumes no debonding or stretching of the test bolt and the simulated borehole behaves extremely stiff in comparison to the short separation length.

The split in energy distribution between the specimen and pivot bar will change with time during the impact. The true energy split depends on the relative stiffness of the specimen to the pivot bar, and yielding of either the reinforcing element and / or its yielding mechanism within the borehole.

Application of impact load

Variations in the impact load arise from the combination of the swing beam and pivot bar, and the potential for non-uniformity in impact of the free moving mass on to the swing beam.

The swing beam does not load the bolt with a pure axial load as it must include a partial shear component from the beam rotating about its pivot point. It is probable that this is of minor importance for low energy tests with small displacements but could be very important for high energy tests with high displacements. Although the test may better represent the underground environment, there is no allowance in the calculations for including a partial shear component.

If the pivot bar is not both strong and stiff when compared to the test bolt, the rotation point can move out of the vertical axis and downwards. These factors introduce variations in the load applied to the sample.

The coefficient of restitution at the impact surface of the free moving mass and swing beam will not be unity. Variation in the vertical component can arise from a non-uniform release, and non-controlled descent. There will also be an increase in potential energy if the mass remains in contact with the swing beam as the beam moves down.

Ground Support Scheme Drop Testing CSIR

The GAP221 Report (1997) was the primary source for the review on this facility, and is the source for Figure 8 (additional comments are annoted). The facility utilised the impact of a free moving mass onto a load distribution system which then loads the element to be examined; in this case surface support systems used in South African mining operations. The load distribution system consists of multiple layers of various sized cement blocks.

- Boundary conditions represented by support elements securely anchored to a from. This could be the case for continuous systems like chain link or wire rope. Mesh securely attached to the support frame to represent an “infinite” support system
- To maintain the load transfer to the lower blocks in the load distribution pyramid and then support element under test following impact, the upper and lowest layers were restrained to preventing spreading.
- The rock bolts were on a 1m by 1m pattern spaciing
- The mesh and fibrecrete sample was 1.6m by 1.6m
- Deformation of the surface support was initially measured in 8 locations following each impact.

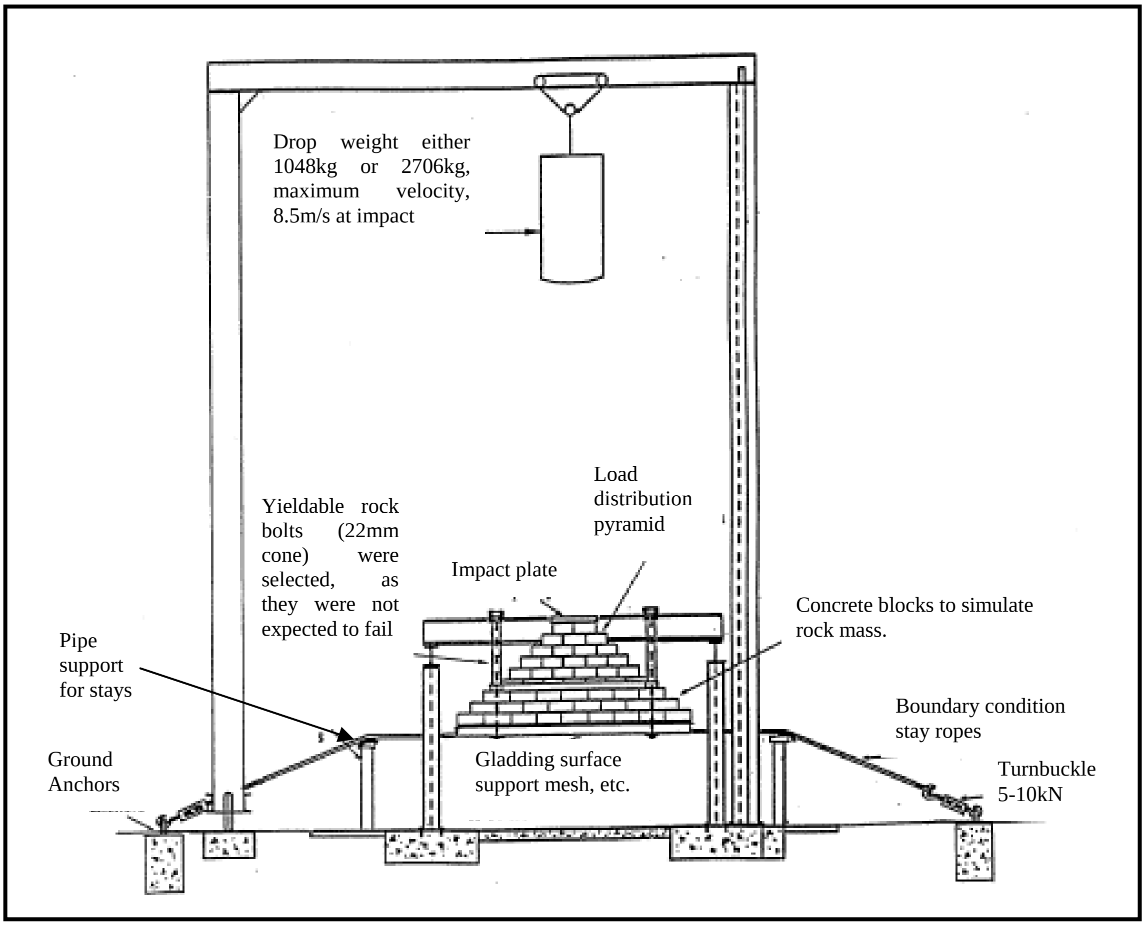


Figure 8: Drop Mass for Ground Support Scheme Testing

Advantages of test facility

The positives of the test facility include:

- First facility developed for multiple tests on the one surface element.
- Edge constraints used to attempt simulation of large rolls of chain-link wire.
- Some degree of qualitative assessment of different support elements without interaction on the reinforcing elements that were tested.

The test configuration has a soft support system when compared with the reinforcement system and a large amount of fractured ground behind the support system may well be representative of some South African rockmass failure conditions prior to dynamic loading.

The test facility boundary conditions appear to be configured for heavily fractured rock. However, there may not be adequate connection of the support system to the reinforcing system; hence they do not function together to control the damage from a dynamic event loading. This could also represent South African ground support installations. However, the configuration of the test facility is not consistent with observations in Australia were blocks of rock are loading the reinforcing elements and the support elements, or for that matter observations reported by Ortlepp (1992 and 1997).

Results were reported as consistent and repeatable, which suggests that the technique and tests may have some merit as a relative ranking for support systems; however there was no attempt at calculating the actual energy absorped by the support element. This was in part due to the complexity of the load distribution device, and only the kinetic input energy was reported. The authors conclude that the results from GAP221 Report (1997) and Stacey and Ortlepp (1999), should only be used as a relative ranking system between tests on different support elements because of the non-consistent energy loss in the concrete blocks (load distribution system) and test frame.

Limitations of the facility

The achieved results are sensitive to the load distribution system. Multiple block geometries in multiple layers increases the complexity of the load distribution system this introduces variations for repeated testing at the same facility and difficulty for other researchers that wish to use the same methodology but on different support elements. This was observed from increasing variability in the results at higher input energies.

GAP221 Report (1997) leaves a number of critical points unanswered:

- No measurements of force-displacement relationships and calculation of energy loss through the load distribution device.

  The GAP221 Report (1997) shows a non-linear relationship for the number of broken blocks and kinetic energy of the falling mass; the curve flattens with increasing energy input. This is probably related to the upper bricks not just being broken but pulverized. Breaking and pulverisation of the bricks will reduce the energy input into the support system but, by differing amounts and perhaps overate the capacity of the "higher capacity" support systems.

- In determining the capability of the support system there is no account for inter-block reactions, and the inefficient nature of energy transmission through the blocks to the support system. The capability of the support system is assessed by measuring the deflection at the centre point and the energy absorbed by the load distribution system.

  A key question relates to the ability for the methodology to sufficiently assess the energy absorption by a support system with a highly variable load transfer device that is where the load transfer device has a significant role in the amount of energy absorbed. Alternatively, it may just be sufficient to provide a relative ranking of support elements.

- A second source of input energy not discussed is the increase in potential energy from the drop mass remaining on top of the concrete blocks and moving downwards. The large mass added 2.6kJ of potential energy change for every 0.1m of displacement downwards after impact.

  The GAP221 Report (1997) does not discuss load transfer to the bolt in terms of the force applied, the displacement recorded, or the requirement to change out bolts. Stacey et al 2002, states “Although yielding rock bolts (22mm cone bolts) were used in this setup, they were not expected to yield during the test. This is due to the fact that they were deliberately over-designed so that they would not need to be replaced during an extended series of tests involving more than 100 drops. In the tests, the bolts therefore did not contribute, by yielding, towards the energy absorbing capacity of the support system tested.” This was the case for kinetic impact energies between 3kJ and 70kJ.

It is clear for the configurations tested there were significant differences between the relative stiffnesses and strengths of the support and reinforcement system.

GAP221 Report (1997) does not define the conditions of interlocking between the bolts and the blocks; the tests were primarily designed to load the surface support elements. Without interaction it would not be possible to tension the cone bolt and the concrete blocks of the load distribution system. The facility was updated with the replacement of 22mm cone bolts by 16mm cone bolts. Those bolts pass through holes in the concrete blocks, and allowed some load transfer if the bolts were tensioned as reported in a subsequent paper (Ortelpp et al 2002).

Update to the CSIR drop test facility for support elements

Ortlepp and Swart (2002) have started to address the limitations by defining their rockburst event.

"Considerable effort was devoted to determining the rationale on which the testing method was founded. It was decided that the distinguishing feature of rockburst damage, which is all-important in determining the testing method, is that large blocks of rock are reduced to much smaller fragments, effectively instantaneously, by the rockburst. The test setup must therefore necessarily be based on the impulse thrusting of smallish element of rock-like material against the containment fabric."

This statement contradicts previous extensive work reported by Ortlepp (1992 and 1997) and by Kaiser et al (1996).

Ortlepp (1992) discussed six different mechanisms of rockbursts; implosion, laminar buckling, strain burst, ejection, inertial displacement, and arch collapse. Four of these involve the movement of large blocks of ground loading the reinforcement elements, and these are documented with photos and figures.

Ortlepp (1997) provides photos and sketches of large slabs of rock ejected from the sides and backs of the drive, as well as complete drive closure with small particles. Where large blocks were displaced, it was not uncommon for bolts to remain anchored to the rock mass. It is considered most of these occurred because of inappropriate surface support elements and / or insufficient integration with the reinforcing elements. A poor selection of collar fixtures may not have allowed the rock mass to transfer load to the reinforcement system.

Ortlepp and Swart (2002) attempt to integrate load cells and geophones to determine energy absorption, however they did not find it possible to undertake the energy calculations. This is not unexpected, as the instrumentation was not a closed loop, with only the measurement of anchor forces and not collar forces or the forces in the control wires. The actual monitoring instrumentation and filtering were not discussed in detail and may not have been appropriate to the task. Geophones on the support element or the base of the load distribution device may not provide reliable velocity data.

OTHER DROP TEST FACILITIES

Three test facilities have been developed in Canada; two run by Laurentian University, Geomechanics Research Centre (GRC), and one at the Noranda Technology Centre

(NTC), which was purchased by CANMET-MMSL. Another facility has been developed Sweden. These facilities are discussed in the following sections.

GRC Support Element Test Facility

A drop test facility for impact testing of face restraint support systems, constructed at Creighton Mine, is shown in Figure 9 (additional comments are annotated). The comments in this section are based on Chapter Four of the Canadian Rockburst Support Handbook, (Kaiser et al, 1996). The facility uses direct impact of a free moving mass onto the support element, rather than a load distribution device as used by the CSIR facility. This is the primary reason why the GRC input energy was much lower than the CSIR support system test facility. The facility was apparently shut down and dismantled at the end of the test program.

The support system tested could be a panel of shotcrete, fibrecrete, or mesh plus shotcrete resting on support plates anchored to concrete pylons. The support plates sit on top of load cells, and these could be tensioned from above.

The available input energy for the tests was not clear. The unit was reported to have a maximum drop height of 4m (potential velocity 8.8m/s, with a kinetic energy = 21.9kJ), but the maximum velocity was reported as 7.7m/s. The maximum reported kinetic energy at impact is 23kJ, but this requires a velocity of 9m/s. f only the one loading mass is used, 7.7m/s only provides 16.7kJ.

The pylons supporting the shotcrete panels, have a bolt area of 0.72m^2 from a 1.2m diamond pattern, and the impact area was 0.28m^2. The effective loading area of 1m^2 was suggested from approximate crack growth. The threadbar anchoring the panels to the pylons was 19mm in diameter.

Advantages in GRC support element test facility

The following positives about the facility are noted:

- A quick setup time should have been possible.
- Once the facility was established, testing of support elements should have been relatively cheap.
- The element size was reasonable to have some representation of edge conditions.
- The facility was reported as well instrumented and should have given reliable, but different, assessment of the energy consumption when compared to the South African facilities.

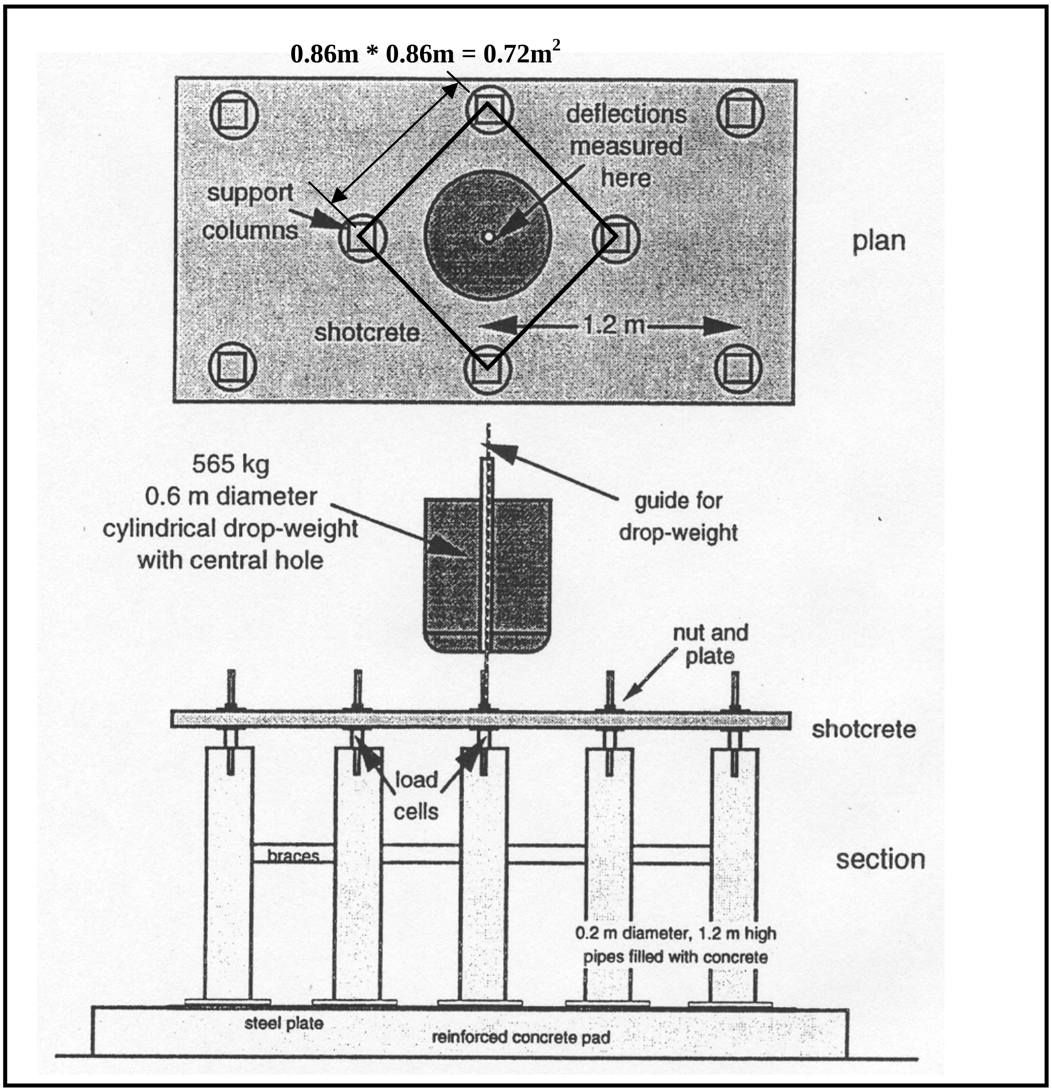


Figure 9 : GRC Shotcrete Test Facility - Creighton Mine

Limitations of GRC support element test facility

Limitations of the system involve the integration of the reinforcement element to the support element (fibrecrete panel) and the energy absorption calculation process.

- the facility tests the performance of the surface support element from a direct impact of a falling mass and not the interaction of the surface attachment with the reinforcing element.
- flat plates controlling the support test element on top of the load cell were 127mm * 127mm * 9.5mm, (cable bolt plates) reported as suffering damage on occasions, but the load cells only reported between 30kN to 120kN but there was no graphs published. Were spherical seats used to assist in load transfer? What was the tension applied to the shotcrete panel?

Kaiser et al. (1996)

"The columns used to support the test panels were relatively stiff and dissipated little of the total impact energy."

This implies that most of the impact energy was lost in plastic deformation of the support element (fibrecrete / shotcrete panel). The relative stiffness and strength of the shotcrete panel compared to the pillars will determine the load transfer measured by the load cells is also likely to effect the crack / deformation area. It is apparent that the support elements will deform plastically. Therefore, other means of calculating the energy absorbed should be investigated.

The energy was described in terms of the maximum impact energy rather than calculating the actual energy absorbed by the shotcrete combinations. The civil engineering application of Yield Line Theory for calculating the energy absorption in concrete and fibrecrete panels from a centre deflection point has a potential application in determining the dynamic energy absorption, Kennedy and Goodchild (2003).

Kaiser et al. (1996)

"For the impact tests, the area of shotcrete directly involved in absorbing the kinetic energy was about $1m^2$."

This allocation to simplify the impact energy so it can be directly related to energy absorption per square metre of dynamic failure needs to be carefully considered when the actual impact area of the falling mass was only $0.28m^2$. Jager (1992), suggested minimum requirements for a scheme was $25kJ/m^2$; but qualified this to say that 50 kJ/m^2 was a better specification, with the yielding elements expected to withstand at least $25kJ/m^2$.

The square metre suggested by Kaiser et al. (1996) was based on the approximate area of the fracture growth after the impact. This assumption would only hold for a limited set of conditions – changing the actual impact area, the bolt spacing, impact area, or the test element would all be expected to change the crack growth. Perhaps a more appropriate solution would have been to report the actual area of the crack growth from each test rather than assuming a uniform square metre.

Of course the assessment of crack growth is only practical with plastic deforming materials or easily assessed plastic deformation. There is no consideration for the elastic deformation or flexing and recovery that support elements such as mesh would have. The application of numerous high capacity strain gauges to assess the area of deflection or three-dimensional analysis of the deformation surface would have provided a higher degree of numerical accuracy

Additionally, the bolt spacing at $0.72m^2$ is actually quite tight, and may be applicable for Canadian operations but would be significantly closer spaced than the bolt geometies used in Australian mining operations.

Comparison of support element tests

The load transfer mechanism, boundary conditions and mounting of the support element of the GRC facility at Creighton Mine and CSIR drop test facility are significantly different. No qualitative or quantitative comparison of results should be undertaken between the two facilities.

Laurentian University, Face Plate and Reinforcing Element Test Unit

A test apparatus developed at Laurentian University is shown in Figure 10. The figure and following discussion are based on the paper from Yi and Kaiser (1994). The facility used scaled down bolts and was then dismantled following the test program.

Practitioners need to decide if the loading mechanism of a free moving mass impacting on a stationary plate simulates what happens in a dynamic failure of rock around an underground excavation.

Advantages in the facility

The positives of the facility are:

- Appears cheap to construct,
- Cheap and fast to run tests on various systems.

The effect from the use of the rubber plates in changing the stress transfer by softening the reinforcement system has practical references, Player (2004) and Li et al. (2002).

Limitations of facility

The limitations of the facility are :

- Installation of the reinforcing element is not considered apart from a point anchor and an open hole.
- The drop height and drop mass were limited, and as such the facility could not break any of the tested bolts on the first attempt. Multiple drops were required to cause failure

The facility was designed to use tensioned bolts, although the initial tension was not reported

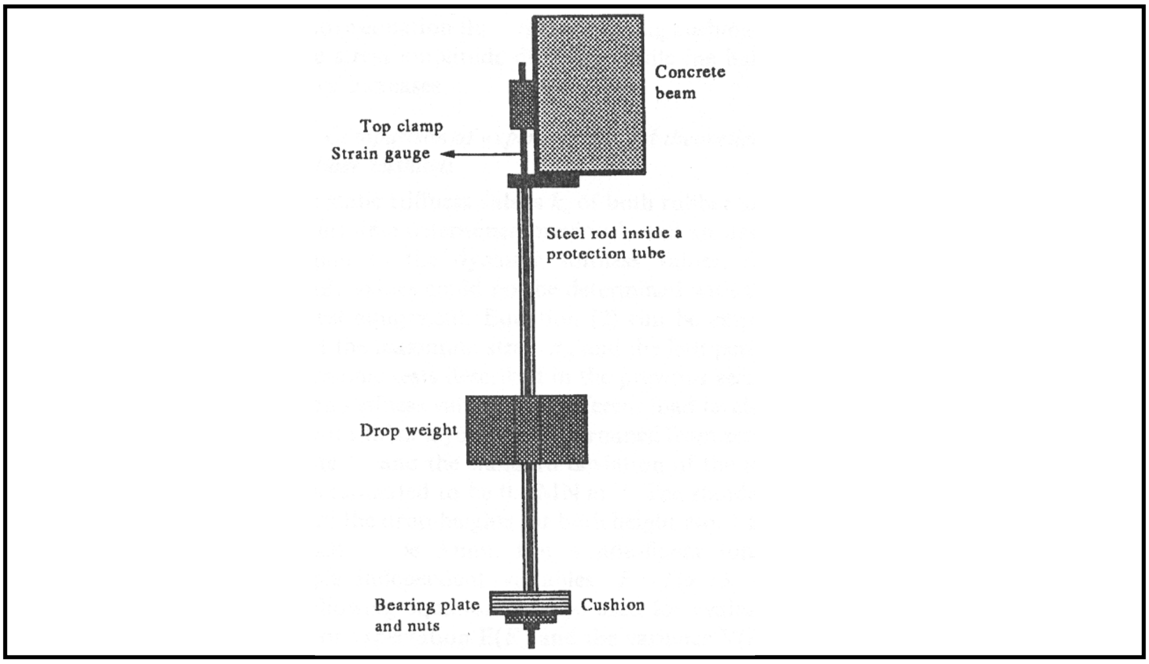
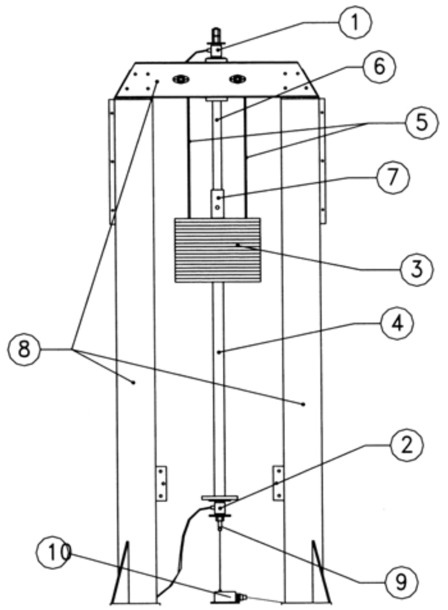


Figure 10 : Laurentian University Drop Unit

Noranda Technology Centre Drop Unit.

This facility uses the same approach as the Lauentian University facility. A free moving mass is dropped down the shaft of the bolt to impact on the surface plate, Figure 11. In this facility the bolts are full scale.



1. Load Cell 1
2. Load Cell 2
3. Drop Weight
4. Sample Holder
5. Holding Rods
6. Spacer
7. Coupling
8. Frame
9. Tendon (in sample holder)
10. Displacement transducer

Figure 11: NTC Impact test rig schematic from Gaudreau et al. 2004

The following comments relate to the facility while it was still with Noranda, as described by Gaudreau et al (2004).

Advantages of the facility

- Relatively fast and cheap to construct and run tests for the Noranda facility
- Assisted examination of impact loading on rock bolts for Canadian applications.
- Can take full scale bolts in simulated boreholes .

Limitations of the facility

- Is the methodology of a free moving mass down the shaft of the bolt to impact against the surface hardward a reliable representation of the dynamic loading problem underground, or is it just a method of providing a dynamic load to a reinforcement system?
- No integration of the rock mass with the reinforcing system, all load transfer are to the reinforcement element via the surface hardware. This is only correct for debonded system, and is a significant limitation for bonded systems. Photos of the and testing and the facility are shown by Simser (2007).
- The suggested approach to solve a non-linear material behaviour with a closed form solution is not correct. The addition of a slider and a spring in series represents the physical reality, but the offered solution represents a slider and spring in parallel with a dashpot.
- It was not clear if the reinforcing unit can be tensioned. The ability to tension the surface plates against the bolt is a key item as this is the situation underground. All threaded bolts have an installed tension, and there would also be an additional tension from ground movement loading the plate.
- If bolts can not be broken on the first hit but instead rely on multiple hits then there is a change in the tension applied at the collar of the hole from the first hit to all

subsequent impacts due to the deformation of the reinforcing element. Research at WASM has shown that the theoretical response of reinforcement systems is affected by both the mechanisms of load transfer between the reinforcement element and the internal and external fixtures, the rock, and the force existing in the element when subjected to an impact loading.

- Limited drop height and mass.
- Flexing in the facilities frame and energy loss through the frame were not considered.

The facility was upgraded in size and instrumentation added as part of the move to CANMET, and has been discussed by St-Pierre et al (2007) and Plouffe et al (2008). A review of these papers would suggest that the analysis technique utilised by Gaudreau et al (2004) is no longer utilised but rather they are adopting an energy balance approach as utilised by the WASM test facility.

It is worthwhile to note that St-Pierre et al (2007) has acknowledged the ambiguity of how the mass hits the face plate. However, his attempt to review the WASM dynamic test facility (Player et al (2004)) and particularly compare it to Ansell (2000) is inaccurate and shows a lack of understanding in the importance of double embedment conditions and simulated discontinuity to provide collar and anchor lengths. Criticism of apparently long response times, is also misplaced as a yielding bolt subject to a heavier impact load will of course respond for a longer period then when subject to a smaller load. The configuration of the surface hardware shown by Plouffe et al (2008) has a rubber plate between the loading mass and the surface hardware, hence changing the performance of the surface hardware, it is also now clear that the surface hardware is not tensioned, and most importantly the mass bounces up and down on the surface hardware following the primary impact test. Despite the upgrade in rig capacity to a kinetic impact energy of 62kJ, it still undertakes multiple loadings at 10-20kJ rather than a single critical loading event on the reinforcement systems.

Ansell Test Facility (Sweden)

This test facility was constructed and described as part of the research work by Ansell (1999) and from that a yielding bolt was suggested. The facility was only used for tests on 6 bolts. The test configuration and its analysis techniques are inconsistent with load transfer of rock to bolts. The approach of using a closed form solution for plastic deformation is also not considered to be valid. There is considered to be limited value in the results obtained from the 6 drop tests or the developed bolt.

WASM DEFINITION OF DYNAMIC ROCK FAILURE

When a seismic wave encounters an excavation there may exist a potential for a dynamic failure, Figure 12. This potential depends on the energy in the wave (eg. radiated energy and seismic moment), seismic source parametres (eg. stress drop, corner frequency, and source radius), and site characteristics of the excavation (eg. degree of fracturing, induced stress, stored strain energy, and rock properties). The installed ground support only acts to stabilise the failed rock, it does not prevent dynamic rock failure from occurring.

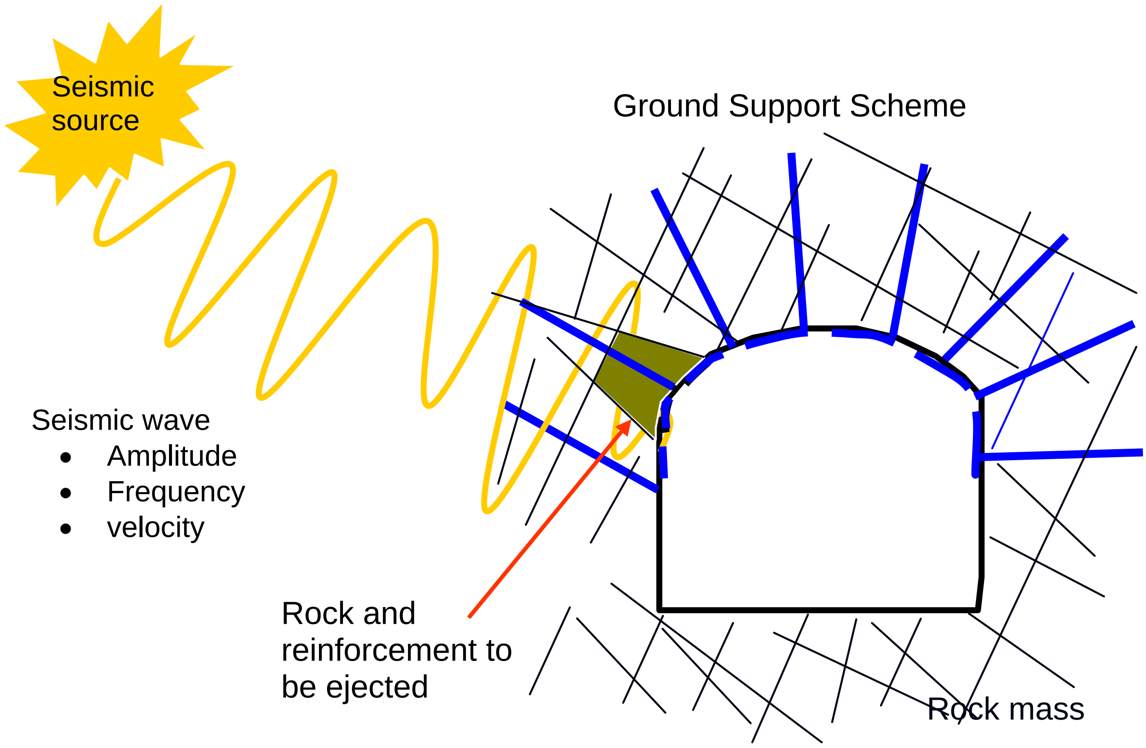


Figure 12: Dynamic Rock Failure Model

When the seismic wave encounters the susceptible excavation a detachment process occurs where a block of rock could be ejected or fragmented from the surrounding rock mass into the excavation. This detachment process is unlikely to be instantaneous, but rather very quick and it will be related to the seismic wave velocity, amplitude and frequency and / or fracture growth velocity within the rock mass. This non-instantaneous process is suggested because the excitation source is a wave that has velocity, frequency and wave length.

WASM DYNAMIC TEST FACILITY

The WASM test facility has been described in Player et al (2004) and Thompson et al (2004). The performance of reinforcing systems has been described in Player et al (2008a) and mesh support elements in Player et al (2208b). The facility is shown in Figure 13. The following discussion mainly examines the testing of reinforcement systems, but the facility has undertaken a significant mesh testing program, and will soon be testing fibrecrete panels, and combined mesh and reinforcement system, using the same principles.

The test facility has adopted the philosophy to establish failure criteria for reinforcement systems subject to axial dynamic loading. The results are used as an index test cataloguing the performance of reinforcement system, were a significant number of reinforcement systems are tested and reported against each other.

The process of critical loading of reinforcement systems has shown that they must be broken from a single load to assess what constitutes a critical load. Adding multiple impacts is incorrect, as it overestimates the capacity of the system. Testing under critical loading conditions has also shown that it is insufficient to only report energy consumed, but must include displacement, velocity and deceleration that results in failure.

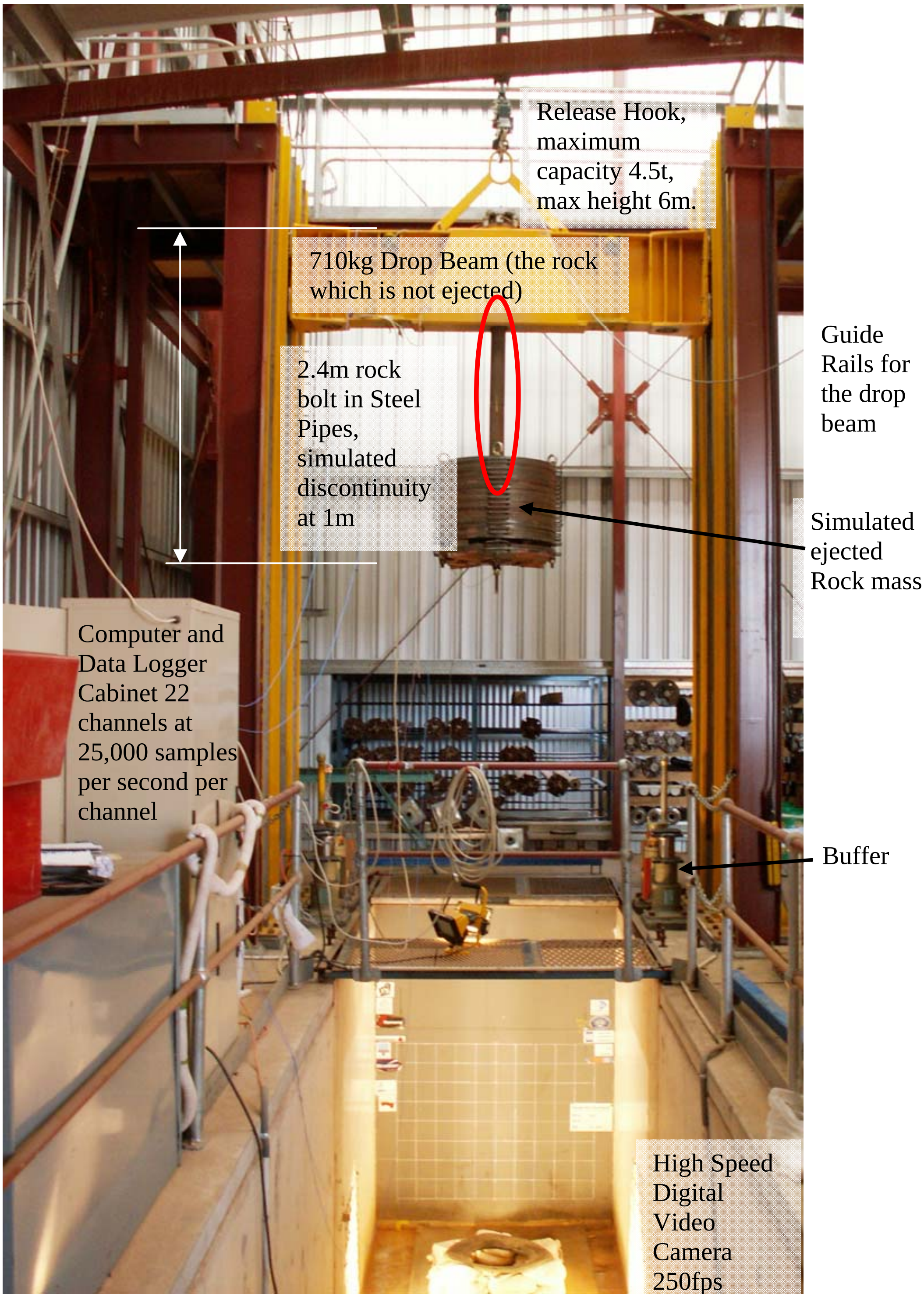


Figure 13 : Constructed WASM test facility

Advantages of the WASM Test Facility

The advantages of the test facility relate to :

- testing of full scale systems,
- integration of the simulated rock mass with the reinforcement system to be tested, used in conjunction with thick wall steel pipe to simulate underground rock mass confinement, (Hyett et al. 1992),

- large input energy available to test reinforcement systems, the facility is not displacement controlled,
- replicates dynamic loading caused by the ejected rock mass,
- extensive instrumentation of the facility and systems tested,
- extensive analysis technique to develop dynamic force displacement curves, velocity, deceleration and energy time graphs of the systems tested,
- data analysis methodology and software to understand the critical loading conditions.

Size and scale

A decision was made early in the project that all testing should be done on full scale rock bolts and surface support elements used or to be developed in the Western Australian mining industry. This removes any questions involved in scale up issues and mechanics, and the problems in construction of half or quarter scale rock bolts.

The unit is capable of testing any 2.4m long reinforcing element with a maximum displacement of 900mm. Longer systems can be tested but this requires consideration of the configuration of the test and the maximum expected displacement.

Ongoing development work at the facility and with sponsors has allowed the development of rough simulated boreholes. These allow the testing of rock bolts that are sensitive to installation technique or equipment. Lachenicht et al (2008) shows the process of installation by the underground mining equipment, recovery of the simulated borehole with installed rock bolt and then testing of the complete system at the WASM dynamic test facility.

Integration of an ejected rock mass

It is important that as closely as possible, the real life interaction between the rock mass and the borehole are correctly represented. Initial trials that loaded the surface hardware on the reinforcement system with a concrete block were identified during commissioning of the facility not to be representative of the loading of a reinforcement system that has an interaction between the reinforcing element, encapsulation material / mechanism and borehole.

The concrete block loading mechanism was replaced by integrated circular steel rings shown in Figure 14. These rings are bolted together about a load transfer ring that is welded onto the collar pipe segment below the simulated discontinuity, thus developing integrated loading by the “rock mass” on the outside of the “borehole” and the surface hardware.

Not to scale diagram of the drop beam, reinforcing element, and the rockmass

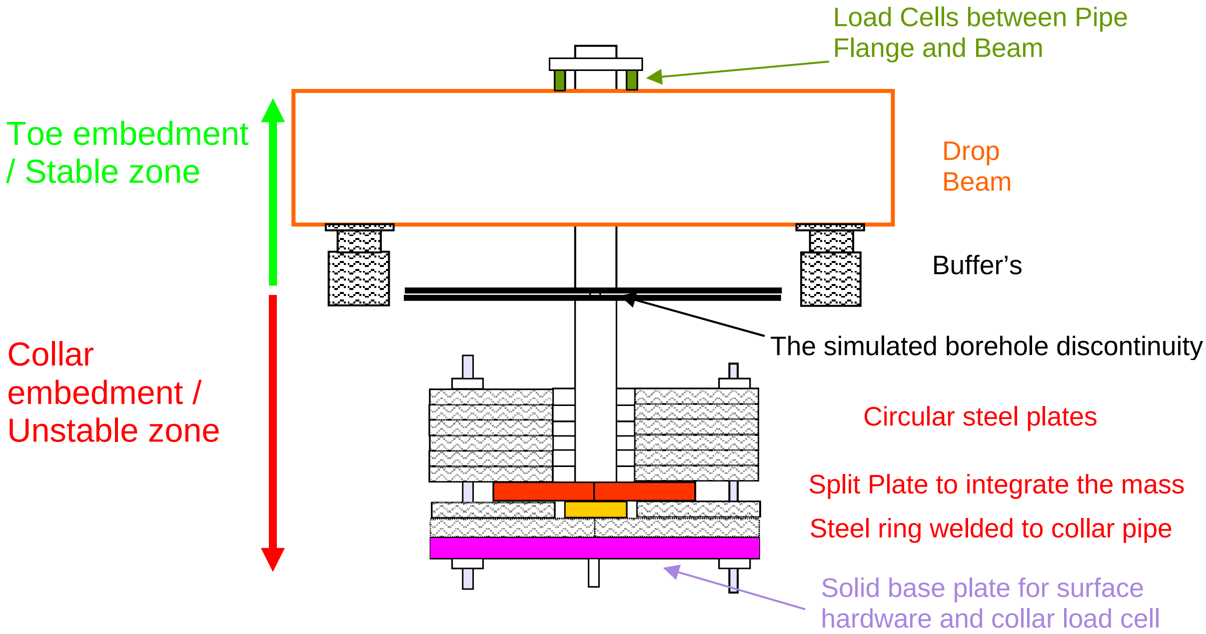


Figure 14: Schematic of load transfer rings and integration with the borehole

Facility instrumentation

- A challenge was the identification of instrumentation that can record the forces, displacements, accelerations, and strains involved in the small time periods. The instrumentation must also allow the calculation of relative velocity of the steel rings (ejected rock mass) compared to the drop beam (rock that remains behind). Instrumentation must be selected that allows measurement or calculation of the critical demand on the reinforcement or support system.
- Fundamental analysis of the mechanisms of load transfer in the test facility was used to identify where instrumentation would be required to measure forces, accelerations and displacements of the reinforcement systems, face restraint and surface support during testing.
- Recording of all instrumentation is triggered as the drop beam passes through a laser beam prior to impact on the buffers, a second laser breaks confirms the velocity of the beam at impact.
- Purpose built load cells records the restraint force at the anchored end of the reinforcement system and a commercial load cell is used between the nut and washer (where applicable) for the force at the collar.
- Accelerometers on the drop beam and loading mass to calculate the deceleration rate of each. Raw acceleration signals must be filtered to enable analysis.
- Digital video capture of the mass and surface hardware at 250 frames per second, enables visualisation of surface fixture failure mechanisms and displacement of the collar of the reinforcement system. The camera has a pixel resolution of 3.3mm in the current test configuration. Auto-tracking software is used for calculating displacements, (accurate to approximately half a pixel), velocities, and accelerations of objects within the video screen. The video

stream is interlinked to all instrument data. Data stream is 25,000 samples per second per channel for the remainder of the instrumentation.

- The buffer compression was measured using an ultrasonic device, and this has been improved by replacement with linear potentiometers which effectively provide a continuous output with displacement.
- Change in physical bolt length is measured after each drop through separation at the simulated discontinuity and the toe of the bolt. This process assists in determining the influence of yielding mechanisms, sliding or plastic deformation bolt performance.

Impact buffers

- Engineered impact buffers provide the simulation of the very quick ejection process by rapidly stoping the beam with typical decelerations of 20g to 60g, "soft" and "weak" reinforcement system result in lower beam decelerations than "tough" and "strong" reinforcement systems. The difference occurs because the momentum of the "ejected rock" (steel rings) must be either transferred by the reinforcement system back to the beam or dissipated by a yielding process and "weak and soft" reinforcement systems respond slower than "tough and strong" systems.
- The buffers provide a repeatable means of applying load to the bolt under standard test conditions where performance is measure and energy consumption assessed. They are simply a load distribution device and its performance is measureable.

Disadvantages of the Facility

The facility has been rated as “the most advanced and the closest replication of a seismic event”, by Brown (2004) in his keynote address. Some perceived disadvantages in the facility relate to the financial and time cost of the facility.

- the facility would appear to be the most expensive mining dynamic test facility ever to be constructed,
- it is likely to have the highest unit test,
- probably has the longest to setup time.

These have all occurred because all prior mining dynamic test facilities have serious deficiencies in being able to correctly load the system or elements being tested or being able to provide valid instrumentation and calculations of the energy absorbed by the systems tested or understanding the parameters that constitute critical loading conditions.

CONCLUDING REMARKS

The *CSIR support element test facility* used a complex load distribution device consisting of multiple layers of interlocking concrete blocks to apply the kinetic load of the falling weight to the element being tested. The device had a non-linear response of number of bricks broken compared to the input kinetic energy. The difference between brick pulverisation and breakage is not clarified. The results are reported as survival of a particular system at a particular input energy, and should only be used a qualitative comparison of the capacities of the tested systems and not against the results of any other facility.

The *CSIR reinforcement system test facility* used no instrumentation and required a significant assumption that the load distribution to the tested yielding element would be the same as that along the pivot bar. This is only is true for a limited set of conditions. The results from this facility should only be used for a qualitative comparisons of bolts tested at this facility and not against results of other facilities.

The *GRC support element test facility* used the direct impact of a free moving mass onto the element being tested. This is a significantly different approach to the CSIR support element test facility and no quantitative comparison of results between the two facilities should be made. The results at the GRC are dependent on the area of the impact weight, and the fixed "tight" spacing of the hold points for the support elements. The results are expressed in terms of the kinetic energy of the mass at impact onto the support element were it was assumed to effect approximately $1m^2$ of the sample when the true impact area was $0.28m^2$. The actually process by which the energy is absorbed by plastic or elastic deformation of the support element was not considered.

NTC drop test unit (*now CANMET-MMSL*) uses a mass moving down the shaft of the bolt and impacting the head of the reinforcement system, which is not considered an adequate representation for a seismic event. There are limitations to this methodology when there is bonding along the shaft of the bolt, and only undertaking non-critical loading test. The previously advocated analysis technique using a closed-form solution on a non-linear plastically deforming material has been abandoned and now uses the energy balance approach. The results from this facility should not be quantitatively compared to the results of other test facilities.

The literature review has shown that the WASM test configuration for the drop test is a novel method in the mining community but has similarities to civil and military configurations. The facility can be configured to test reinforcement systems, support systems, or ground support schemes.

The *WASM momentum transfer concept* is an index test that uses the principle of dropping the simulated rock mass (rock to be ejected) and rock reinforcement and support systems (inside a specifically designed frame) on to engineered impact absorbing foundations (buffers). This results in deformation of the reinforcement and support systems to either control the 'ejected rock' displacement (by absorption of the energy) or failure of one or more components of the ground support scheme. This mechanism of loading is considered to closely simulate the situation underground.

A key feature of the facility is the assessment of the system energy at any time during the test, including the amount lost in yielding or deforming the reinforcing system, and the amount absorbed by the buffers. The WASM dynamic test facility has the loading capability where test systems are failed on the first load, and reporting the critical parameters of displacement, velocity, deceleration and energy dissipated.

REFERENCES

Aki, K and Richards, P.G. 1980. The Seismic Source: Quantitative Seismology – Theory and Method Ch14 Vol 2 pp799-911.

Albrecht, J and Y. Potvin. 2005. Identifying the Factors that Control Rockburst Damage to Underground Excavations. *Sixth International Symposium on Rockbursst and Seismicity in Mines*, (eds Potvin and Hudyma) Perth, Australia pp519-528

Ando, T. Kishi, N. Mikami, H and Matsuoka, K.G. 2000. Weight Falling Impact Tests on Shear-Failure Type RC Beams with Stirrups. *Structures Under Shock and Impact VI* (eds Jones and Brebbia) Cambridge England pp579-587.

Ansell, A, 1999. Dynamically Loaded Rock Reinforcement. PhD Thesis. Royal Institute of Technology Department of Structural Engineering Sweden. ISSN 1103-4270

Ansell, A. 2000. Testing and Modelling on an Energy Absorbing Rock Bolt, In *Structures Under Shock and Impact V*I (eds Jones and Brebbia) Cambridge England pp417-426

Brown, E.T. 2004 The Dynamic Environment of Ground Support and Reinforcement . *5th International Symposium of Ground Support and Reinforcement Practice in Mining*. (eds Villescusa, Potvin) Balkema, pp3-16.

GAP221 – Testing of Tunnel Support : Dynamic Load Testing of Rock Containment Systems (eg wire mesh) Safety In Mines Research Advisory Committee Report, South Africa 1997. Authors Ortlepp and Stacey

GAP423 – Dynamic Loading of Rockbolt Elements to Provide Data for Safer Support Design, Saftey Im Mines Research Advisory Committee Report, South Africa, June 1998. Authors Ortlepp and Stacey

GAP709 – The Meaningful use of Peak Particle Velocities at Excavation Surfaces for the optimisation of the Rockburst Criteria for Tunnels and Stopes. Safety In Mines Research Advisory Committee Report, South Africa 2002. Authors Milev, Spottiswoode, Noble, Linzer, Van Zyl, Daehnke, and Acheampong.

Gaudreau, D., Aubertin, M. and Simon, R., 2004. Performance Assessment of Tendon Support Systems submitted to Dynamic Loading. *5th International Symposium of Ground Support and Reinforcement Practice in Mining*. (eds Villescusa, Potvin) pp299-312

Gibowicz, S.J (1990) The Mechanism of Seismic Events Inducted by Mining. *Rockbursts and Seismicity in Mines,* (ed Fairhurst) Balkema, Rodderdam. pp3-27

Hanssen, G., Auestad, T., Tryland, T., and Langseth, M., 2003. The kicking machine: A device for impact testing of structural components 2003 *International Journal of Crashworthiness* ISSN: 1358-8265 Volume: 8 Issue: 4 pp385-392

Heal, D (2005) Dynamic Resistant Ground Support, in Mine Seismicity and Rockbursting Seminar, March 2005, *Course 0502w.* Australian Centre of Geomechnics, Perth.

Hyett, A., Bawden, W and Reichardt, R, 1992. The Effeot of Rock mass Confinement on the Bond Strength of Fully Grouted Cable Bolts. *Int. J. Rock Mech. Min. Sc.& Geomech. Abstr..*, V29, pp503-524

Ishikawa, N. Katsuki, S. and Takemoto, K. 2000. Dynamiuc Analysis of Prestressed Concrete Beams under Impact and High Speed Loadings. *Structures Under Shock and Impact VI* (eds Jones and Brebbia) Cambridge England pp 247-256.

Iskhakov, I. and Ribakov, Y. (2000) Full-Scale Dynamic Testing of an 11-story RC Building and Interpretation of the Results from the Seismic-Resistance Viewpoint. In *Structures Under Shock and Impact VI* (eds Jones and Brebbia) Cambridge England pp331-338

Kaiser, P.K and Malony, S.M. 1996. Ground Motion Determination for Rock Support Design. *Rock Mechanics Tools and Techniques, NARMS* 1996, (eds Aubertin, Hassani and Mitri) Balkema, pp217-224

Kaiser, P. McCreath, D. and Tannant, D. 1996 Canadian Rockburst Support Handbook. Geomechanics Research Centre, Lauentian University Ed's Kaiser, McCreath, Tannant.

Kennedy and Goodchild 2003. Practical Yield Line Design. British Cement Association. 175pp, ISB N 0 7210 1585 9.

Kishi. N. Ikeda, K. Konno, H. and Kawase, R. 2000 Prototype Impact Test on Rockfall Retaining Walls and its Numerical Simulation. In *Structures Under Shock and Impact VI* (eds Jones and Brebbia) Cambridge England pp351-360)

Jaeger, A.J., Wojno, L.Z. and Henderson, N.B. 1990. Ne Development in the Design and Support of Tunnel under High Stress Conditions. *Technical Challenges in Deep Level Mining,* SAIMM. Johannesburg pp1155-1172.

Jaeger, A.J 1992. Two New Support Units for the Control of Rockburst Damage. *Rock Support in Mining and Underground Construction.* Balkema, Rotterndam. pp621-631.

Lachenicht, R., Varden, R, Player, J. Thompson, A. and Villaescusa, E. 2008 Development and Implementation of the Garford Bolt at the Kanowna Belle Mine, *10th Underground Operators Conference,* Launeston, AusIMM.

Li. T, Villaescusa E. and Finn. D, 1999. Continuous Improvement in Geotechnical Design and Practice, *Australian Journal of Mining.* Vol 14 , No 146, pp 46-51.

Li. T, Singh, U., and Coxon. 2002. J. A Case Study of Management of High Stress and Seismicity at Juntion Mine. *International Seminar on Deep and High Stress Mining. Section 29.* Australian Centre of Geomechanics, Perth.

Lu, Y. Hao, H., Ma, G., and Zhou, Y. 2000. Shear Force in Structural Response to Blast Induced Ground Excitations. In *Structures Under Shock and Impact VI* (eds Jones and Brebbia) Cambridge England pp 99-107

Masuya, H. Yamamoto, M. Toyama, M. and Kajikawa, Y. 2000. Experimental Study on the Perforation of Steel Fibre Reinforced Concrete Slab by Impact. In *Structures Under Shock and Impact VI* (eds Jones and Brebbia) Cambridge England pp 205-214

McGarr, A. 1991, Observations Constraining Near-Source Ground Motion Estimate from Locally Recorded Seismograms, *J. Geophy. Res.* Vol96 #B10, pp 16495-16508

McGarr, A Spottiswoode, S.M. Gay, N.C. Ortlepp W.D. 1979. Observations Relevant to Seismic Driving Stress, Stress and Efficiency. J. *Geophy. Res. B.* Vol84, pp2251-2261

McGarr. A. 1999. On Relating Apparent Stress to the Stress causing Earthquake Fault Slip. *J. Geophys. Res*. Vol104, pp 3003-3011.

Milev, A.M. Spottiswoode, S.M. Rorke, A.J. and Finne G.J. 2001. Seismic Monitoring of a Simulated Rockburst on a wall of an Underground Tunnel. *J. Sth Afr. Institute Mining and Metallury* Vol101 No.5 pp 253-260

Ortlepp, W. 1992. Invited lecture: The design of support for the Containment of Rockburst Damage in Tunnels - An Engineering Approach. *Rock Support in Mining and Undergorund Construction.* Bakema, Eds Kaiser and McCreath. 1992. pp593 - 609

Ortlepp, W. 1997. Rock Fracture and Rockbursts an Illustrative Study. Monograph Series 9. SAIMM, 1997.

Ortlepp, W. and Stacey. T. 1996. The Performance of Containment Rock Support such as Wire Mesh under Simulated Rockburst Loading. *Proc. Geomechanics* 1996. A.A Balkema, pp81-87.

Ortlepp, W and Stacey, T. 1997. Containment of Rockburst Energy with Appropriate Tunnel Support. *International Symposium on Rock Support – Applied Solutions for Underground Structures.* Norway 1997. pp 609-620

Ortlepp, W. and Stacey, T. 1998. Performance of Tunnel Support under Large Deformation Static and Dynamic Loading. *Tunnelling and Underground Space Technology* Vol13, No1, pp15-21 1998.

Ortlepp, W. Stacey, T. and Kirsten, H. 1999. Containment Support for Large Static and Dynamic Deformations in Mines. *In International Symposium in Rock Support and Reinforcement Practice in Mining* (eds Villasescusa, Windsor, Thompson). pp359-364

Ortlepp, W and Swart, A. 2002. Dynamic Testing of Rockburst Support for Tunnels. *International Seminar on Deep and High Stress Mining. Section 36.* Australian Centre of Geomechanics, Perth. 2002.

Ortlepp, W., Human, L., Erasmus, R.N. and Dawe, S. 2005. Static and Dynamic Load Displacement Characteristics of a Yielding Cable Anchor - Determined in a Novel Testing Device, *Sixth International Symposium on Rockbursst and Seismicity in Mines*. (eds Potvin and Hudyma) Perth, pp 529-534

Player, J.R. 2004. Field Performance of Cone Bolts at Big Bell Mine. In *5th International Symposium of Ground Support and Reinforcement Practice in Mining*. (eds Villescusa and Potvin). Balkema, pp 289-298

Player, J.R., Villaescusa, E. and Thompson A.G. 2004. Dynamic Testing of Rock Reinforcement Using the Momentum Transfer Concept. I*n 5th International Symposium of Ground Support in Mining and Construction* (eds Villaescusa, and Potvin). Balkema. pp 327-340

Player, J.R, Villaescusa, E and Thompson A.G. 2008a. Dynamic Testing of Reinforcement System. *In 6th International Symposium of Ground Support in Mining and Construction* (eds Stacey and Malan) SAIMM pp 597-622

Player, J.R. Morton, E, Thompson, A.G. and Villaescusa. 2008b. Static and Dynamic Testing of Steel Wire Mesh for Mining Applications of Rock Surface Support. *In 6th International Symposium of Ground Support in Mining and Construction* (eds Stacey and Malan) SAIMM pp 693-706

Plouffe, M., Anderson, T., and Judge, K. Rock bolt testing under dynamic conditions at CANMET-MMSL. *In 6th International Symposium of Ground Support in Mining and Construction* (eds Stacey and Malan) SAIMM pp 581-596

Roberts, M.K and Brummer, R.K. Support Requirements in Rockburst Conditions. *Journal South African Institute Mining and Metallurgy.* Vol88, No 3, pp97-104.

Scholz, C.H. 1990. The Mechanics of Earthquakes and Faulting. Cambridge University Press, 439pp.

Simser, B. 2007. The Weakest Link – Ground Support Observations at Some Canadian Shield Hard Rock Mines, *Fourth International Seminar on Deep and High Stress Mining* (ed Potvin) ACG. Perth, pp335-348

Smart, G.S and Schleyer G.K. 2000 Failure Charaterization of Clamped Aluminium Plates under Pulse Pressure Loading. *Structures Under Shock and Impact VI* (eds N. Jones, C.A Brebbia) Cambridge England pp 321-330.

Spottiswoode, S and Churcher, J, 1988. The effect of backfill on the Tansmission on Seismic Energy. *Proc of SAIMM Symposium, Backfill in South African Mines*. Johannesburg pp203-217.

St_Pierre, L. Hassani, F.P. Ouellet, J and Radziszewski, P. An Investigation on the Dynamic Testing, Properties and Responses of Support Systems. *11th Congress of the International*

Society for Rock Mechanics (eds Olalla and Grossmann) Taylor and Francis, London, pp175-178

Stacey, T and Ortlepp, W. 1999. Retainment Support for Dynamic Events in Mines. *International Symposium in Rock Support and Reinforcement Practice in Mining*. (eds Villasescusa, Windsor, Thompson) Balkema pp 329-333

Stacey , T and Ortlepp, W. 2002. Yielding Rock Support – The Capacities of Different Types of Support and Matching of Support Type to Seismic Demand. *International Seminar on Deep and High Stress Mining. Section 34.* Australian Centre of Geomechanics, Perth.

Talebi, S (2005) Ground Motion and Scaling Laws of Mine-Induced Seismicty, *Sixth International Symposium on Rockbursst and Seismicity in Mines*, (eds Potvin and Hudyma) Perth, Australia pp541-545

Thompson, A.G. Villescusa, E. Player, J.R. 2004. Simulation and analysis of dynamic loaded reinforcement systems. *In 5th International Symposium of Ground Support in Mining and Construction.* (eds Villaescusa and Potvin) Balkema. pp 341-358

Wagner, H. 1982. Support Requirements of Rockburst Conditions. *In Proceeding of 1st International Conference on Rockburst and Seismicity in Mines*. Johannesburg, pp209 – 218.

Windsor, C. and Thompson, AG. 1993. Rock Reinforcement – Technology, Testing, Design and Evaluation, *in Comprehensive Rock Engineering – Principles Practice and Projects, Volume 4, Chapter 16*, Eds J. Hudson, E, Brown, C. Fairhurst, and E. Hoek. Pergamon Press

Whitesands Test Facility

http://www.wsmr.army.mil/capabilities/st/testing/lab_fac/dyntest.html

US Department of Defense – General Testing Facilities

http://jcs.mil/technology/army.html

Yi, X (1996) Characteristics of Different Types of Support Systems in Rockburst Conditions. *Rock Mechanics Tools and Techniques*, *NARMS 1996*, (eds Aubertin, Hassani and Mitri) Balkema, pp347-355

Yi, X. and Kaiser, P.K. (1994). Impact testing for rockbolt design in rockbust conditions. *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts*, 31 (6): pp671-675.