Safety in Mines Research Advisory Committee

Final Project Report

Extended use of the Savuka dynamic test facility to improve material and analytical technology in deep-level stope support

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Executive summary

The submitted proposal for the GAP 818 project was formally approved during the first week of May 2001.

The objectives of the proposed programme were, broadly, to examine possible ways of preventing the collapse of fractured rock from the essentially unsupported roof area between individual support units. Specifically, it was intended to examine the potential, in this context, of the following:

- The use of long headboards on hydraulic props as a means of increasing the areal coverage of the support units.

- The potential benefit of simple mesh straps sandwiched between the tops of adjacent conventional timber elongates and the hangingwall surface above, as a means of linking individual support units and supporting potentially loose blocks between them. These would be relatively cheap and expendable.

- For the same purpose as outlined above, using more appropriately engineered linkage systems that might be more expensive but were potentially re-useable where conditions permitted.

As understanding of certain instability mechanisms developed during the course of the testing programme, it became apparent that support which permitted some rotational freedom of rock blocks immediately above, could pose a risk of sometimes promoting instability. It was thought worthwhile to devote two tests to briefly explore this possibility.

The planned programme comprised 14 tests grouped into four series. These are listed in Table 3.1 Testing of the 3 tests of Series II commenced 8 May 2001 and concluded on 5 June 2001. Series I testing involved 2 tests that were completed during the period 30 August and 5 September 2001. The 7 tests of Series III extended from 12 September to 30 November 2001. The final 2 tests, grouped together as Series IV, were carried out between 11 December and 19 December 2001. The intervals between testing resulted from the need to use the same technicians on the more demanding programme of project GAP 810.

The dynamic stope support test unit that was designed and built under the SIMRAC GAP 611 programme, was upgraded and used as the testing facility for this GAP 818 project.

Two important improvements to the facility, compared with its use in the preceding project GAP 611, were introduced at the beginning of the programme. These resulted in major gains in productivity and improvements in the quantitative control of one important aspect of the testing procedure. The replacement of the compressed air hoist used previously, with an electrically-driven hoisting arrangement for handling the 10 ton drop weight, greatly improved the reliability and speed of the entire operation. The fitting of a load-cell to the tensioned steel bar that applied the axial clamping force on the centre Voussoir beam enabled close control of this very important variable in the test method.

To a large extent the objectives of the GAP 818 project were satisfied by the results obtained from the 14 tests. Useful advances in the broader understanding of the interaction between support units and discontinuous hangingwall rock were made.

Importantly, the experience gained during the tests strengthened ones appreciation of how complex the processes of interaction between the support and the fractured rock really are. It also reinforced the conviction that it will never be possible to closely simulate the reality of the underground situation. Nevertheless the facility is uniquely useful and invaluable for enabling quantitative comparisons to be made between different variations of similar support systems under conditions that resemble reality in most vital respects.

This makes it possible for support manufacturers to test entirely new and innovative ideas and make necessary alterations and developments under easily accessible and controllable conditions.

In respect to the more specific objectives of the programme it was possible to reach some conclusions with a fair degree of confidence:

- Long headboards are only partially effective as a means for eliminating fall of rock from between individual support units. With increasing length the potential for rotational instability becomes a potential hazard.

- A system of simple mesh straps linking timber elongates showed some promise in reducing rockfall between timber props. Indications were that the strength needed to be increased considerably and the yielding mechanism made more positive.

- The more sophisticated, potentially re-useable collar-and-web device appeared to be effective at moderately high values of input energy. Further work is needed to establish its upper limit of capacity.

- Two tests on pack support showed that large fluid-filled diaphragm-type pre-stressing devices show a potential for rotationally-unstable behaviour which might tend to promote collapse under certain conditions. More analytic and experimental work is needed to examine this tendency.

- The results of the GAP 818 programme and the response of the manufacturers who used the facility, unquestionably give strong encouragement for the continued use of the research facility as a proof-testing ground and a research tool.

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1 Introduction and background

The criteria for the design of stope support that is most often referred to in mines' codes of practice is one which is based upon the height of hanging wall collapse that would include 95 percent of all 'fall-of-ground' incidents that have been recorded on the mine during a representative period prior to the compilation of the code.

This approach to design has been endorsed by the conclusions of GAP 032 – Stope Gulley Support (Roberts et al 1995). In essence it means that appropriate support units must be spaced at densities such that the distributed load-bearing **capacity** matches the distributed load **demand** imposed by the characteristic '95 percent height-of-collapse'. Values of 50 kN/m^2 (for rockfalls) and 60 kJ/m^2 (for rockbursts) have been widely used by the gold mining industry.

The assurance is given, albeit implicitly, that the rockfall will be prevented if the support units (at the designed spacing) can meet these demands without failing, or incurring too much deformation. A further requirement to ensure effectiveness is that the support should be as stiff as possible without compromising its ability to yield progressively as the load approaches the maximum capacity required by the design. The intention is to limit relative movement between fracture-delineated blocks and slabs and thereby preserve as far as possible the integrity and frictional stability of the fractured stope hangingwall.

There can be no doubt that these design guidelines have benefited the industry and led to some decrease in accident rate during the last decade or so. However, in the continued striving for improvements in safety particularly when mining depths increase and seismicity becomes more common, the adequacy of this design rationale needs to be re-examined.

It has been argued for some time that, in addition to the foregoing basis for design, the likelihood that rock can collapse **between** support units without any collapse of the support itself, must also be taken into account. In deep stopes where fracturing of the surrounding rock is inevitable and often intense, and where rockbursts are an additional hazard, collapse of rock **between** supports may be the greater problem.

It is the belief that this problem area requires more attention and more innovative development of equipment and methods than any other in the field of underground support, that motivated the creation of the Savuka dynamic stope test facility some three years ago.

At the start of SIMRAC year 1999, GAP 611 enabled the design and construction of a dynamic test facility that would permit testing of stope support under much more realistic conditions than had previously been possible. The important features afforded by the new facility, which totally changed the paradigm of testing of stope support, included the following:

- The area that can be supported by the equipment under test is 5,5 m x 6,5 m in extent, which is large enough to permit the installations of a representative section of a support system. All other testing facilities are limited to testing individual support units.

- The central roof area of 3 m x 3 m consists of three Voussoir beams, each comprising 12 robustly reinforced concrete blocks 1,0 m wide and 0,25 m thick. The blocks are initially held together with a clamping force of 200 kN but, during the passage of the dynamic impulsive test force, the blocks may collapse individually or in batches.

- The blocks are normally clamped and suspended so as to present a flat, plane undersurface which forms the hangingwall of the test stope. However one set of 12 blocks is provided with irregular steeply-contoured undersurfaces so that one Voussoir beam can be made to represent the rough, stepped roof that is most commonly encountered in a deep-level stope.

- Immediately overlying the collapsible roof, a pyramid of accurately-dimensioned steel-clad concrete blocks represents the upper hangingwall strata that would transmit the kinetic energy of the seismic event without itself being significantly damaged in the resulting 'rockburst'.

- The impulsive energy that potentially might cause rockburst damage to the stope hangingwall, is imparted to the more remote strata by the impact of a 10 000 kg steel mass on top of the load-distribution pyramid. Dropping the mass from a maximum height of 3,0 m generates an energy impulse of almost 300 kJ impacting at a velocity of 7,7 ms^{-1}.

By end of April 2000 proof testing of the facility was complete and the facility was launched in mid-July 2000.

An extra allocation of funding enabled the GAP 611 project to be extended to include a brief series of 5 tests to partially calibrate the performance of the facility at lower energy levels.

2 Summary of previous results

2.1 GAP 611

Apart from simple proof-tests on single free-standing packs to test working components of the facility itself, tests of only two different types of support systems were undertaken as the concluding part of GAP 611.

In the first test, six 400 kN Elbroc hydraulic props were spaced at 1,5 m separation (in the strike direction) leaving the centre four blocks of each beam completely unsupported. The initial clamping force in the beams was estimated to be about 250 kN. Two successive impulses of 70 kJ and 150 kJ were imparted to the load-distribution pyramid.

The first impulse caused 150 mm of relative displacement of the central blocks (maximum sag of the roof) between the props, and the second impulse caused complete collapse of all four unsupported blocks of the centre Voussoir beam.

The second test examined the response of the roof when supported by means of 6 identically-spaced Ebenhaeser 2000 timber elongates, the tops of which were linked by means of simple ‘ties‘ of flexible wire rope. Similar limited sag as in the first test, occurred after the 70 kJ first impulse while the ties remained almost slack. The potential ejection of the four ‘ unsupported ‘ central blocks by the second impulse of 150 kJ was very effectively prevented by the ‘ catch net ‘ effect of the wire rope ties. (It is important to note that the initial 250 kN force giving the Voussoir clamping effect was completely lost during the second 150 kJ impulse)

2.2 GAP 611 Extension

The extended GAP 611 project was aimed at determining the characteristics of the test facility in terms of its repeatability of prop compression results, its consistency in reflecting the roof convergence profile between the support units and, finally, gaining some idea of the distribution of the total energy between the six props that made up the most common support configuration.

At relatively low energy levels of up to 150 kJ (cumulative total after 3 or 4 drops), the repeatability of support convergence and roof deflection were very good. The distribution of energy was also consistent, with between 83 percent and 86 percent of the energy absorbed into the support, being concentrated in the two props supporting the central Voussoir beam. The remaining 14 to17 percent was somewhat erratically shared between the four corner support units.

It is obviously also of considerable interest to know how the total energy that is absorbed by all of the support units compares to the energy imparted to the impact plate at the top of the loaded distribution pyramid, by the falling drop-weight.

The yielding resistance of a hydraulic prop is constant through its full compression range with all props yielding consistently at loads very close to their specified value (200 kN in the case of the de-tuned props used in these tests). This makes it simple to determine the total energy, in kilojoules, absorbed and harmlessly dissipated in each prop, or the total dissipated for each impulse, from the product of the yield load (200 kN) times the respective convergence values (in metres) from Tables A2, A3 and A4 (see GAP 611 Extension report).

By means of this exercise, it has been determined that the efficiency of energy transfer through the pyramid was about 56 percent for the first impulse but reduced with successive impulses to 44 percent and 34 percent for the third drops on props at 1,2 m and 1,75 m spacing, respectively. This suggested that the efficiency might be a function of span between props, with a tendency for energy transfer efficiencies to be higher with closer spacing. The energy efficiency determination could not be done for the test on the 150 mm diameter timber elongates of Table A1 (see GAP 611 Extension report) because their yield response is not constant and, in fact, has actually never been established for the particular type of yielding mechanism (‘pencil point’ prop) employed on the prop used in GAP 611 Extension.

3 Motivation and scope of project

The results of GAP 611 strongly encouraged the further development of innovative ways of preventing the collapse of fractured roof between supports. It seemed advisable, however, to look at the potential of, and possible limitations of more conventional methods of limiting the unsupported span such as longer headboards.

The results of GAP 611 Extension suggested that, for ease of interpretation, comparative tests should always be performed with the prop configuration as near identical as possible.

The broad purposes of testing were thus decided as follows:

- A limited number of tests would be carried out on sets of commonly used 200 mm diameter elongates without interconnections at higher energy inputs than used in GAP 611.
- Headboards of three different lengths would be tested with standard hydraulic props.

- Two types of timber elongates, one with a simple inexpensive expendable strap inter-linking system and the other with a solidly engineered, potentially re-usable inter-linking system, would be more exhaustively tested.

The details of the programme are set out in Table 3.1.

Table 3.1 Detail of tests performed

Series I - Tests on available products at higher loads						
Test No	**Support type**	**Spacing (m)**	**Roof beam comp.**	**Number of Tests**	**Impulse (kJ)**	**Date completed**
4	Ebenhaeser 2000 6 props	1,25	210 kN	1	150	30.08.01
5	Ebenhaeser 2000 9 props	1,125	220 kN	1	50 + 150	05.09.01
Series II - Testing of increased areal effect i.e. headboards of increased lengths						
Test No	**Support type**	**Spacing (m)**	**Roof Beam Comp.**	**Number of Tests**	**Impulse (kJ)**	**Date completed**
1 2 3	Elbroc RYHP 400kN With channel headboards of increasing length	1,5 1,5 1,5	212 kN 224 kN 227 kN	1x400 mm 1x600 mm 1x800 mm	122 140 140	08.05.01 28.05.01 05.06.01
Series III - Testing of various alternative linkage systems between props						
Test No	**Support type**	**Spacing (m)**	**Roof Beam Comp.**	**Number of Tests**	**Impulse (kJ)**	**Date completed**
6	Ebenhaeser 2000 Props interlinked with single Samson straps	1,25	206 kN	1	50 + 90	12.09.01
7	Ebenhaeser 2000 Props interlinked with double Samson straps	1,25	225 kN	1	50 + 90 + 150	18.10.01
8	As in test 7	1,25	216 kN	1	150	24.10.01

Test No	Support type	Spacing (m)	Roof Beam Comp.	Number of Tests	Impulse (kJ)	Date completed
9	Same prop configuration with short Samson straps, side by side.	1,25	225 kN	1	85 + 200	01.11.01
10	Buffalo props with Mandirk's linkage	1,25	221 kN	1	90 + 150	13.11.01
11	Repeat of configuration of test 10	1,25	228 kN	1	150	19.11.01
12	Repeat of configuration of tests 10	1,25	228 kN	1	290	30.11.01
Series IV - Rotational stability of pack pre-stressing device						
Test No	**Support type**	**Spacing (m)**	**Roof Beam Comp.**	**Number of Tests**	**Impulse (kJ)**	**Date completed**
13	Inflatable steel pre-stress pad on 600 mm Durapak	2,0 centres	230 kN	1	90*	11.12.01
14	Settable grout pre-stress bag on 600 mm Durapak	2,0	234 kN	1	90 + 150	19.12.01

4 Test method

The GAP 818 programme was carried out using the dynamic stope support test facility at Savuka (AngloGold West Wits Operations Satellite training centre) which was designed and built by SRK Consulting as part of the GAP 611 project. The essential layout of the facility is shown in Figure 4.1. The impulsive load was imparted by dropping the 10 ton mass from heights that ranged from 0,5 m to 2,9 m, on to the top of a load-distribution pyramid made of steel-clad concrete blocks.

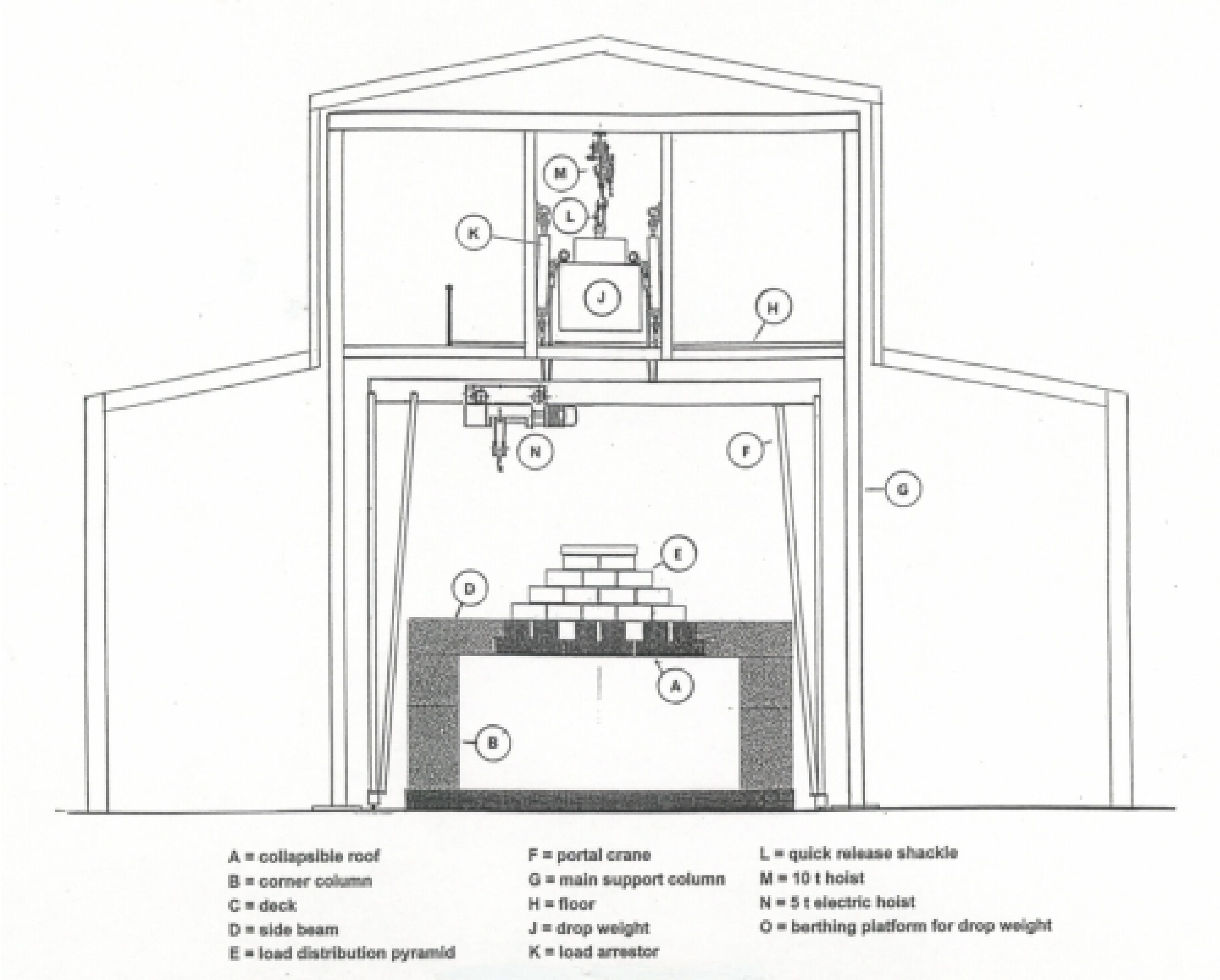


Figure 4.1 ***General view of test facility – looking South***

Twelve of the fourteen tests examined the stability of the discontinuous roof when it was supported by prop-type supports – either steel rapid-yield hydraulic props (RYHP) or turned timber elongates. Two of the tests made use of packs built from pre-cast light-weight cellular cement slabs. In order to achieve a simpler more-efficient distribution of the load impulse in these two tests, the pyramid was made two-dimensional – Figure 4.2.

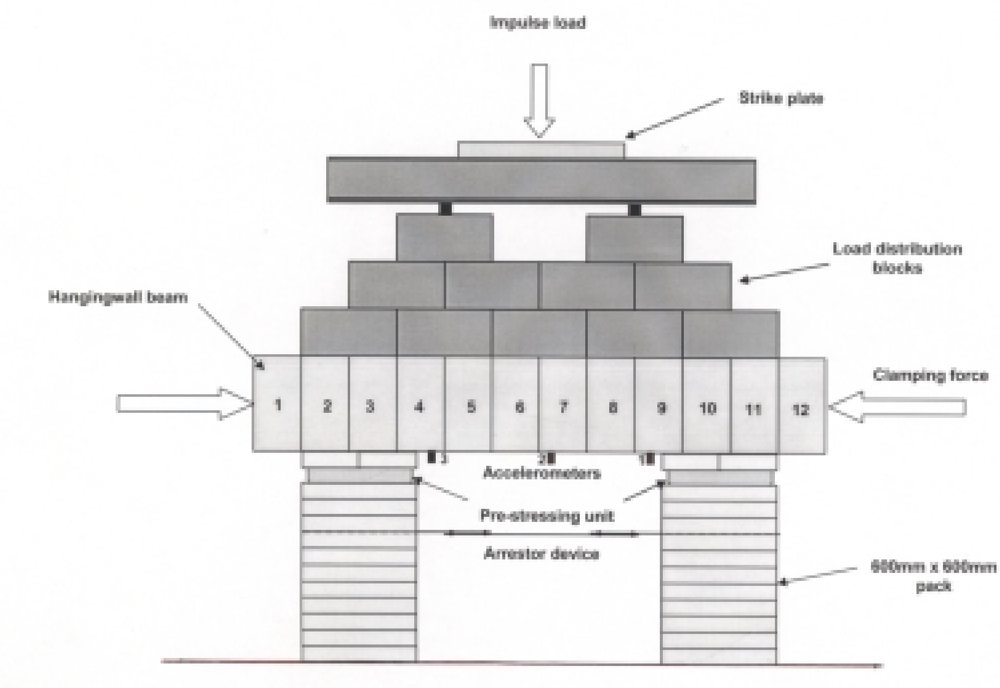


Figure 4.2 ***Two-dimensional loading arrangement***

5 Results

5.1 Series I – Tests on available products at higher loads

The purpose of the first limited test series was to examine to what extent relatively large impulses of energy would disrupt the continuity of the hangingwall and yet would not disturb the overall stability of the support system. This behaviour would form the reference base against which the behaviour of the **linked** elongated systems would be compared.

In the first test, six props were disposed symmetrically, at a strike spacing of 1,25 m (between prop axes) to leave the four central blocks of the clamped Voussoir beams totally free to drop. In the second test a third prop was installed at the mid-length point of each Voussoir beam. There were thus nine props constituting the total pattern and three blocks on either side of the central prop which were then potentially free to collapse completely.

5.1.1 Series I – test # 4

A further purpose of the first test of Series I was to determine the stability of the collapsible roof when subjected to a moderately strong impulse of 150 kJ over the same support as had been used in the early GAP 611 test with interconnecting 'ties' of flexible rope. In that test the beam-clamping force of ± 250 kN dropped to zero during the 150 kJ impulse and the blocks had appeared to have been successfully caught after relatively little sag.

In order to be able to claim that it was exclusively the effect of the interconnecting wire rope ties that had prevented the collapse of the four unsupported hangingwall blocks, it was necessary to examine how the roof would have behaved with no inter-link ties and with the clamping force maintained until much later in the convergence cycle. If it could be demonstrated that the unsupported blocks would have collapsed completely between the supports, with the clamping force disappearing only when the blocks dropped below the hangingwall surface, then clearly the linking rope ties of the earlier test had been solely effective in preventing the collapse of the roof.

The 36 mm diameter steel rod that clamped the 12 blocks of the centre Voussoir beam were equipped with a hollow-cylinder electrical resistance load cell for the new test. This enabled the value of the clamping load before the impulse to be set at 202 kN in test # 4. The 200 mm diameter Ebenhaeser timber elongates were positioned below blocks 4 and 9 at a spacing of 1,25 m as indicated in Figure 5.1, leaving the four blocks (numbers 5 to 8) unsupported. The pre-load in each elongate was set at 95 kN. The 10 ton mass was dropped from a height of 1,5 m to impart 150 kJ of kinetic energy. Photograph 5.1 shows the four centre blocks moving, in unison, about 50 milliseconds after impact with an acceleration greater than that due to gravity.

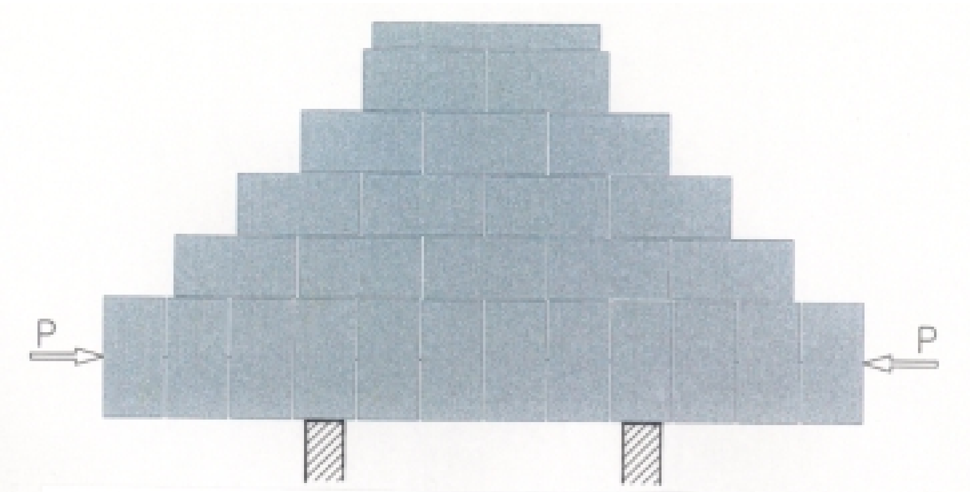


Figure 5.1 Diagrammatic view of load-distribution pyramid and Voussoir beam showing position of Ebenhaeser timber elongates

Photograph 5.1 Test # 4, approximately 50 milliseconds after impulse of 147 kJ at impact velocity of 5,4 ms^{-1}

This higher rate of ejection is demonstrated by the fact that the small weights at the ends of the block measuring tapes are falling more slowly than the blocks, and the tapes are crumpling. Close examination of the right hand edge of Photograph 5.1 will show that blocks 11 and 12 are not yet significantly displaced at this instant. Shortly afterwards, as the centre four blocks fell completely away from the tensioning rod thereby totally relaxing the clamping force, blocks 1 to 3 and 10 to 12 also collapsed (Photograph 5.2).

Photograph 5.2 Test # 4, all roof blocks collapsed except those directly above the elongates.

Apart from the presence of the linking rope ties in the early GAP 611 test, all the other constraints in test # 4 were identical. In the former test an impulse of 150 kJ produced only limited sag of the unsupported hangingwall while the same impulse caused dramatic collapse of the unsupported roof blocks in test # 4. **Clearly the rope links were very effective in preventing collapse of roof between supports.**

Due to inexperience, the elongates had been installed with the pre-stressing unit (PSU) and the yielding device uppermost. The convergence-monitoring tapes were attached at the top turned shoulder of the timber elongate. The consequence was that almost all of the convergence in the stope would result from distortion of the PSU and its penetration into the yielding part of the elongate above the point of measurement. The compression of the elongate props was therefore not registered and no useful estimate of the energy absorbed in the support could be made.

5.1.2 Series I – test # 5

In this test nine elongates of the same type used in test # 4 were arranged at 1,125 m centre spacing. This had the effect of leaving three concrete blocks entirely unsupported on either side of a central prop, in each Voussoir beam – Figure 5.2.

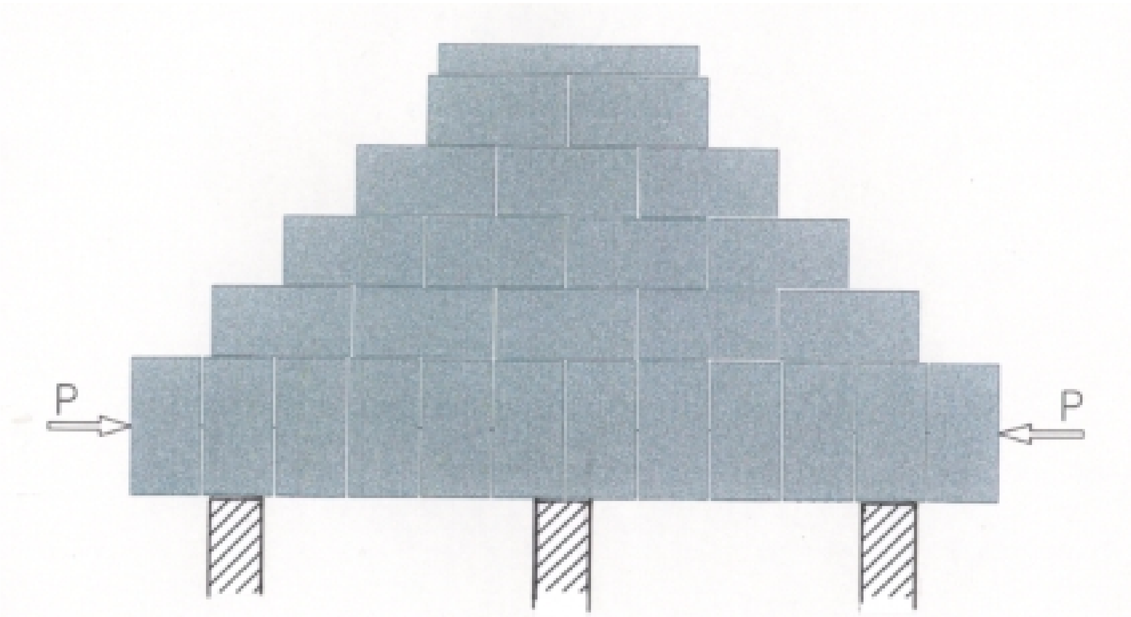


Figure 5.2 View of pyramid and Voussoir beam showing the 3-prop spacing of test # 5

The value of the clamping force in the centre beam was 229 kN before the first impulse of 50 kJ was imparted to the top of the load-distribution pyramid. The tension in the clamping bar dropped to 158 kN after the first impulse and decreased further to 108 kN after the second impulse of 150 kJ.

Because the centre elongate prop under the centre beam was directly below the point of impact, the values of convergence observed in the supports were all very small except for the centre elongate.

Apart from central convergence of 38 mm for the first impulse and 88 mm for the second, the measured convergences were too small to allow reliable estimation of the energies absorbed by the various support units. From load-displacement curves provided by the manufacturers – Figure 5.3 – it can be estimated that 20 kJ and 65 kJ were absorbed at the central position during the 50 kJ and 150 kJ impulses, respectively.

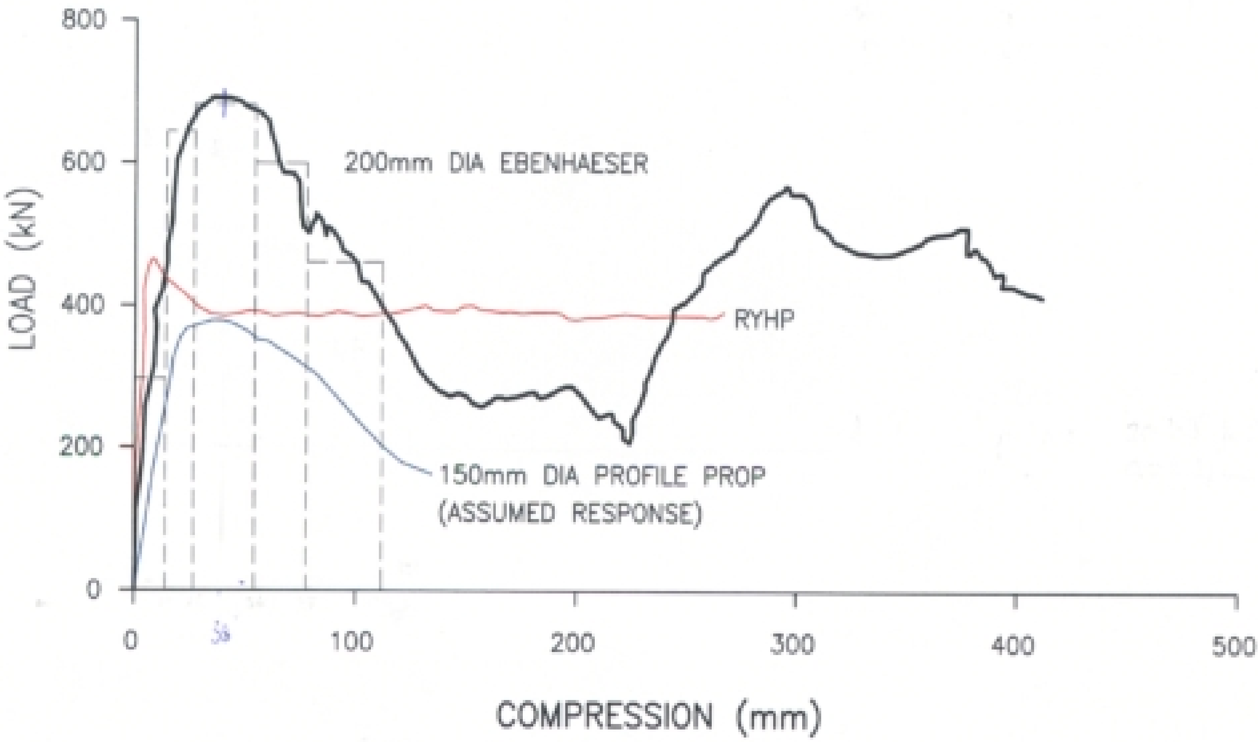


Figure 5.3 ***Dynamic load-compression characteristics for 200 mm diameter Ebenhaeser elongates compared to 400 kN RYHP***

As might have been expected, and was clearly confirmed by this test, the stability of the 3-block unsupported span between supports was dramatically improved compared with that of the four-block unsupported span of the previous test. The maximum block displacements of the northern 3-block unsupported span was 41 mm and 176 mm, and of the southern 3-block span was 57 mm and 143 mm, after the 50 kJ and 150 kJ impulses respectively. Photograph 5.3 shows the relatively limited and uniform nature of the roof deformation between the North prop and the centre prop.

Photograph 5.3 Test # 5, after impulse of 147 kJ at impact velocity of 5,4 ms^{-1} showing 88 mm convergence on centre elongate.

It is likely that the closely-spaced support pattern of this nine-unit configuration would have ensured stability of the roof blocks at considerably higher values of impulse loading. However since the test facility is only intended to examine concepts and principles and does not purport to represent quantitative reality, there was no purpose in repeating the experiment with higher loads.

5.2 Series II – Testing of increased areal effect

The overall objective in this part of the programme was to examine the effect on roof stability of increasing the areal coverage of stope support by employing longer headboards. The strike spacing between the props would remain constant at 1,5 m between prop centres.

It is worth noting that, at the time of conducting the tests, the use of steel RYHP's was probably at its lowest ebb of popularity since their introduction into the gold mining industry three decades ago. At the time of writing this report, however, there appeared to be some indication of a resurgence in their popularity.

Elbroc, who are currently the largest supplier of rapid-yield hydraulic props (RYHP's), manufactured only one standard length headboard (400 mm long) at the time of testing. It was decided that the principle of increased areal coverage could be adequately explored by using lengths of 200 mm x 75 mm mild steel channel section placed over the standard headboard to represent longer headboards.

The same pattern of props would be used in the three tests, with steel channels of 600 mm length and 800 mm length placed over the standard 400 mm long headboards in tests # 2 and # 3.

The clamping force exerted by the tensioning bar was similar for all three tests at 212 kN, 224 kN and 227 kN. The mass was dropped from a height of 1,415 mm to generate a kinetic energy impulse of 140 kJ for each of the three tests.

5.2.1 Series II – test # 1

The 400 kN Elbroc props were spaced 1,5 m apart, symmetrically about the centre of each Voussoir beam. The North prop axis aligned with the common surface between blocks 3 and 4 and the South prop axis located beneath the common surface of blocks 9 and 10 – see Figure 5.4.

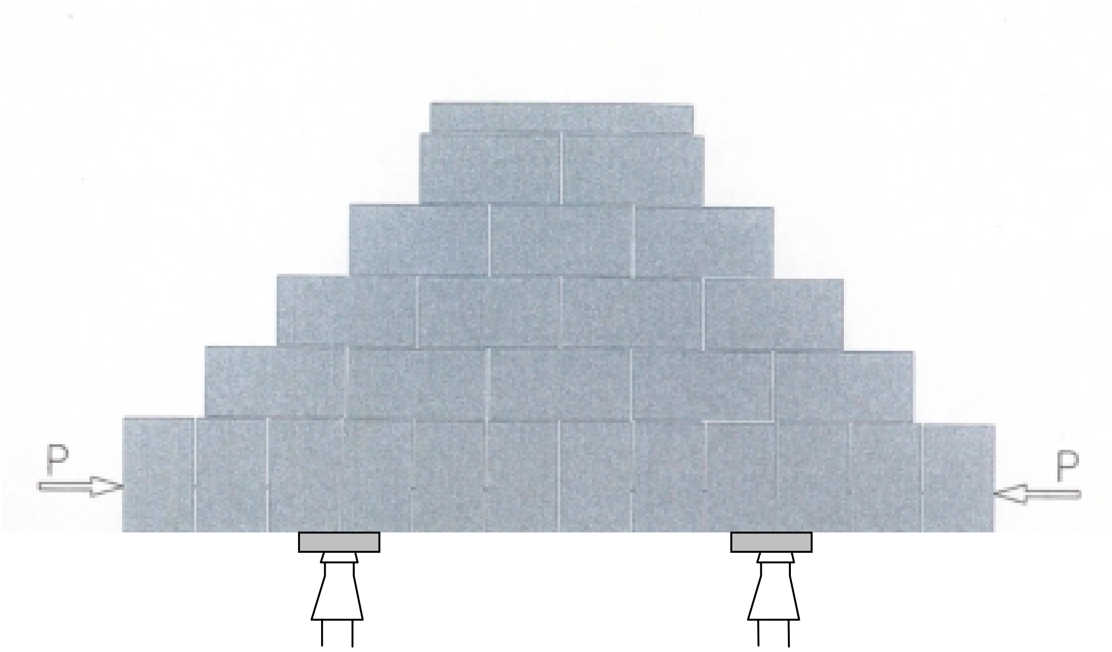


Figure 5.4 Location of Elbroc props in test # 1

The impulse of 1,415 m drop height imparted 140 kJ to the top of the load distribution pyramid. This energy input caused 55 mm and 42 mm convergence to the North and South props causing them to absorb 22 kJ and 17 kJ respectively. The other four props experienced convergences of between 8 mm and 25 mm absorbing 23,6 kJ altogether.

The two props of the centre Voussoir beam thus received 62 percent of the total 62,6 kJ which was absorbed by the six Elbroc props. This total was 45 percent of the 140 kJ energy imparted to the top of the 140 kJ load-distribution pyramid.

The effect of the impulse was to completely dislodge the four centre blocks between the props. Photograph 5.4 shows the ejected blocks some small fraction of a second after the instant of impact. Shortly after this, the remaining blocks, # 1 and # 2 at the North end and # 11 and # 12 at the South end of the centre Voussoir beam, also fell down – Photograph 5.5. Photograph 5.6 shows that the centre four blocks of the East Voussoir beam (furthest from camera) and the West Voussoir beam (closest to camera) were also displaced significantly downward but not far enough to be completely dislodged.

It is presumed that the balance of the 140 kJ which was not absorbed by the props would have been partly expended in overcoming the friction between the ejected blocks and blocks 3 and 4 and 9 and 10 which remained supported by the North and South props.

Photograph 5.4 Test # 1, possibly 100 milliseconds after impact of 140 kJ striking at impact velocity of 4,8 ms^{-1}. Note vapour expelling from SW prop.

Photograph 5.5 ***Test # 1, all blocks collapsed except above each 400 mm headboard.***

Photograph 5.6 ***Test # 1, showing significant sliding of centre four blocks in East beam and in West beam.***

The remainder of the unaccounted energy would have largely been carried away as kinetic energy in the ejected blocks. The fact that the initially-tensioned measuring tapes were dramatically crumpled in Photograph 5.4 shows that the blocks were subjected to downward acceleration considerably greater than the 9,8 ms^{-2} that the gravitational constant would impose. If the impulsive acceleration was twice that of gravity, say 2 g, then the kinetic energy contained in the four centre blocks (each of which has a mass of about 250 kg) would have been about 10 kJ.

Importantly, it was clearly demonstrated that the standard headboard was easily capable of transferring its share of the dynamic load of the entire mobilised loading system above, onto its hydraulic prop. However the four concrete blocks between the tips of opposing headboards were not prevented at all from sliding away from the supported blocks to collapse completely to the floor.

5.2.2 Series II – test # 2

In this test, the 400 kN Elbroc props were spaced 1,5 m apart as in test # 1. The 600 mm long pieces of 200 mm x 75 mm steel channel section which enclosed the standard headboards, extended 50 mm under blocks # 2 and # 5 in the case of the North prop and blocks # 9 and # 11 in the case of the South prop – see Figure 5.5.

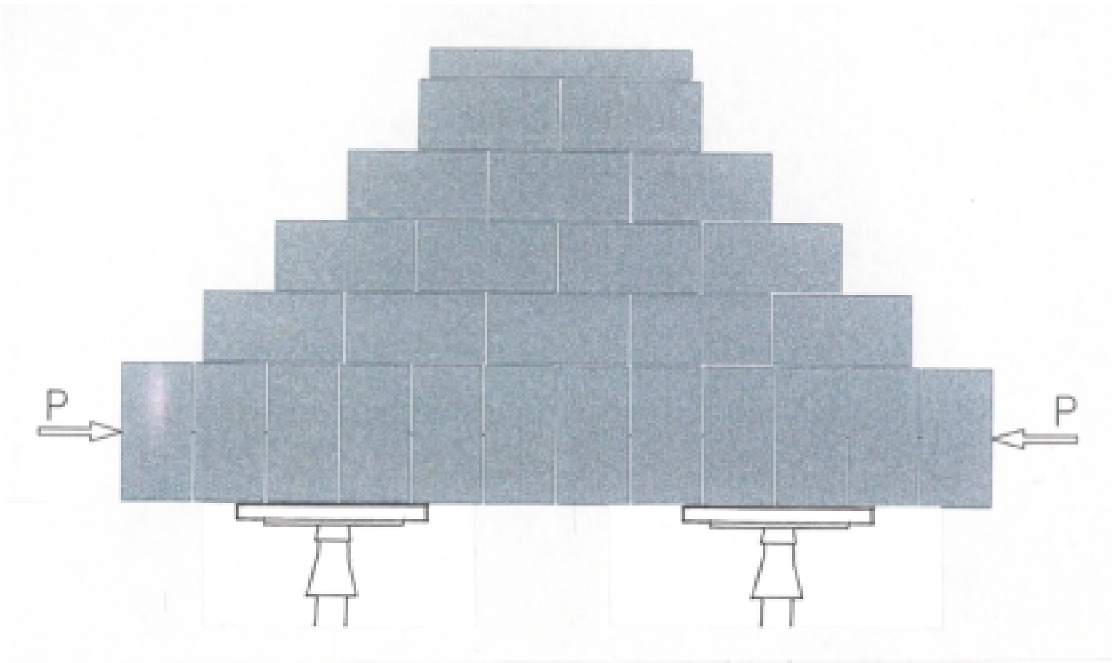


Figure 5.5 Location of Elbroc props and headboards in test # 2

The impulse of 140 kJ caused the collapse of blocks # 1, # 6, # 7, # 8 and # 12. Photograph 5.7 shows that the 50 mm purchase of the South end of the 600 mm northern headboard was sufficient to support block # 5. The counterpart 50 mm ‘overlap’ of the North end of the southern headboard did not prevent the collapse of block # 8, however. With the loss in clamping force along the length of the three centre blocks, blocks # 1 and # 12 at the extreme ends of the beam also collapsed. The 600 mm long headboards were, not unexpectedly, more effective in maintaining hangingwall stability than the shorter standard headboards.

Photograph 5.7 Test # 2 showing loss of three of the centre roof blocks after 140 kJ impulse which impacted at a velocity of 5,3 ms^{-1}.

Convergence measured on the northern prop of the centre beam was 40 mm and, on the southern prop was 35 mm. These represent absorbed energies of 16 kJ and 14 kJ respectively. The total of 30 kJ was 23 percent less than the 39 kJ absorbed by the two centre props of the previous test. The reason for this is not readily apparent.

The greater effectiveness of the larger areal coverage afforded by the longer headboards was evident in that one less central concrete block broke free than occurred with the standard 400 mm headboard.

5.2.3 Series II – test # 3

In the final test of this series, the 800 mm long headboards were positioned so as to provide a 50 mm overlap across the outer edges of the two central blocks, # 6 and # 7. This meant that no roof block was completely free of support. In order for the prop axes to be spaced 1,5 m apart consistent with tests # 1 and # 2, the headboards had to be located asymmetrically with respect to the prop axis – Photograph 5.8. The fact that the headboards might be subjected to a degree of rotational moment was not viewed with great concern because, it was argued, such eccentric loading must often occur in reality where the stope roof undulates and may make point contact with the headboard at varying distances from the prop centre-line.

Photograph 5.8 Test # 3, showing asymmetrical location of 800 mm headboards.

It transpired that the eccentricity proved to be the immediate cause of total collapse. Photograph 5.9 shows that blocks No. 6 and 7 have pulled apart as a result of outward rotation of the two halves of the centre Voussoir beam. The relatively steeply-inclined headboards have caused the tops of the North and South props to slide outwards very rapidly. Photograph 5.9 shows that the northern headboard has disappeared while only the lower portion of the prop is still visible in the lower left corner of the photograph. The top of the southern prop has slid along the headboard and is about to disappear! The final result was that the entire centre Voussoir beam collapsed en-masse throwing the prop and headboard several metres northward – Photograph 5.10.

Photograph 5.9 ***Test # 3 approximately 50 milliseconds after impulse of 139 kJ with an impact velocity of 5,3 ms^{-1}.***

Photograph 5.10 ***Test # 3, showing collapse of centre Voussoir beam and dramatic ejection of northern prop.***

Under the circumstances it was not possible to draw any inferences regarding the distribution of energies.

The unstable response of the prop/headboard unit was an artefact of the testing situation in as much as the headboard had been deliberately asymmetrically arranged. However it is self-evident that rotational effects can easily occur in reality underground when the roof profile is particularly rough. Such rotational effects would probably be more commonly encountered when long headboards are used.

5.3 Series III – Testing of various alternative linkage systems between props

The original motivation for the construction of a dynamic stope support test facility was based largely on the recognition that innovation in design and development of stope support was hampered by the inability to simulate collapses of fractured rock from between support units. The testing of devices that aim to control these vulnerable areas by physical interconnection of the prop units, is one of the ultimate goals of the entire programme. The two innovations tested in the six tests of Series III represent the first attempts to meet this objective.

5.3.1 Series III – test # 6

In this test six Ebenhaeser 2000 timber elongates were spaced at 1,25 m centres to leave the four centre blocks of each Voussoir beam unsupported. 'Samson' straps provided by Mondi Mining Supplies were located along the centre-line of each beam and held in position by the saw-cut end of the timber elongates – see Photograph 5.11. The straps were made from 5 mm diameter wire with apertures of 90 mm x 100 mm. The pre-stress units (PSU) were pumped to 6,5 MPa to give a setting load of about 120 kN to each prop.

The clamping load applied to the centre Voussoir beam was 206 kN initially which then reduced to 163 kN after the first impulse of 49 kJ and to 154 kN after the second impulse of 88 kJ.

The resulting convergences of the 2 centre beam props were 21 mm and 25 mm after the first impulse and 65 mm and 59 mm after the second impulse. The combined energies absorbed by these two props were 14 kJ and 87 kJ.

The four centre blocks moved almost en-masse, varying from 110 mm at block # 5 to 122 mm at block # 8 for the first impulse, and from 145 mm to 157 mm respectively for the second impulse. The resulting differential movements (or 'step' displacements) between each prop and the nearest adjacent hangingwall block was 89 mm and 97 mm after the first impulse and 80 mm and 58 mm after the second impulse – Photograph 5.11. It is this 'step' displacement that imposes the 'shearing' strain on the Samson strap. Although the measurements showed, somewhat surprisingly, that the step had decreased with the second impulse (and this was confirmed by careful study of the photographs) the strap broke only after the second energy pulse.

Photograph 5.11 Test # 6 after the second impulse of 88 kJ which impacted at a velocity of 4,3 ms^{-1}.

Careful examination of Photograph 5.11 shows that the Samson strap has fallen slightly away from the undersurface of the blocks demonstrating that it no longer has any restraining effect. The fact that 154 kN of clamping force remained in the centre Voussoir beam proved that it was totally stable in its final position without any support from the strap. This suggested strongly that the presence of the strap probably played an insignificant part in limiting the displacements that resulted from the two impulses. Because the second impulse was transmitted through a slightly disarranged load-distribution pyramid the efficiency of its transmission is considerably lower than is the case with a first drop on an undisturbed pyramid. The uncertainty about how much energy arrives at the four centre concrete blocks makes it impossible to confidently assert that the single Samson strap significantly assisted in maintaining stability.

5.3.2 Series III – test # 7

In this test, the props and prop spacing were the same as before but the Samson straps were doubled in a side-by-side arrangement. Each strap had an over-lapped junction at a point somewhere along its length, between the two centre props – see Photograph 5.12.

Photograph 5.12 Test # 7 after third impulse of 147 kJ at impact velocity of 5,4 ms^{-1}.

Successive impulses of 49 kJ, 88 kJ and 147 kJ were imparted to the top of the pyramid. The clamping load applied to the centre beam was 225 kN which decreased to 183 kN after the second drop and 165 kN after the third drop.

The respective measured convergences were 21 mm, 40 mm and 78 mm on the northern elongate and 24 mm, 43 mm and 86 mm on the southern elongate. These values are compared with the convergences from the two impulses of test # 6 in Figure 5.6. The consistently lower rate of convergence for test # 7, where two Samson straps were used, suggests that doubling the strength of the straps did, in fact, exert significant restraining effect on the sliding of the roof blocks between the supports.

Taking account of the decreasing efficiency of energy transfer through the load-distribution pyramid the three successive impulses were estimated to be equivalent to about 150 kJ applied as a single blow. In test # 1 of Series II, 140 kJ had produced complete expulsion of the four unsupported blocks between similarly configured hydraulic props. This strongly suggests that the doubled Samson straps had a significant restraining effect on movement of the unsupported blocks and, importantly, on their stability.

The step displacements of test 7 were significantly less than those of test # 6 for similar pulse energies – see Figure 5.7. This further confirms the indication that the doubled (side-by-side) Samson straps were effective to some extent in preventing collapse of the hangingwall between the point supports.

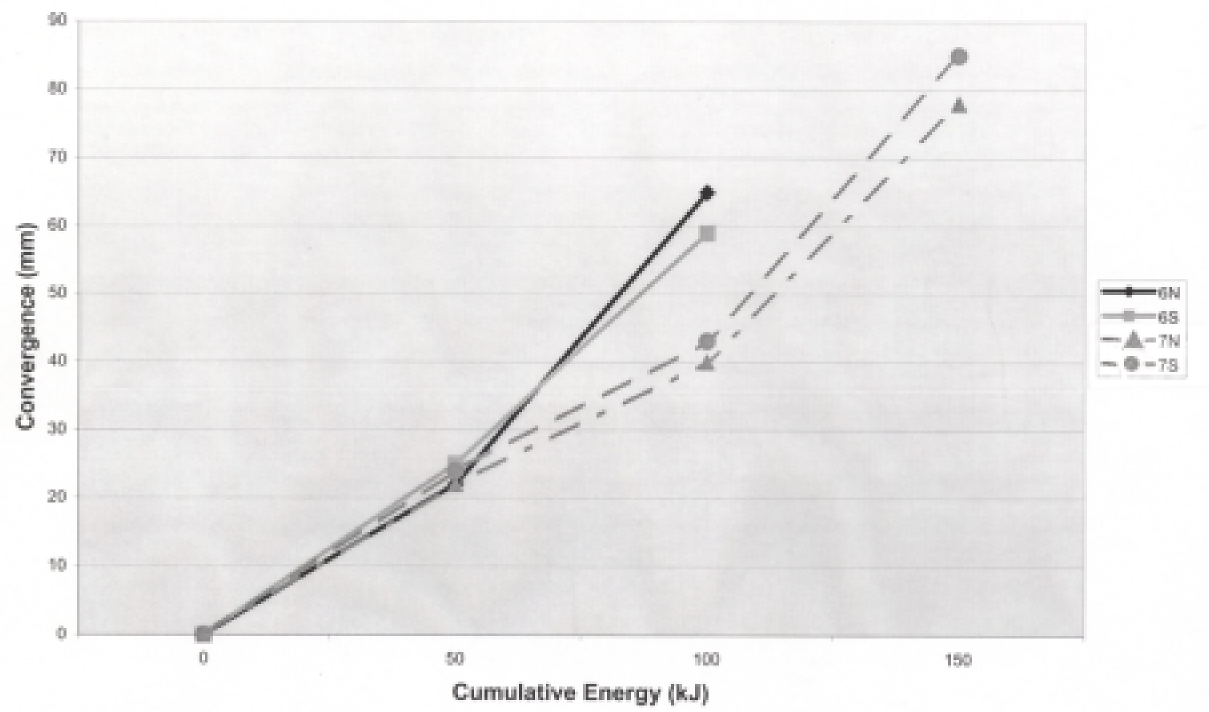


Figure 5.6 ***Plot of convergence of North and South elongates in test # 6 and # 7***

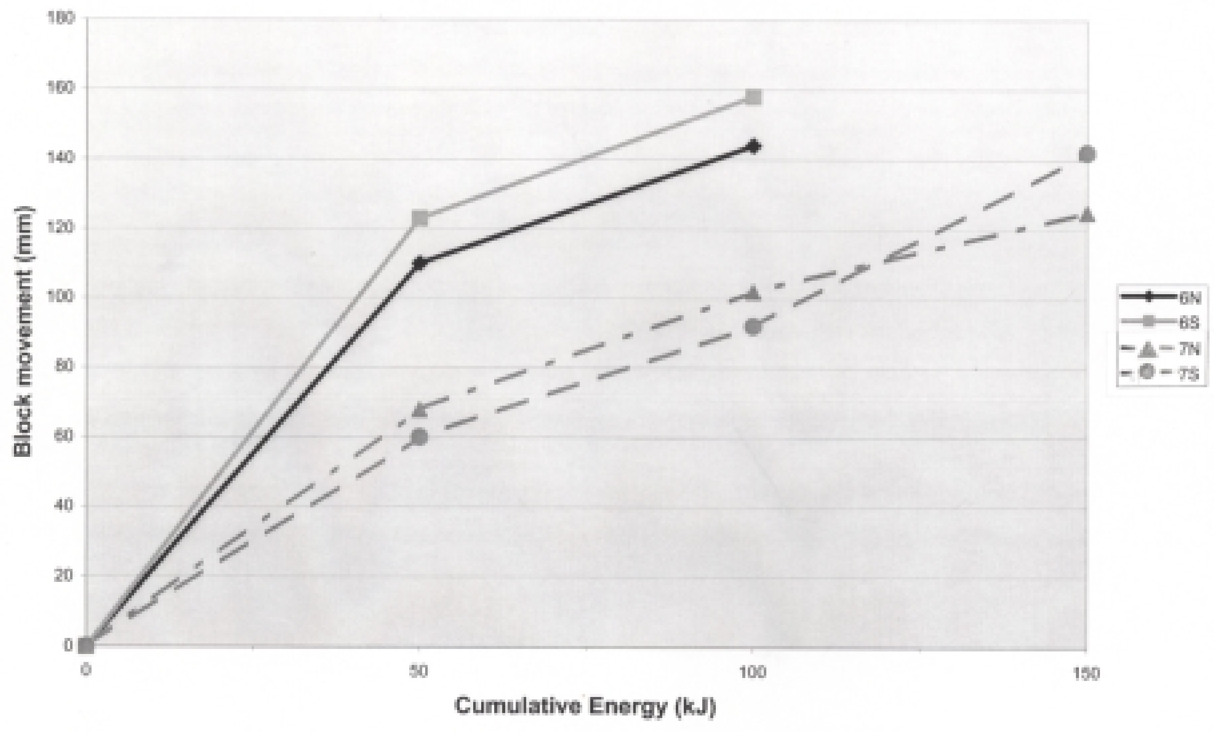


Figure 5.7 ***Plot of step displacements adjacent to North and South elongates in test # 6 and # 7.***

The closer views of the Samson straps in Photograph 5.13 and Photograph 5.14 show that the overlap yielding device came into play at block # 8 adjacent to the South elongate and also at the southern block of the eastern Voussoir beam. This may well have been the reason that the strap survived the 57 mm step displacement experienced against the South prop.

Photograph 5.13 Test # 7 showing 57 mm of step displacement at the southern prop and overlap starting to open.

Photograph 5.14 Test # 7 showing close view of the overlap of the Samson strap at the southern end of the East beam.

5.3.3 Series III – test # 8

To confirm the above indication, in a further test of the same support elements and configuration, a single impulse of 147 kJ was imparted to the load-distribution pyramid of test # 8. The results of this impulse was that the straps failed and the four centre blocks were dramatically ejected – Photograph 5.15. It appears from a close examination of Photograph 5.16 that the Samson straps most probably pulled apart at their folded overlap as they can be seen draped down along the North and South elongates.

Photograph 5.15 Test # 8 some 200 milliseconds after impact of 147 kJ impulse at a velocity of 5,4 ms^{-1}.

Photograph 5.16 Test # 8 indicating that Samson straps pulled apart at central overlap.

It appears from this comprehensive collapse that the energy losses accompanying the second and third impulses were greater than estimated and that the ‘one-blow’ equivalent of the 284 kJ total accumulated from the three impulses of test # 7 was, in fact, less than the 147 kJ imparted to test # 8 which caused the complete collapse.

5.3.4 Series III – test # 9

In an endeavour to improve the survivability of the interconnecting straps, in test # 9, three folded overlap yielding sections were incorporated into the two Samson straps which linked each pair of elongates.

The initial clamping force in the centre beam was 225 kN, after the first drop it was 235 kN and after the second drop it was zero.

Photograph 5.17 shows that the first energy impulse of 83,5 kJ did not cause any unfolding of the overlap connection. Convergences of 28 mm and 64 mm resulted at the North and South elongates respectively with rather small step converges of about 40 mm and 20 mm respectively in the roof profile adjacent to the props.

Photograph 5.17 Test # 9 showing en masse movement of centre four blocks after the first impulse of 83,5 kJ with no visible unfolding of Samson strap overlap.

The second impulse of 196,4 kJ caused complete collapse of the four unsupported blocks and large displacements of the end blocks. Photograph 5.18 shows that blocks # 1, # 2 and # 3 experienced large step displacements, presumably when the clamping force dropped to zero. One of the Samson straps extending across the North end of the Voussoir beam to the elongate under the outer deck, has yielded partially but is supporting the weight of three blocks (about 7,5 kN). The other strap has pulled apart at the overlap and is hanging free.

Photograph 5.18 Test # 9, after the second impulse of 196,4 kJ at an impact velocity of 6,2 ms^{-1}. View of North elongate showing one Samson strap pulled open while the other appears to have helped support blocks 1, 2 and 3.

The reason for the complete collapse becomes evident from a study of Photograph 5.19. The yielding device at the base of the North elongate of the centre beam failed asymmetrically causing the elongate to lose its resistance abruptly and its top end to shift laterally towards the North. The southern elongate then toppled inwards to dramatically remove the last vestige of support. It is very probable that the Samson straps linking the North and South elongates and, importantly, those linking the South elongate to the fixed upper deck would have pulled apart early in this failure process.

The failure mode in this instance underlines the importance that all the support units in each strike-orientated line, must remain linked together throughout the convergence episode.

Photograph 5.19 Test # 9, after complete collapse resulted from asymmetrical 'point-brush' failure of base of North elongate.

5.3.5 Series III – test # 10

Developing the notion that prop-type supports need to be linked in the dip direction as well as the strike direction, Mandirk Ltd developed a system of chain and rope ties that would achieve two-dimensional linking of pre-stressed timber elongate props. For the purpose of this report the linking system will be referred to as the 'collar-and-web' device.

The system consists essentially of two components. A 'collar' comprising short lengths of chain and steel plate locking segments is fastened around the rim of an inflatable steel pre-stressing unit (PSU). The 'web' is a length of 10 mm diameter flexible wire rope which is threaded through the end links of four short lengths of alloy chain and then joined to form a closed circle.

The four short lengths of chain are each extended diagonally to connect via a 'key-hole' latching arrangement, into the nearest 'collar' – see Photograph 5.20. Pulled taut by hand, the wire rope is formed into a square which is held in position against the hangingwall by the resiliency in the rope.

The resulting distribution of point-load elongate supports and collar-and-web linking systems (or 'safety-nets') is shown in Figure 5.8. The timber elongates were of the type known as the Buffalo which has a more regular yielding characteristic than the Ebenhaesers used in tests # 6 to # 9 but which operates at a yield load of 200 kN which is about one-half that of the Ebenhaeser.

Photograph 5.20 Test # 10 shortly after impact of 88 kJ impulse at velocity of 4,2 ms^{-1}.

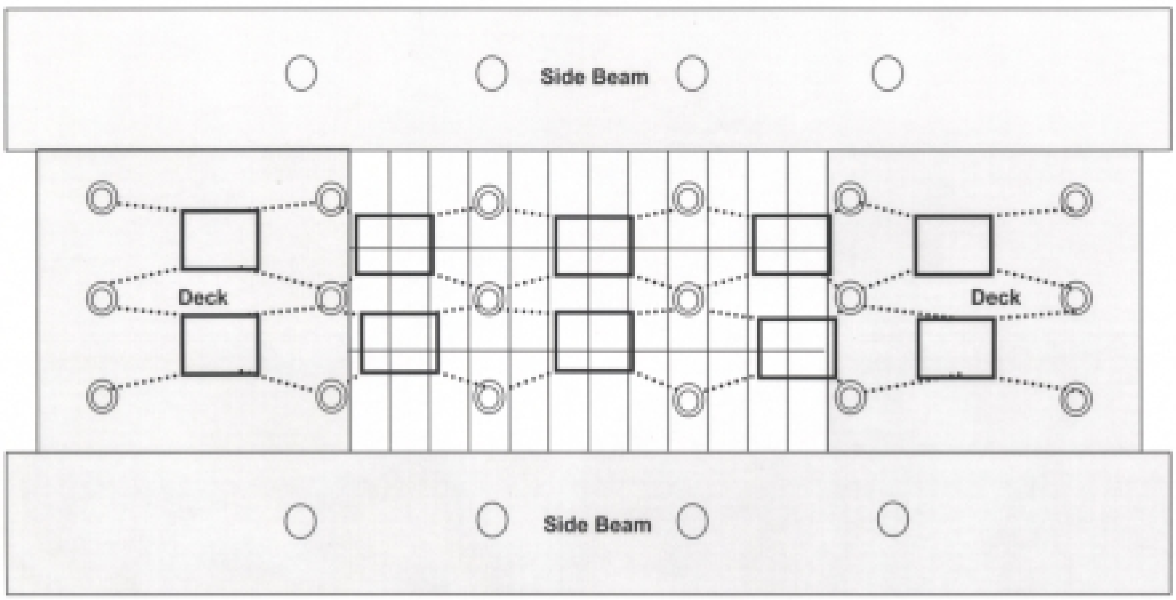


Figure 5.8 Mandirk 'collar-and-web' – test # 12.

In the first test (# 10) two impulses of 88,4 kJ and 147,3 kJ were imparted to the top of the load-distribution pyramid striking it with velocities of 4,2 ms^{-1} and 5,4 ms^{-1} respectively. The initial clamping force in the centre beam reduced from 221 kN to 159 kN after the first drop and to 154 kN after the second drop.

Convergences of 122 mm and 80 mm were caused in the North and South props by the first drop and 193 mm and 176 mm by the second drop, respectively. The corresponding absorbed energy amounts, determined from the manufacturers load-distribution curves (Figure 5.9), were 24 kJ and 15,8 kJ in the case of the first impulse and 38 kJ and 35 kJ in the case of the second impulse.

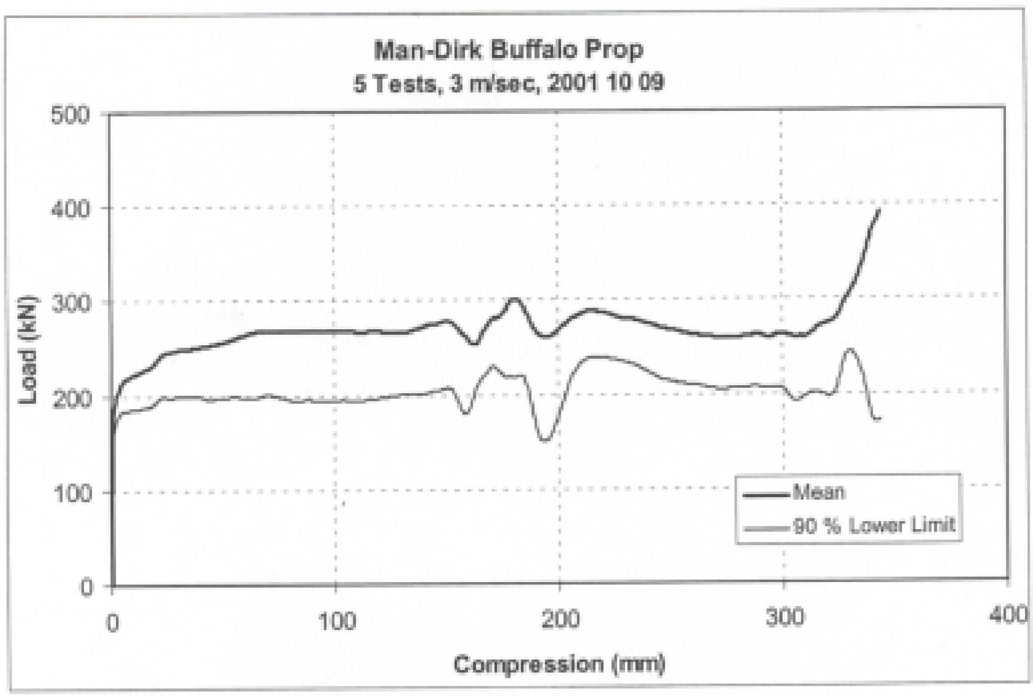


Figure 5.9 Dynamic load characteristics of Buffalo timber elongate.

Because of the softer characteristics of the Buffalo elongates the average convergence of the North and South centre props was more than twice as much as had occurred in test # 9 for very similar energy inputs.

After the first impulse the downward displacements of the four centre blocks were rather uniform, varying between 117 mm and 152 mm. These were only 30 mm to 40 mm greater than the convergence of the elongates flanking them. This meant that there was relatively little step displacement to strain the 'collar-and-web' ties where they stretched across the interfaces between the unsupported centre blocks and the supported blocks above the elongates. There was a greater 'step' or relative displacement between the near edge of the centre Voussoir beam and the West beam – see Photograph 5.20.

After the second impulse of 147,3 kJ (1,5 m drop height), the block displacements were again very similar, ranging between 207 mm and 234 mm and again only about 30 to 40 mm greater than the convergences on the adjacent timber elongates – Photograph 5.21.

Photograph 5.21 Test # 10, shortly after second impulse of 147 kJ impacted at velocity of 5,4 ms^{-1}.

Although it seemed likely that the presence of the collar-and-web device had prevented collapse of the four centre hangingwall blocks, once again there was relatively little step displacement to impose significant strain on the various components of the linking device. The collar around the PSU of the North centre-beam prop had somehow become loose – Photograph 5.22. This had the effect of relaxing the adjacent webs, further reducing the straining of the linking device. This meant that its effective capacity was still undetermined.

Photograph 5.22 Test # 10 showing loosened collar around North prop.

5.3.6 Series III – test # 11

This test was essentially a repeat of test # 10, different only in that the 147,3 kJ impulse (1,5 m drop) was the first and only energy input onto an undisturbed load-distribution pyramid.

Convergences of 135 mm and 130 mm at the North and South elongates were measured which, according to the manufacturers test characteristic, represented energies absorbed of 26,8 kJ and 26,3 kJ respectively. Together this meant that, typically, 72 percent of the energy absorbed by the support went into compressing the two props supporting the central Voussoir beam.

The displacements of the centre four blocks ranged from 149 mm to 183 mm which was 20 mm to 48 mm greater than the convergences of the adjacent elongates. Once more the step displacements were so small as to have exposed the chain linkages to relatively low amounts of straining. This is evident from Photograph 5.23, which is barely distinguishable from Photograph 5.21 of test # 10.

Photograph 5.23 Test # 11 after first impulse of 147 kJ at impact velocity of 5,4 ms^{-1} showing small step displacements similar to those of test # 10 (Photograph 21).

5.3.7 Series III – test # 12

In order to ensure that large step displacements would occur, a single large impulse of 287 kJ was imparted by dropping the 10 ton mass from a height of 2,92 m to impact at a velocity of 7,5 ms^{-1}. Photograph 5.24 shows that the short length of chain linking the rope 'web' to the South elongate prop has pulled free from the 'button-hole' of the collar around the PSU of the South prop. The square web of wire rope has distorted into a triangle and removed all support from blocks # 5, # 6, # 7 and # 8 which consequently collapsed dramatically.

The convergences measured on the six Buffalo props are listed in Table 5.1 together with the energies absorbed in each prop as calculated from the manufacturers test curve – Figure 5.9.

Photograph 5.24 Test # 12 shortly after impact of first impulse of 290 kJ at velocity of 7,5 ms^{-1}.

Table 5.1 Measured convergences and calculated energies on Buffalo props

Position of prop:	**NW**	**North**	**NE**	**SE**	**South**	**SW**	**Total**
Measured Convergence (mm)	33	212	52	38	230	54	-
Calculated energy (kJ)	6,4	42,0	10,0	7,2	45,6	10,4	121,6
Percentage of total	5,3	34,5	8,2	5,9	37,5	8,5	99,9

Typically, the North and South elongates absorbed 72 percent of the total energy absorbed by the support which was 121,6 kJ. This total was only 42 percent of the 286 kJ impulse imparted to the load-distribution pyramid. This was somewhat less than the 52 percent and 50 percent load transfer efficiency indicated by tests # 10 and # 11, respectively. In neither test was kinetic energy removed from the system in the form of ejected hangingwall blocks. If it is assumed that transmission losses through the pyramid were normal, i.e. about 50 percent, then 143 kJ would have been available to cause 'damage' in the form of convergence of props or movement of blocks. Since 122 kJ can be accounted for by the measured convergence of the Buffalo elongates, it can be argued that 21 kJ of frictional and kinetic energy was lost in ejecting the four roof blocks.

Close examination of the 'buckling' of the suspended measuring tapes in Photograph 5.24 indicates that the blocks were indeed ejected at a considerably enhanced velocity that might be expected only in a severe rockburst.

Photograph 5.25 shows that the chains and wire ropes of the 'web' portion of the prop-linking device were undamaged. Failure of the system was due to spreading of the 'button-hole' in the 6 mm thick steel latching segment of the collar – see Photograph 5.26. A minor change in configuration of this element would considerably increase the probability that even violent collapse of the rock between prop-type supports could be contained.

Clearly, further development and testing of this promising support innovation should be encouraged.

Photograph 5.25 Test # 12, showing collapse of four centre blocks after web link to SE collar pulled free from latch segment.

Photograph 5.26 Test # 12, close view of SE collar segment with 'button-hole' stretched open.

5.4 Series IV – Rotational stability of pack pre-stressing device

Consideration of the factors that could influence the stability of the clamped, vertically-jointed and uniformly blocky Voussoir beam will lead to the realisation that there is a greater complexity in its kinetic behaviour than was first contemplated. Amongst the more important of these factors would be the 'shape' of the distribution of the impulse load along the length of the beam. This would be largely determined by the number and spacing of the 'point-load' supports under the Voussoir beam. Clearly, as was demonstrated in test # 5, the presence of a third prop at the mid-point of the Voussoir beam would significantly change the kinematic response of the blocks to the centrally-aligned impulse.

To a large extent the possibility of potentially misleading complications of this nature was avoided throughout the GAP 818 programme by using only two symmetrically positioned props per beam and maintaining the same or very similar spacing distances between them. There were, however, indications that any tendency for even a small degree of rotational freedom to exist at the point of contact between the support unit and the roof block might severely compromise the stability of the beam. This was particularly evident in test # 3 of Series II.

The wish to gain further insight into this ‘rotational stiffness’ aspect of Voussoir beam stability was partly the reason why it was decided to replace prop-type supports with pack-type supports in Series IV testing.

It was believed that packs, particularly those that are engineered to display very uniform yielding behaviour such as the Grinaker Durapak, would provide a very stable non-rotating ‘abutment’ at each end of the beam.

5.4.1 Series IV – test # 13

In test # 13, two 600 mm Durapak packs were placed near each of the three Voussoir beams so that there was 1,25 m of unsupported roof space between them – see Figure 4.2. Each pack consisted of eleven layers of precisely-dimensioned, light-weight compressible ‘concrete’ slabs with an inflatable steel diaphragm PSU and blocking slabs on top – see Photograph 5.27.

Photograph 5.27 Test # 13, showing tilted blocking layer of South pack.

Another major change intended to make the distribution of the impulse load much simpler, was in the configuration of the load-distribution pyramid – Figure 4.2. The pyramid was made twin-peaked and two-dimensional so that the impulse load would be entirely concentrated on the central Voussoir beam and distributed more uniformly along its length – see Figure 4.2 and Photograph 5.28.

Photograph 5.28 Showing the two-dimensional load-distribution pyramid before impact.

In order to attempt to estimate the kinetic energy of the blocks should they be ejected, an arrangement of 'yielding' wire ropes was sandwiched between the seventh and eighth layers of each pack to arrest the collapsing blocks. The device successfully arrested the blocks – see Photograph 5.29 - but yielding of the ropes occurred in the pack anchorage where it could not be measured so it was not possible to estimate the energy change.

Photograph 5.29 Test # 13, shortly after impact of first impulse of 88,4 kJ at velocity of 4,2 ms^{-1}.

The first impulse of 88,4 kJ imparted to the load-distribution pyramid caused complete collapse of the four centre hangingwall blocks with the original clamping force of 230 kN dropping to zero. The crumpled tapes show that the hangingwall blocks are falling at a velocity significantly higher than that due to gravity, and are about to make contact with the arrestor device. The blocks were brought to a stop after about 200 mm of further movement – Photograph 5.30 – with the arrestor ropes cutting deeply into the seventh pack layer – Photograph 5.27. The extent of disarrangement of the pyramid as a result of the collapse of the roof-beam below is shown in Photograph 5.31.

Photograph 5.30 Test # 13, showing arrested centre blocks.

Photograph 5.31 Test # 13, showing disarrangement of two-dimensional pyramid after impact of 88,4 kJ.

In the context of the ‘shape’ of the load distribution and the consequent displacement along the Voussoir beam it is worth noting that the four collapsing blocks appear to be moving, not en-masse, but at similar rates and along parallel trajectories.

The packs appeared to suffer only small amounts of compression, with 42 mm measured at the North pack and 28 mm at the South pack. Because the fluid-filled, thin-walled pre-stressing unit has no rotational stiffness, a certain amount of inward tilting occurred in the blocking layer of the pack and the hangingwall blocks above. This made it impossible to accurately measure the compression of the packs. A degree of rotational freedom may also have existed which might have facilitated the ejection of the four collapsed hangingwall blocks.

5.4.2 Series IV – test # 14

Test # 14 was a repeat of test # 13 except that the rotational ‘softness’ of the fluid-filled pre-stressing pad was eliminated by using non-weeping pre-stress bags pressure-filled with a settable grout slurry. The axial compression in the centre Voussoir beam was 234 kN compared with the 230 kN of test # 13.

The same impulse of 88,4 kJ was imparted, at the same velocity of 4,2 ms^{-1}, to the two-peaked pyramid. The effects were very different from those observed in test # 13. Overall compression of the two packs was 17 mm and 13 mm at the North and South respectively, without any sign of rotation. The four totally unsupported centre blocks slid downward, en-masse, by 62 to 65 mm and the two blocks that were partially supported by the inner edges of the Durapak slabs slid down by 37 mm and 58 mm at the North and South packs respectively. This latter movement was the result of crushing of the top Durapak slab by the hardened grout of the pre-stressing bag – Photograph 5.32.

Photograph 5.32 Test # 14, showing no tilting at uppermost layer of South pack after first impulse of 88,4 kJ at a velocity of 4,2 ms^{-1}.

For the purpose of quantitatively determining the initiating velocities of the collapsing roof, accelerometers had been attached to roof blocks 4, 7 and 9 by seismological engineers from CSIR Miningtek. The amplification of the accelerometers on blocks 4 and 9, where velocities were expected to be much lower than at block 7, was set too high and the records were saturated. The particle acceleration at the lower surface of block 7 was well recorded and is displayed in Figure 5.10. Integration of this accelerogram yielded a maximum value [peak particle velocity (PPV)] of 2,3 ms^{-1} which is 55 percent of the impact velocity of the imposed dynamic load.

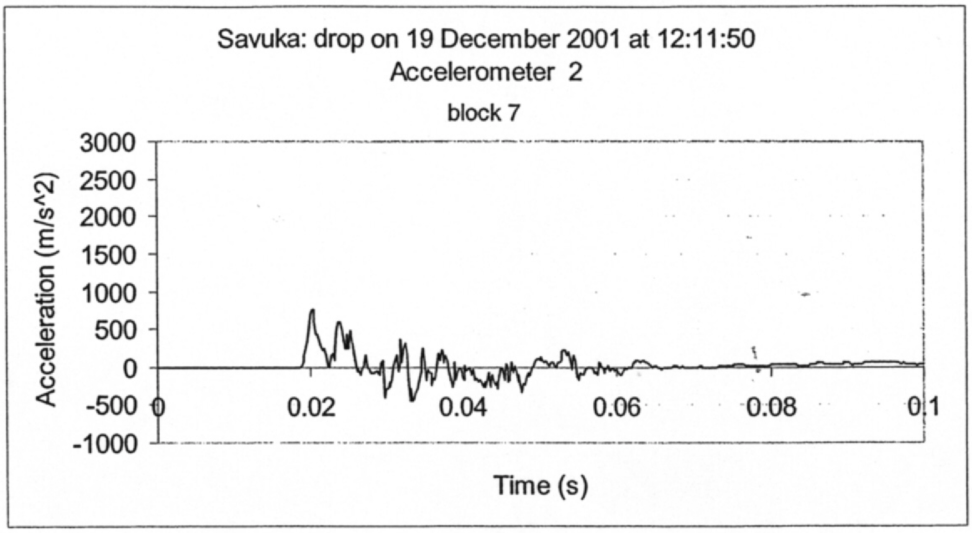
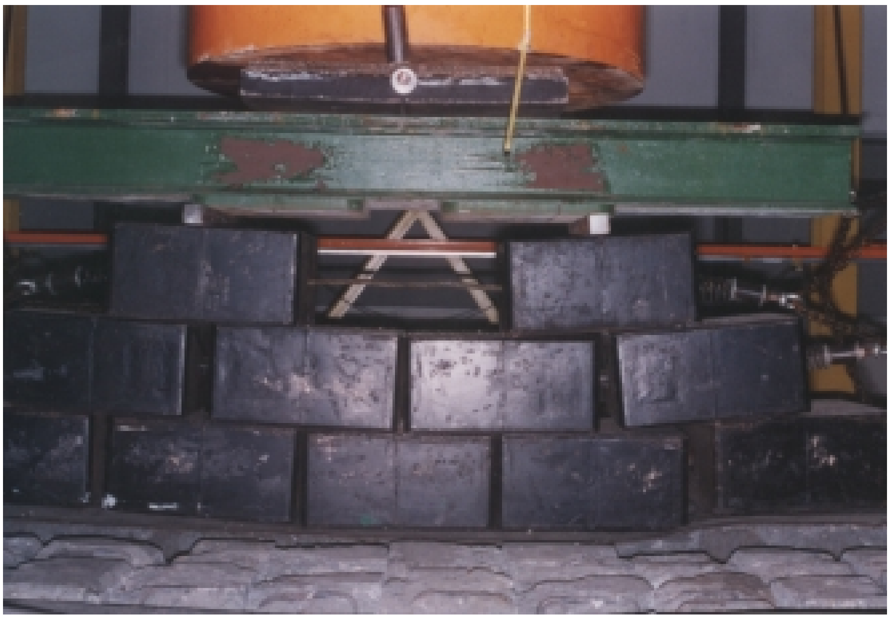


Figure 5.10 Accelerogram recorded by A2 from drop # 1

Because there was very little disarrangement of the load-distribution pyramid (Photograph 5.33) it was considered that a second, larger impulse would be effectively transmitted from the impact plate through to the hangingwall beam and the support packs below it.



Photograph 5.33 Test # 14, showing relatively little disarrangement of load distribution pyramid after first impulse.

The second impulse of 147 kJ, impacting at a velocity of 5,4 ms^{-1}, caused the violent ejection of the four unsupported roof blocks (see Photograph 5.34) and further compression of the packs to total 66 mm at the North and 51 mm at the South. There was some indication that the second energy transfer through the pyramid was possibly more efficient than that following the first impulse, inasmuch as the three-fold increase in impulse energy produced a four-fold increase in energy dissipated in deformation of the support.

Photograph 5.34 Test # 14, shortly after impact of second impulse of 147,3 kJ at velocity of 5,4 ms^{-1}. Accelerometer visible on block 4 gave velocity estimate of 3,3 ms^{-1}.

All three accelerometers captured good accelerograms – see Figure 5.11, Figure 5.12 and Figure 5.13. Blocks 7 and 9 displayed sharp initial peaks of 1400 ms^{-2} and block 4 was subjected to an even higher peak of 2840 ms^{-2}. The respective velocities (PPV's) of the two supported blocks 9 and 4 were 3,19 ms^{-1} and 3,32 ms^{-1} The unsupported block number 7 which was violently ejected, had an initial velocity of 3,59 ms^{-1}. This was 66 percent of the impact velocity at the top of the pyramid. The fact that the measured velocities were so similar in magnitude was surprising considering the great difference in kinematic freedom. It is thought possible that the uniformity in velocity might reflect the uniformity in distribution of dynamic load which it was hoped to obtain from the twin-peaked two-dimensional load distribution pyramid shown in Figure 4.2.

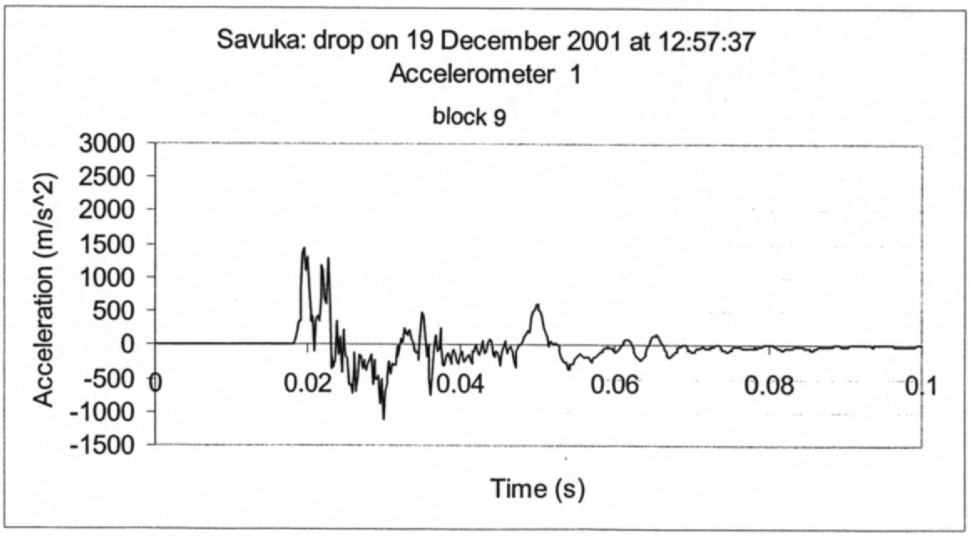


Figure 5.11 Accelerogram recorded by A1 from drop # 2.

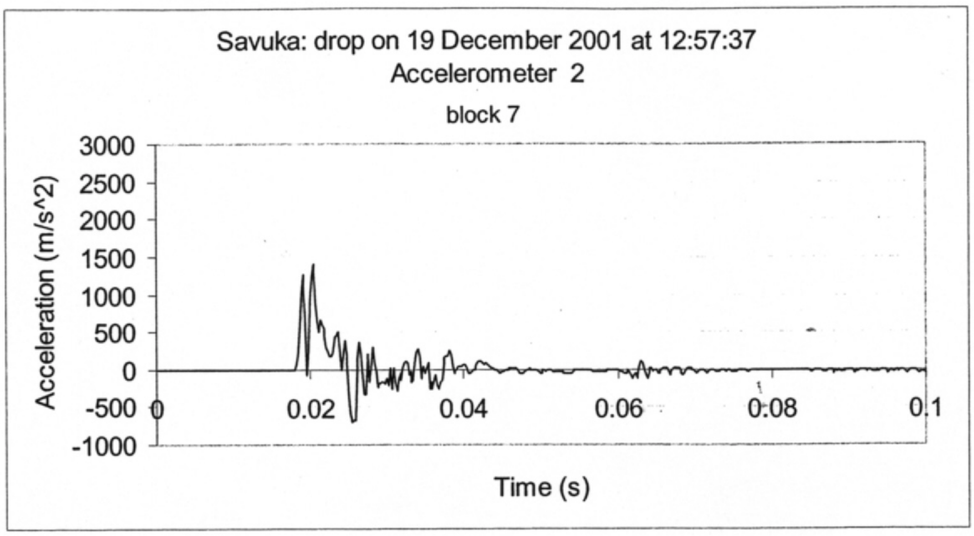


Figure 5.12 Accelerogram recorded by A2 from drop # 2.

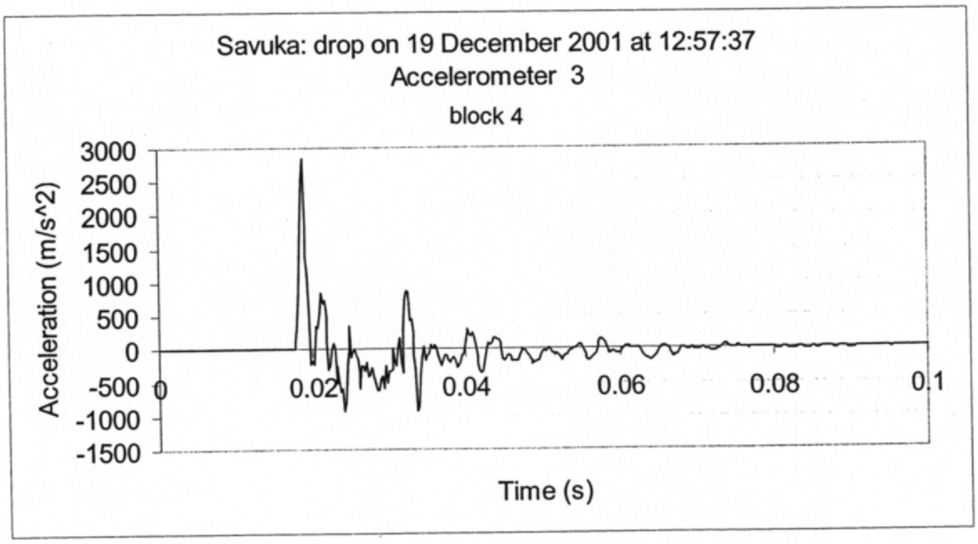


Figure 5.13 Accelerogram recorded by A3 from drop # 2.

The ejected blocks in Photograph 5.34 appear to be about to break through the rope arrestor device. In fact block 8 was arrested well above the floor while blocks 5, 6 and 7 tipped sideways so that their western edges just made contact with the floor. The eastern ends of these blocks were held up 500 mm to 600 mm above the floor. This indicates clearly that the kinetic energy, which they acquired after ejection from the roof beam, was not much more than that possessed by the same blocks arrested 400 mm above the floor in test # 13.

The important conclusion inferred from the above observation is that it required almost three times more input energy to disrupt the stability of the hangingwall beam of test # 14 than was necessary in test # 13. The significantly less stable hangingwall beam of test # 13 was thus almost certainly due to the rotational ‘softness’ of the fluid-filled steel diaphragm-type pre-stressing pad.

6 Discussion

There can be little doubt that the testing exercises carried out in the four series of the GAP 818 project were very informative and of considerable practical usefulness. More quantitative descriptions of simple block movements and support compressions were obtained than in the previous GAP 611 projects. Unfortunately, this did not clarify issues and mechanisms as much as it showed how complicated the problems of discontinuous rock stability and interaction with support must be, in reality, in the underground situation.

Despite this, the exercise of trying to understand the kinematics of the test facility somehow actually does assist in visualising likely actual behaviour. It soon brings the realisation that there is no way that even the simplest of idealised real situations can be properly simulated. **Provided that this reality is continually borne in mind, it is soon appreciated that very useful comparative-type studies can nevertheless be validly undertaken that would be quite impracticable or impossible to attempt underground.**

7 Conclusions

The results of the GAP 818 testing programme confirmed again what was believed after the first two GAP 611 projects, viz that the dynamic stope testing facility is a uniquely useful testing ground for the development of innovative support designs.

Although it cannot be claimed that it correctly simulates even the most idealised underground situation, the facility is able to subject most components of a support **system** to differential movements at displacement velocities that could very possibly occur in rockburst situations underground. It was demonstrated in test # 14 that the commonly accepted rockburst convergence rate of 3,0 ms^{-1} could readily be attained.

In respect of the more specific objectives of the programme it was possible to reach the following conclusions with a fair degree of confidence:

- longer headboards are obviously effective, to a perhaps limited extent, in reducing the potential for rock blocks to collapse between the support units. However, at the longer lengths, limitations in practicability become apparent. The headboard must articulate at the top of the prop to avoid destructive bending stresses. The resulting complete lack of 'rotational stiffness' then introduces a strong possibility of the prop 'rolling' out if irregularities in the hangingwall cause eccentric loading on the headboard.

- By linking together the tops of adjacent props, the rolling-out tendency will be largely avoided. Importantly the links will resist the tendency of rock wedges to fall out or parallel-sided blocks of rock to slide out from the discontinuous 'beams' that constitute the hangingwall of a deep stope.

- If the links are sufficiently strong, with a degree of inherent compliance or resiliency, they will resist the collapse of large wedges or blocks even if these are, ejected at considerable velocity.

- With proper design, which may perhaps require that there is a measure of controlled yieldability somewhere in the linkage, it is probable that collapse of hangingwall between support units can be contained even in very severe rockbursts.

- Fluid-filled pre-stressing units of the sheet-steel diaphragm type appear to introduce an element of potential instability into the support /fractured rock interface. While such tendency would be less likely to result in 'rotational instability' in an actual underground stope, it is a possibility that requires further consideration.

As an overall assessment, it is considered that the various aspects of the dynamic support problem that have been explored in the GAP 818 programme, have been partially elucidated but not definitely resolved. Further work is justified particularly in determining the upper limits of capacity of the two types of inter-linking device, the 'embryo' first versions of which have been examined in this programme.

There is an obvious need for a more **quantitative** basis for comparing different support products at varying spacings and configuration. It is also recommended that substantial further effort should be directed towards the development of methods of dynamic monitoring of loads and displacements.

8 Acknowledgements

The success of the GAP 818 project is due, in no small part, to the enthusiastic co-operation of the support manufacturers. Gratitude is here expressed to Elbroc, Mondi Mining Supplies and Mandirk and their respective staff, for their valuable contributions.

The conscientious and reliable efforts of the sub-contractors in the completion of the programme are gratefully acknowledged.

The quantitative value of the results was considerably enhanced by the measurement of acceleration and velocity performed by Alec Milev of CSIR Mining. This valuable assistance is gratefully acknowledged.

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