Mine safety net development and applications

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Synopsis

Safety nets have been used selectively in several South African mines over the years. Recently, however, an increased emphasis on mine safety has seen a resurgence of their utilization underground. This renewed interest has, however, also raised questions about the design and performance of these nets and their practical applications underground; these are the subjects of this paper.

Generally, mine safety nets are used to protect personnel from falling rock in temporarily supported development ends, tunnels, ASGs and stopes. These diverse applications each require specific net designs, resulting in a wide product range. As a rule, however, mine safety nets need to carry specified static or dynamic loads with the least possible deformation.

Because of the application-specific characteristics of mine safety nets, there is no South African national standard for them. Consequently, neither the SABS, nor the CSIR, performs standard tests on these components. In 2007, therefore, SIMRAC made available their Savuka facility for the testing of mine safety nets; the Savuka drop test became the accepted industry test standard for mine safety nets. From late 2007 to mid 2009, Norsenet, in collaboration with SRK Consulting, the designated operators of the site, conducted approximately 200 tests, which formed the core of Norsenet's database of safety net performance under various loading conditions.

The test specimens comprised a wide range of net materials and configurations; the materials included: high density polyethylene, polypropylene, polyester, nylon, as well as a blend of polyester and polypropylene used primarily for reinforcement ropes. Net configurations encompassed the following parameters: net type, i.e., knotted nets or sewn nets; net strand type, i.e., braids, twines, or webbing; strand size; mesh size; mesh orientation, i.e., parallel or oblique to the net edge; net edge reinforcement, i.e., knotted, tied, with or without reinforcement ropes; internal reinforcement ropes, i.e., diagonal ropes and/or orthogonal ropes; as well as net attachment options, including loops and chainlinks.

From the number of variables listed above, and the limited number of tests available, it can be appreciated that the findings of the test series required careful scrutiny. Nevertheless, principal performance factors clearly emerged: besides the obvious net mesh variables, such as net strand material, strand diameter and mesh size, it was the configuration of the reinforcement ropes and their attachment to the net panel which had the strongest influence on net performance. All the structural elements of a safety net need to work together to transfer the imposed load from the net panel, through the reinforcement ropes, to the net attachment points. In this load transference chain, the weakest link limits the strength of the structure.

From this development work, Norsenet has gained valuable expertise to custom-design and manufacture nets to clients' specifications. The examples presented in the paper will also show the experience acquired in the installation of nets underground. Future work will include the establishment of a state-of-the-art net testing facility at Norsenet's factory in Vredenburg..

Keywords

Mine safety net, safety net, protective device, mine safety, safety net design, safety net performance, safety net applications.

Background

Norsenet (Pty) Ltd manufactures an extensive range of safety nets for the mining industry, where they are generally used to protect personnel from falling rocks in temporarily supported development ends, stopes and advance strike gullies, as part of permanent tunnel support systems, including tunnel side walls, and as protective netting along conveyor belts. These diverse applications each require specific types of nets, resulting in a wide product range with nets of different strengths, configurations and materials.

As part of Norsenet's product development and certification programme, over 200 certified tests were carried out on mine safety nets at accredited institutions, including the SABS and the CSIR. Most tests, however, were carried out at the industry-owned SIMRAC testing facility at the Savuka Mine; these tests were done in collaboration with SRK Consulting, who were appointed by SIMRAC to conduct all tests at the facility.

The information gained in the design, development and product testing phase was, of course, not merely of academic interest, but laid the foundations for Norsenet's commercial range of mine safety nets. Nevertheless, many valuable lessons about mine safety nets were learned in the process, which should be shared with the industry in the interest of enhanced mine safety; that is the purpose of this paper.

Safety net testing

As mentioned above, most of the testing done for the design and development of the mine safety nets discussed in this paper were carried out at the SIMRAC Savuka drop test facility.

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Despite some shortcomings of the facility in terms of a lack of instrumentation, valuable insights were gained into the behaviour and performance of mine safety nets under dynamic and static loading. Indeed, Savuka drop tests became the accepted industry standard for mine safety net appraisals.

At this stage it is perhaps important to mention that the Savuka multiple impact tests represent a very severe type of loading, as damage to the nets is cumulative from drop to drop. This is not the type of loading experienced in practice underground, where, after a severe fall of ground, it is recommended to check the net thoroughly and replace it, if it is in any way damaged.

In the following sections, the test facility and the applied testing procedures will be discussed in detail.

The Savuka test facility

The core of the Savuka drop test facility is a reinforced concrete structure, designed to replicate a horizontal tabular mining stope of 1.2 m stoping width. The central portion of the stope hangingwall between the four corner pillars is open to the top. Using an overhead crane, this opening can be partially or fully closed with sets of concrete blocks suspended from the edges of the opening. Single blocks, or clusters of these blocks, can selectively be released to drop into the stope, thereby loading support elements to be tested. An alternative testing method involves the dropping of a loading mass directly from the overhead crane through the opening in the hangingwall onto the support element to be tested. This second procedure is the principal method used for the testing of mine safety nets.

Dynamic test procedure

The standard drop test for safety nets at Savuka involves the repeated dropping of a pair of flexibly connected, identical steel/concrete blocks onto a safety net suspended from Camlok props against the hangingwall of the test stope below; the combined mass of the drop blocks is 450 kg, their combined impact area is 0.5 m^2 (twice 0.5 m × 0.5 m, adjoined).

The positions of the test stope pillars restrict the positions of the four Camlok props used to suspend the test net against the hangingwall; this, in turn, limits the square test net size to 1.5 m × 1.5 m. The net is attached to the Camloks' headboards and is stretched taut for the test run.

At the outset of a test run, a 'static' load test is performed, whereby the blocks are slowly lowered onto the safety net. After that, the sequential test drops commence: the first drop from 10 cm above the net centre, subsequent drops from progressively increasing heights, incremented by 10 cm, always as measured from the current centre elevation of the unloaded net to the underside of the drop mass. This dropping sequence is continued until net failure occurs, or until the height limit of the overhead crane is reached at about 2.0 m (depending on the stretch of the test net). Figure 1 shows a typical mine safety net test conducted at the Savuka test facility.

Test measurements comprise the elevation of the unloaded net centre prior to any loading, as well as the elevation of the loaded net centre. From these elevations, the sag of the net under load and the stretch of the unloaded net is determined for all loading episodes of a test run. A detailed drop height and net elevation measurement log is kept for each test run; detailed observations on net performance and damage sustained by the net are also entered into the log.

Furthermore, a digital photographic and videographic record is kept of the entire test run: still photographs are taken of the net before and after each loading episode, as well as of any visible damage sustained by the net during loading. Each loading episode is filmed using a digital video camera. At the end of the test run, the test net is laid out and photographed to show the general condition of the net after the test.

Deadload testing

One of the drawbacks of the Savuka dynamic testing procedure is that from the data produced, it is very difficult to estimate the deadload capacity of a net, i.e.: what is the heaviest block of rock a net will safely hold. The purpose of such a test is to remove the additional dynamic loads of a

Figure 1—Safety net test at Savuka, showing the 450 kg twin drop mass arrested by the safety net. Note the diagonal and perimeter net reinforcement ropes attached to the Camlok prop hooks

falling body from the equation. A standard Savuka deadload test determines a specific capacity: a 2000 kg load is slowly lowered onto the suspended net to see if the net will hold that particular load. The facility is not equipped, however, to determine maximum deadloads.

Unless one can measure the maximum deadload directly, an option not available at Savuka, the only alternative is to back-calculate it from standard Savuka drop tests. The approach is to calculate the force of the falling drop mass, which is transferred to the net, as the 450 kg blocks are decelerated to zero velocity by the mesh. This force transference is called impulse and from it, the deadload equivalent can be calculated by dividing the impulse by the deceleration time. This is the difficult part of the procedure; since the Savuka test facility had no instrumentation to record forces on the net in real time, the only way to determine the deceleration time is to use the video recordings of the drop events, which were taken at every drop episode. Looking at the recording frame by frame, and knowing the recording speed, one can get a reasonable estimate of the time it took to decelerate the drop mass

Test data presentation

The results of Savuka drop tests generally take the form of x-y graphs, with kinetic energy, [kJ], shown on the abscissa and sag, [m], (net deformation under load) shown on the ordinate. Since the sequential drops of a test run represent discrete measurement points, the straight line connections on the graph are necessarily interpolations between the individual test drops. This is not a problem, as long as the net survives the sequential drops, i.e., absorbs the kinetic energy of each increasingly severe drop. Once the net has failed, however, it is no longer possible to interpolate to the last drop episode; for that reason, the last (failure) point is omitted from the graph; the entire graph, as shown, therefore, reflects the performance of the generally intact net.

In order to present large amounts of data concisely in comparative graphs, individual performance curves of identical samples in a test batch are presented as average performance graphs. The process of averaging the respective single performance graphs is done with circumspection: each set of performance graphs is plotted and compared to its calculated average graph. This visual check allowed the correction of minor sag deviations in the average due to samples failing at different energy levels; the maximum energy absorbtion, too, is corrected downwards, where appropriate, to reflect the average performance of the batch. All the raw data, together with the single performance graphs and corrected averages, are, of course, recorded in a database and can be revisited at any time.

Safety net design

Depending on a range of diverse applications and site-specific conditions in mining excavations, a wide variety of mine safety nets is being used underground. All of these nets, however, show a number of common design features, born out of their common purpose: to safely arrest rocks falling from the hangingwall with the least possible deformation.

Basically, a mine safety net consists of a net mesh panel, a net periphery, reinforcement ropes and net attachment loops. All of these structural elements, correctly matched to each other and working in synergy, are vital to the optimal performance of the safety net. If any one of those elements fails, the effectiveness of the entire net is compromised.

In use, the net is suspended against the hangingwall on mine support elements such as rock anchors, mechanical props, or prestressed elongates. In the event of a rockfall, the dynamic and static forces exerted by the arrested rock on the net are initially absorbed by the net mesh and the reinforcement ropes, deforming them in the process, and are then transferred in part directly to the net suspension points, and in part to the net perimeter and along that to the net suspension points on the rock anchors and mechanical props. The full performance potential of the net is, therefore, only realized if all the net elements work together to transfer the rock's impact and gravitational forces to the mine support units.

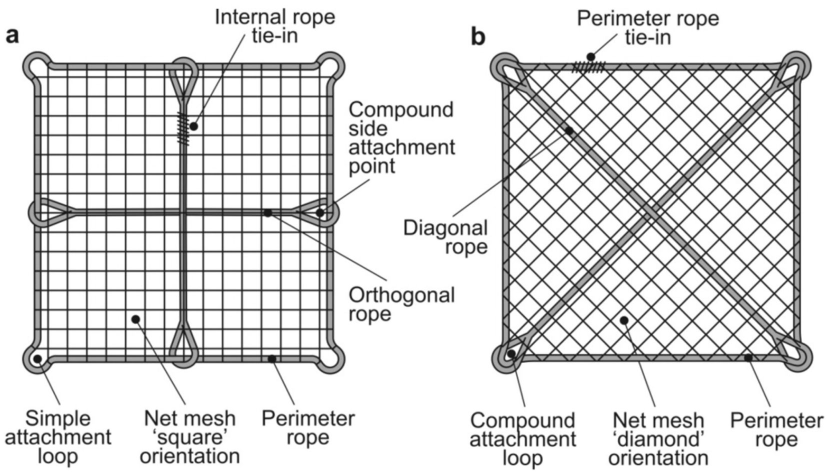

Figure 2—Typical safety net configurations, as tested at Savuka, showing the primary structural net elements. (Not to scale.)

Even though the basic structural elements are common to most safety nets, these elements can differ substantially in their form and specifications. Therefore, the configurations and performances of safety nets designed for diverse applications can be quite dissimilar. Bearing that in mind, it is useful to separately describe the structural elements of safety nets, as well as the choices of materials of which they are commonly manufactured. The performances of the different net configurations will then be described in the following chapter on test results.

Structural elements of Mine Safety Nets

This paper deals with the design and development of the Norsenet range of mine safety nets and this section will, therefore, be confined to that company's polymer safety nets. Figure 2 below shows the structural elements of two typical net configurations.

Net mesh panel

The net mesh panel is the central component of the mine safety net; to a large extent, it determines the overall strength of a well designed net. Since the net mesh forms the main part of the net's area, it is the component most likely to be subjected to the initial impact force of a falling rock. The mesh panel absorbs the dynamic and gravitational loads and distributes them across the net, partially to the net perimeter (and along the perimeter to the attachment points) and partially directly to the attachment points. If the mesh panel is too weak, or damaged, its ability to absorb and distribute load is restricted, in bad cases causing the rock to break directly through the net. There are a number of parameters which determine the strength and performance of the mesh:

- *Mesh strands*—the type of tendon of which the net mesh is constructed. There are three major types of polymer strands: braids, twisted twines and webbing. Braiding is the most common type of net strand, typically ranging in size from 4 mm to 8 mm diameter, the latter forming the base of the strongest standard types of mine safety nets. Twisted twines are generally used for low performance nets, such as might be used for sidewall netting or protective netting along conveyor belts. Twisted twine sizes, as used for mesh panels at Norsenet typically range from about 2.5 mm diameter to 4 mm diameter. Webbing straps are woven tapes of polymer fibres; they are typically 50 mm wide and their strength is determined by the webbing thickness. Webbing is normally used for medium to high strength net meshes with low deformation under load (sag).
- *Mesh strand materials*—the type of polymer making up the mesh strands. The great majority of safety net meshes are made up of two materials: braids and twines normally consist of high density polyethylene (HDPE), whereas webbing is normally made of polyester (PET). Other materials are being used for special applications, e.g., polyester or nylon braids may be used for very high strength netting.
- *Mesh construction*—nets made of braid or twisted twine are (machine) knotted and subsequently stretched in a frame to tighten the knots. This knot-fastening process is an important step in the fabrication of nets, as it pretightens the knots, thereby substantially reducing initial net sag under load. Knot fastening is generally confined to machine-made nets. The webbing of web-nets is woven and the webbing tapes are sewn together at their intersections.
- *Mesh size*—the open distance between two parallel mesh strands, invariably for both directions: i.e., machine made meshes are normally square, e.g.: 100 mm × 100 mm. Since mesh size is a measure for the net density, it stands to reason that for any given strand size, a smaller mesh size provides for a stronger mesh. In knotted nets, mesh sizes typically range between 50 mm and 125 mm; in web-nets, the mesh size is usually set at 150 mm.
- *Mesh orientation*—the alignment of the mesh strands relative to the mesh perimeter; if the mesh strands are parallel to the perimeter, the mesh panel is said to be in 'square' orientation; where the strands are at a 45° angle to the perimeter, the mesh panel is in the 'diamond' orientation. For the normal rectangular net configuration, 'diamond' meshes transfer loads more efficiently to the corner attachment points than 'square' meshes do; this has been confirmed in tests.

Net perimeter

The net perimeter is an essential structural pathway to transfer loads from the net panel to the net attachment points. Its strength contributes greatly to the overall performance of the net. When a net is knotted on a loom, the longitudinal edges are formed by continuous (usually double-) mesh strands and are stable. When the net is cut to size, however, the edges formed by cutting across the net need to be stabilized to prevent the exposed knots from unravelling; this is usually done by knotting an additional strand onto the cut edge. The finished knotted net panel, therefore, has at least a double strand edge all around. On webnets, the perimeter is formed by the outermost webbing strands.

Perimeter reinforcement

Because of the importance of the net perimeters in the transfer of loads from the net meshes to the net attachment points, the perimeters of high performance safety nets are invariably reinforced with ropes. These perimeter reinforcement ropes are threaded along the entire net periphery and are closed by splicing the ends of the ropes together. The ropes, together with the net panel perimeter, should be directly attached to the primary mine support elements (e.g.: props or rock anchors) to ensure maximum load transfer.

All reinforcement ropes used by Norsenet are 'Danlines', proprietary high strength ropes constructed of two different polymer fibres: polyester (PET) and polypropylene (PP). Danlines come in a range of sizes, but the 10 mm and 12 mm diameter ropes are commonly used to reinforce mine safety nets.

Mesh reinforcement

The net mesh is the largest component, by area, to be exposed to the initial impact of a falling rock. To enhance the net's resilience against this impact force, the mesh is often reinforced with ropes, threaded across the net and fastened at both ends to the perimeter rope, preferably at the net attachment points. The formation of smaller area compartments (i.e., fully supported cells) in the net panel as a result of inserting reinforcement ropes serves two main purposes:

- The internal reinforcement ropes are likely to intercept, at least partially, a large mass of rock falling onto the net. A large portion of the impact load is, therefore, transferred by the internal ropes to the perimeter, or, preferably, directly to the net attachment points, reducing the stress on the net mesh.
- The main impact force of the rock spreads only to the nearest reinforcement and perimeter ropes which transfer it to the net attachment points, rather than across the entire mesh panel. This reduction in the cell size results in a marked reduction in net sag, an important safety factor in low mining excavations.

Two different configurations of internal reinforcement ropes are used: orthogonal ropes which run across the mesh from one perimeter rope to the opposite perimeter rope, i.e., they run parallel to the net edges (Figure 2a); and diagonal ropes, which, as the name implies, run diagonally across the mesh (Figure 2b). Reinforcement ropes which terminate at other ropes, with no direct connection to a solid net attachment point, merely transfer loads to those ropes; such 'floating' ropes are of limited effectiveness. It is best practice, therefore, to terminate internal reinforcement ropes at primary support units, such as props or rock anchors, so that they can transfer loads directly into these units.

Reinforcement rope tie-in

The main purpose of the safety net reinforcement ropes is to absorb a portion of the impact load and to help transfer that shared load, ultimately, to the net attachment points on the mine support units. The optimization of this load sharing and transfer duty requires a load-binding connection between the rope and the net mesh.

Reinforcement ropes which are threaded into the net mesh (i.e.: alternating above and below the net from mesh to adjacent mesh) can effectively absorb loads at right angles to the direction of the rope, but fail to do so with obliquely applied loads, or loads in the direction of the run of the rope. In order to make a load-binding connection from the rope to the net mesh, which allows oblique and in-line forces to be transferred, the rope is physically tied to the net mesh by means of (4 mm) nylon braids. This tight, wrapped and knotted connection is so effective in practice, that even upon failure of the reinforcement rope, the nylon tie-braids continue to carry substantial reinforcement loads. Tests have shown conclusively that the tie-in of internal reinforcement ropes (i.e., diagonal and orthogonal mesh reinforcement ropes) is imperative, whereas the tie-in of perimeter reinforcement ropes is less critical to net performance.

Net attachment points

Most of the energy of a fallen rock, which has been arrested by a mine safety net, must, ultimately, be dissipated safely, via the primary support units, into the mining excavation's rock mass. The load transfer from the safety net to the mine support unit is, therefore, of critical importance; this task is performed by the attachment loops (or points) of the net. Dedicated attachment loops are provided at each corner of a safety net; large nets, however, need to be suspended along their sides as well. The number of attachment points and their distances along the sides of the net are usually determined by the spacing of the primary support units in the mining excavation; these dimensions typically range between 1.5 m and 3 m. If the net is fitted with internal reinforcement ropes, it is best practice to terminate these ropes at those net attachment points on mine support units (Figure 2a: side compound attachment point).

As was pointed out earlier, each high performance safety net is fitted with a perimeter reinforcement rope. The rope forms a closed loop around the entire periphery of the net and a large portion of the forces exerted on the net by a falling rock is transferred from the net to the perimeter rope and along the rope to the attachment points. To ensure that the loads are transferred fully from the rope to the mine support unit, it is crucial that the perimeter rope is attached directly to the support unit. With simple corner attachment loops, such as those shown in Figure 2a, this is done by hooking the loop onto a prop's headboard hook, or attaching it to the washer of a rock anchor by means of a suitably dimensioned S-hook. When attachment points coincide with reinforcement rope terminations (Figure 2: compound attachment points or loops), as is best practice, both, the perimeter rope and the reinforcement rope termination loop should be hooked to the mine support unit. Along net edges without reinforcement rope terminations, the perimeter reinforcement rope should be hooked to the mine support unit by itself.

Some mine safety nets are fitted with chain links at the attachment points, usually as a special request of a client. At the attachment loops or points, the perimeter rope is threaded through the chain link and that chain link is then hooked onto the mine support unit. Chain links have no effect on net performance; they act merely as flexible extensions of the support units' steel hooks and add no strength to the net attachment loops or points.

Safety net performance

A mine safety net is designed for a site- and application-specific duty; as such, its performance criteria are defined by specifications issued by a mine's rock engineering department. Since, in general, a net should be able to safely arrest a falling rock mass with the least possible deformation (sag), a minimum performance specification will normally encompass a maximum load bearing capacity of the net, as well as the largest acceptable deformation of the net at the maximum sustained load. Since the sag of a safety net is strongly correlated with the density of mine support units (i.e., the smallest possible size of a fully supported net cell), rock engineers should, from the outset, consider the use of safety nets in their support planning. This is particularly important in low stoping width environments.

Minimum performance specifications

The size of the largest rock likely to fall from the hangingwall at a particular location, i.e., the maximum static net loading expected at that place, will be determined by the responsible rock engineer, who will use his expertise and knowledge of the site for this estimate; that largest likely mass will then be multiplied with the applicable safety factor. In addition to the maximum static load, the dynamic load of the falling rock will also have to be determined; that will depend on the free fall distance of the rock into the net. Furthermore, additional dynamic loads may apply under seismic conditions, when rocks may be ejected from the rock face at velocities higher than the mere gravitational acceleration. All of these load factors are conveniently expressed in terms of the maximum kinetic energy (KE, [kJ]), a net needs to safely absorb and dissipate into the mine support units.

In addition to the load bearing capacity of a safety net, its deformation under that maximum load will also have to be considered. It stands to reason, that a safety net installed in a production stope of, say, 1.2 m stoping width, cannot be allowed to sag by 0.7 m in the event of a rockfall; that would provide little protection to miners caught under that rock. In a 3 m high development end, however, a maximum sag of 1 m may well be acceptable. In terms of practical net design, the acceptable deformation under load is an important issue, as it may afford more choices for net configurations and, therefore, may result in more cost-effective solutions.

A further aspect of safety net performance, which should be considered when reviewing test results and drafting specifications, is the actual free-fall distance of rocks in the planned installations. In typical safety net applications, the overhead net is installed as close to the hangingwall, as possible, usually between about 10 cm and 30 cm from the hangingwall. That distance reduces the dynamic load on the net by a falling rock significantly, when compared to the net's full load capacity. In many applications, therefore, it is only the lower end of the graph, up to about 0.5 m (Savuka) drop height (i.e. 2.21 kJ), which is required in practice.

Factors governing safety net performance

In the previous section on mine safety net design, a number of structural elements were described, which together constitute the configuration of a typical mine safety net. Each element by itself contributes a specific aspect to the net's performance, but the unique balance of the entire assembly, too, shapes the performance profile of each unit. Considering the number of individual factors and their many possible combinations, it becomes clear that even the approximately 200 tests conducted at Savuka, including duplicates, covered only a portion of the possible permutations. Nevertheless, by judiciously pursuing successful design directions and quickly abandoning unsuccessful dead ends, Norsenet utilized those tests to develop a good understanding of the factors governing mine safety net performance; those factors will be discussed in the following sub-sections. It is understood that in the comparative graphs below, all test variables, apart from the compared parameters, were kept constant, unless otherwise stated.

Mesh strand size

Figure 3 shows the effect of the safety net mesh braid size on net performance, as measured at the Savuka test facility.

Figure 3 compares the performances of nets with 4 mm, 6 mm and 8 mm HDPE mesh braids. Apart from the braid size, all other net parameters are identical: all have tied-in 10 mm Danline perimeters and diagonals. The curves all go according to expected form, with the 4 mm nets' maximum kinetic energy absorbtion at 2.21 kJ, the 6 mm nets' at 3.09 kJ and the 8 mm nets' at 5.74 kJ. It can also be seen that the nets become stiffer with increasingly stronger braid size, i.e., the heavier nets show less sag under load. Note the onset of serious net damage on the 6 mm braid net at 2.65 kJ, followed by a large increase in sag and failure after 3.09 kJ.

Mesh size

Figure 4 shows the effect of the safety net mesh size on net performance, as measured at the Savuka test facility.

Figure 4 compares knotted 8 mm HDPE braid nets with mesh sizes of 75 mm, 100 mm, and 125 mm, respectively; the 125 mm mesh net's reinforcement ropes were not tied in. According to form, the 125 mm mesh samples were substantially weaker than the heavier nets (3.97 kJ KE), both, because of the lighter mesh and because of the untied ropes.

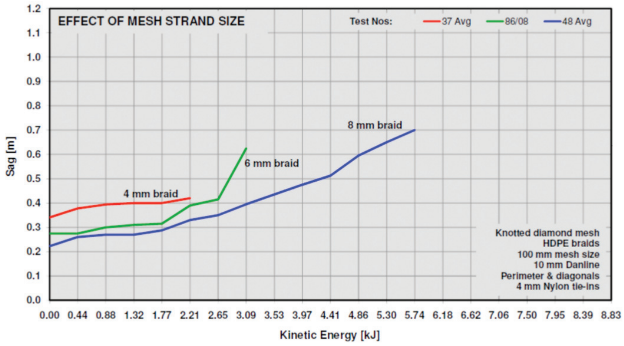

Figure 3—Effect of mesh strand size on safety net performance. Savuka test results

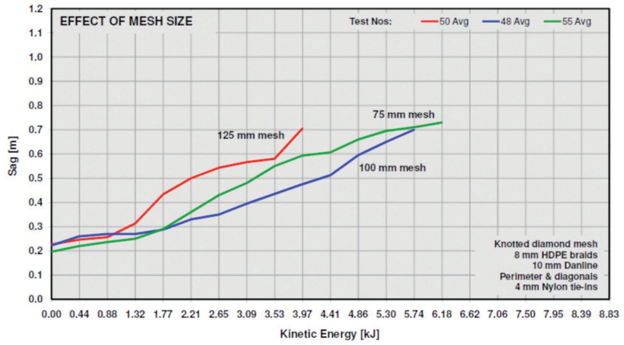

Figure 4—Effect of mesh size on safety net performance. Savuka test results

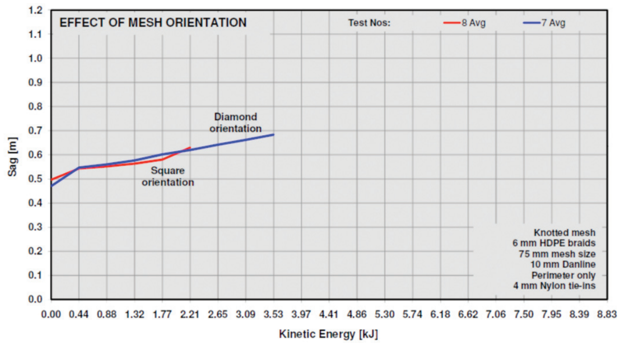

Figure 5—Effect of mesh orientation on safety net performance. Savuka test results

Similarly according to form, the 100 mm mesh samples averaged a maximum KE level of 5.74 kJ and the 75 mm mesh samples reached a maximum KE of 6.18 kJ, as expected, the strongest nets. The fact that over two thirds of the test run the heavier 75 mm mesh samples showed higher sag (softer response) than their 100 mm counterparts is consistent with their higher energy absorbtion capacity; this is substantiated by the fact that the 100 mm samples showed substantial damage to their net meshes, whereas the 75 mm net meshes remained undamaged in the test runs.

Figure 4 also illustrates the effects of the diagonal reinforcement ropes and their fitting into the net structure: up to 0.88 kJ (20 cm drop height), all samples' diagonals were intact. It should be remembered that all of the samples' diagonals were identical, the only difference between batches being that the 75 mm and 100 mm mesh samples' diagonals were tied to the net mesh with nylon braid, whereas the 125 mm samples' diagonals were not tied into the meshes.

After the 0.88 kJ KE point, the 125 mm mesh samples' diagonals began to fail gradually, a process that took about two more drops, up to 1.77 kJ to complete. With the tied samples, the onset of diagonal failure was delayed to 1.32 kJ and even then failure was much more gradual, barely noticeable with the 100 mm mesh samples and more pronounced with the 75 mm meshes because of the greater difference in mesh elasticity relative to rope stiffness. Once more, the aspects of reinforcement rope tie-in will be addressed in more detail later.

Mesh orientation

Figure 5 shows the effect of the safety net mesh orientation on net performance, as measured at the Savuka test facility.

Figure 5 illustrates the effect of 'square' versus 'diamond' orientation of the net mesh on performance. It can be seen that in terms of energy absorbtion capacity the diamond mesh (KE 3.53 kJ) is substantially stronger than its square counterpart (KE 2.21 kJ). This effect is particularly noticeable on square nets, such as those illustrated in Figure 2 above. The effect is explained by the partial direct load transfer from the net mesh to the corner attachment points in the 'diamond' net configuration, along the diagonal net strands. The 'square' orientated net mesh transfers loads mainly to the perimeter rope, with a much diminished direct load transfer into the attachment points. Apart from the different energy absorbtion capacities of the two nets, their deformation behaviour is virtually identical.

Mesh strand type

Figure 6 shows the effect of the safety net mesh strand type on net performance, as measured at the Savuka test facility.

Figure 6 compares the three mesh strand types, i.e.: braid, twisted twine and webbing. Since these strand types are so different in their behaviour and applications, one is really comparing three different net types. All of these nets were fitted with perimeter and diagonal reinforcement: 10 mm Danline tied-in rope on the knotted nets and sewn webbing on the webnet.

The 'twine' knotted net panel consists of 24 ply twisted HDPE twine, a lightweight strand, making this type of net a cost-effective alternative for low-performance duty, such as conveyor belt side protective netting. At 2.21 kJ KE absorbtion capacity, it is, however, not a weak net; note that at 1.77 kJ, diagonal failure set in, quickly resulting in mesh failure after 2.21 kJ.

In comparison, the other two nets are substantially stronger, both reaching 4.86 kJ KE absorbtion. The 8 mm HDPE braid knotted net is marginally softer than the web-net, but compares well, particularly in terms of cost. The web-net is a fully sewn construction of 4 t tensile strength polyester (PET) webbing. It can be seen that this net is substantially stiffer than the 8 mm knotted net, a quality which may be important in very low mining excavations. Note the diagonal webbing failure between about 3 kJ and 4 kJ; beyond that, these nets tend to fail near the corner attachment loops.

Reinforcement rope configuration

Figure 7 shows the effect of the safety net reinforcement rope configuration on net performance, as measured at the Savuka test facility.

Figure 7 shows the effect of various reinforcement rope configurations on the 8 mm HDPE braid, 100 mm mesh nets; none of ropes were tied into the net mesh.

In the graph, the '25 Avg' batch with no reinforcement ropes sets a low benchmark for comparison; still the nets reached an average energy absorbtion of 2.21 kJ, failing at, or near, the attachment point perimeters.

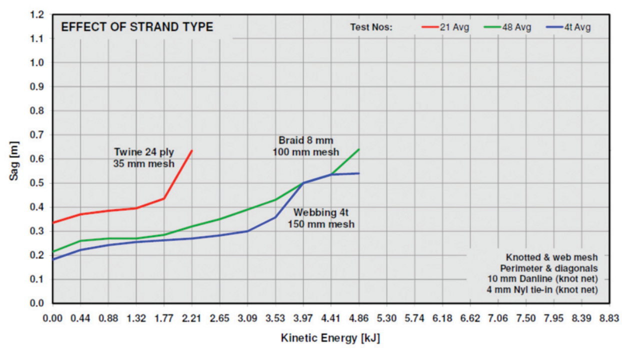

Figure 6—Effect of mesh strand type on safety net performance. Savuka test results

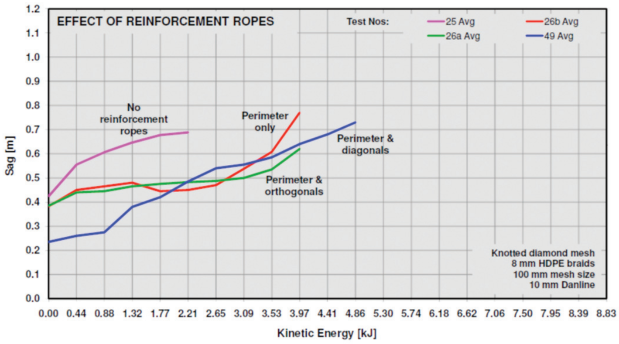

Figure 7—Effect of reinforcement rope configuration on safety net performance. Savuka test results

The addition of a loose 10 mm Danline perimeter rope substantially improves, both, the energy absorbtion capacity (KE 3.97 kJ) and the stiffness of the net, with the sag contained below 0.5 m for much of the curve.

The addition of 10 mm Danline orthogonal reinforcement ropes to the perimeter rope made almost no difference at all when compared to nets with loose perimeter ropes only; there was an improvement in sag over the last third of the curve, but the absorbed energy was identical at 3.97 kJ. This demonstrates the virtual ineffectiveness of 'floating' orthogonal reinforcement ropes terminating at perimeter ropes.

A real difference is made by diagonal ropes. The samples of batch '49 Avg' had loose diagonals added to their loose perimeter ropes; the entire curve is dramatically improved, starting at a much lower initial sag of about 23 cm, the nets ultimately absorbed 4.86 kJ of KE. Relative to the orthogonal rope samples, this was achieved at the minor increase of the cost of a 40% lengthening of the internal reinforcement ropes, and, of course, a different net layout.

It must be borne in mind, however, that orthogonal ropes do play an important role in net design. When they terminate at net attachment points, orthogonal ropes perform like properly attached diagonals, only in a different direction. Sometimes, even 'floating' orthogonal ropes play a role, even if they terminate in perimeter ropes: they reduce the exposed mesh area, creating smaller mesh cells, similar in effect to a secondary overlay net of larger mesh size.

Reinforcement rope tie-in

Figure 8 shows the effect of the safety net reinforcement rope tie-in on net performance, as measured at the Savuka test facility.

Figure 8 shows the effect of fastening reinforcement ropes to the net panel; at Norsenet this is done using 4 mm nylon braid. This tie-in is very strong: in Savuka tests it was frequently observed that even after a Danline rope had failed, the nylon ties kept the tendon functional for one or two more drop episodes. The more important function of tie-ins, however, is the transfer of load from the net to the reinforcement ropes, and vice versa, thereby forming a stronger net structure by mutual reinforcement.

This effect is particularly strong with diagonals. In the graph, batches '49 Avg' (loose diagonals) and '48 Avg' (tied diagonals) are compared: up to 0.88 kJ, the diagonals are undamaged and the nets behave identically. Then, the loose diagonals sustain initial damage, and as they have no 'back-up' from the net or the nylon ties, they fail very quickly and no longer contribute to the net strength. The tied diagonals, on the other hand, are much tougher: not only is the onset of diagonal failure delayed because of the added strength of the net mesh, but so too, is the onset of mesh failure delayed because of the added strength of the diagonals.

Looking at the perimeter rope tie-in, however, it is evident that there is only a marginal improvement in sag for the tied-in perimeter reinforcement ropes.

Safety net applications

Mine safety nets are generally used to protect personnel from falling rocks in temporarily supported development ends, stopes, advance strike gullies, and as part of permanent tunnel support systems, including tunnel sidewalls. Other applications include production stope face nets in rockburst prone areas and as protective netting along conveyor belts. All of these diverse applications require specific types of nets, and pose specific challenges in their installation and maintenance underground.

Because of the highly site- and application-specific nature of safety net installations, only a typical installation will be described, along with some important installation principles and lessons learnt underground.

Typical safety net installation

Figures 9 and 10 show a typical board-and-pillar hangingwall safety net installation underground. Such nets are generally installed temporarily at the beginning of the shift and are taken down before blasting. The nets cover the hangingwall between the stope face and the first row of permanent support units at the rear.

Generally, hangingwall safety nets are installed from the rear edge of the net forwards towards the working face. At the outset, the net is laid out on the footwall in its correct position and the rear net edge is lifted up to the hangingwall where the attachment loops and net edge are suspended from the rock anchor washers by means of S-hooks or C-hooks. In

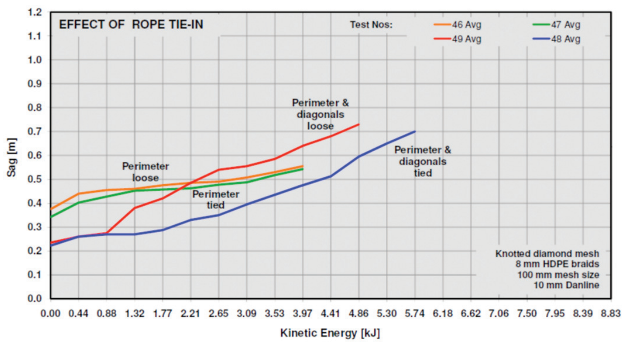

Figure 8—Effect of reinforcement rope tie-in on safety net performance. Savuka test results

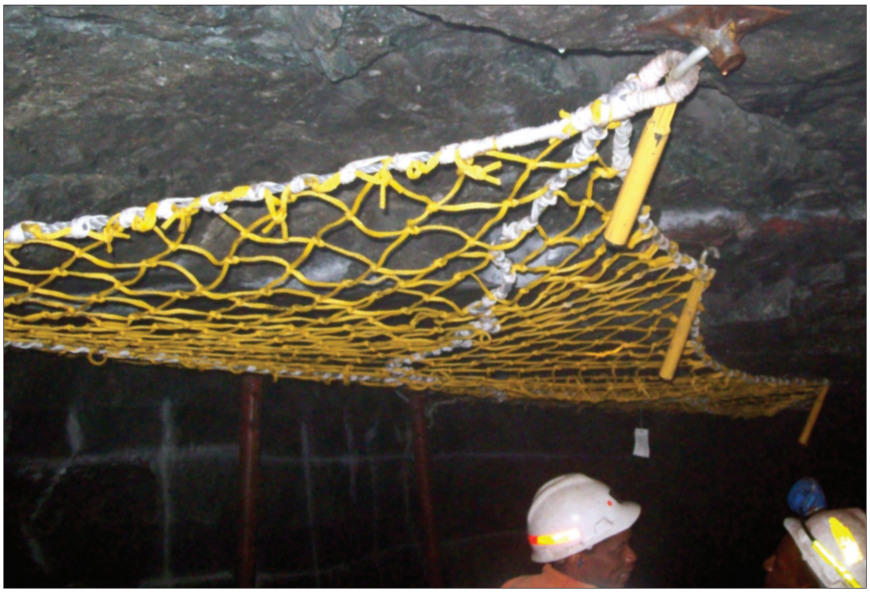

Figure 9—Typical stope hangingwall safety net installation showing the rear of the net suspended from rock anchor washers with 'Ezihook' C-hooks

Figure 10—The same installation as in Figure 9 showing the Camlok props clamping the net front edge against the hangingwall at the stope face

Figure 9, the rear of the net is shown with the corner attachment loops suspended with 'Ezihooks', proprietary C-hook installation accessories with extension handles. The net edge is similarly attached, as can be seen in the middle 'Ezihook' in Figure 9.

After the rear edge of the net has been suspended from the rock anchors at the back, the front net edge is lifted and attached to the hangingwall with mechanical props, usually Camloks. Where possible, it is recommended that the net should be attached to the props' headboard hooks. More often than not, however, the net is tensioned by hand and clamped against the hangingwall with the props' headboards. Figure 10 shows the front of the net clamped against the hangingwall in that fashion. As long as there is no danger of damaging the net in the process, this has proven to be an acceptable procedure.

Figure 11 shows two common accessories used for the installation of hangingwall nets. The first is an 'Ezihook', as described earlier. Note the correct attachment of the net perimeter reinforcement rope to the anchor washer. The second common accessory is a net tensioner: this accessory is often needed when the rear edge of the net cannot conveniently be attached to a nearby rock anchor; in that case, an anchor further towards the back needs to be used, requiring a stiff tensionable connection, as supplied by this accessory.

Figure 11—Two common installation accessories: 'Ezihook' remote C-hook at the left and net tensioner at the right

Alternative installation sequences in other mining situations

In the previous section, a typical safety net installation was described for a board-and-pillar mining situation. There are, however, a number of different mining situations, requiring different installation sequences, dictated by different support unit types and layouts. They are listed below and described in short point form, sorted according to specific mine support units. These instructions will be clear to those involved in safety net installations underground; they are the result of two years' installation experience at many different mines.

Props and roof bolts

- ➤ *Props with hooks*—net to props; then hook to bolt washers with tensioners.
- ➤ *Props without hooks*—net to bolt washers; then to props; then tensioning.

Props and elongates, no bolts

- ➤ *Net to props*—then tension to elongates.

Two lines of props

- ➤ *Net to front row of props*—then attach to second line of props, either directly or by reverse tensioner.

Stope face rockburst netting

Use Camloks or eyebolts, together with 'Spiralink' net connectors.

Tunnels

- ➤ *Bolts*—use 'Ezihook' extensions to bolt washers.
- ➤ *Props*—attach to two lines of Camlok props.

Net installation recommendations

Over the past two or three years, many safety net installations were performed and supervised by Norsenet and several audits were conducted of routine installations. From this field experience, as well as from extensive testing practice, a few important installation requirements have emerged; they are listed below. These requirements do not include basic safety rules and regulations—these are considered as given and should, of course, always apply.

- ➤ Always inspect safety nets before installation. Look for broken or severely abraded strands and ropes, holes in the mesh, as well as broken or missing reinforcement ropes. Replace damaged nets, according to the mine's safety standards.
- ➤ Strictly follow the manufacturer's and the mine's installation procedures.
- ➤ Always use the net of the right size for the installation; do not improvise by bunching or rolling up parts of the net to make it fit the area.
- ➤ Under no circumstances cut or trim a safety net to size, thereby destroying the net's load bearing and load transfer ability. Do not forcibly modify the net in any way.
- ➤ Always attach a safety net by its attachment loops and/or by the perimeter rope. Do not attach a net by its mesh strands—they are too weak and will break in the event of a rockfall.
- ➤ Whenever possible, attach a net by its attachment loop or the perimeter rope to the steel hook of a mechanical prop. When this is not possible, make sure that the net is not damaged by sharp rock edges, when clamping it against the hangingwall.
- ➤ Always install a net as close as possible to the hangingwall; this reduces the free-fall distance of rocks, and with that, the dynamic loads on the net.
- ➤ Do not install nets on loose or unstable mine support units—they will not carry the load in the event of a rockfall. Make sure of a sound and secure attachment connection.
- ➤ Do not use undersized or damaged S-hooks or C-hooks to attach the net to the mine support units. Do not tie the net to a support unit by means of a knotted rope.
- ➤ After taking the net down, store it in a safe place; do not tread on it or place heavy equipment on the net.

Work in progress

With the uncertain future of the SIMRAC Savuka test facility, Norsenet decided to establish its own state-of-the-art testing facility at the factory in Vredenburg. The facility will have a hydraulic actuator and will allow the testing of nets up to 4 m × 4 m in size to destruction. It will be fully instrumented, computer controlled, and will produce load-deformation curves of the nets in test. The test rig will also allow impact drop tests, identical to those done at Savuka, in order to assess the dynamic loading behaviour of future safety net designs.