School of Mining Engineering

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

# A HOLISTIC APPROACH TO THE DESIGN OF TWO TONNES TEMPORARY SUPPORT SYSTEMS (NETS, MECHANICAL PROPS, HOOKS AND ROOF BOLT FACE PLATES)

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science.

Johannesburg, 2024

# DECLARATION

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“In memory of my beloved grandmother Mohlago Chaisa Modika, whom I lost while conducting this study. I promised to carry the study to completion for you Koko”.

# ABSTRACT

In 2019, Thembelani Mine experienced a high number of injuries caused by Falls of Ground (FOGs) in the face area. To address this issue, safety nets with a capacity of two tonnes were urgently introduced. The two tonnes safety nets were intended to hold FOGs with a maximum mass of 1.78 tonnes, thereby providing a factor of safety of 1.1. However, in 2020 a FOG accident occurred during a drilling shift when a rock with a mass of 1.65 tonnes fell, leading to the death of an employee. The square headboard mechanical props with headboard dimensions of 130 mm x 130 mm, which were supposed to hold the safety net, were pulled out by the FOG, thereby allowing the safety net to collapse with the FOG. The slipping out of the square headboard mechanical props was due to a smaller headboard surface area of 130 mm x 130 mm in contact with hangingwall and a pretensioned load of 0.86 tonnes to 1.43 tonnes which could not sustain a falling rock with a mass of 1.65 tonnes. As a result, the square headboard props were immediately replaced with T-shaped Grease box mechanical props with average pretension load of 2.23 tonnes, larger and longer headboards of 370 mm x 100 mm to increase resistance to slipping out. The T-shaped Grease box mechanical props come with 16 mm flexible G-hooks attached to the headboards. The T-shaped Grease box mechanical props were tested at a drop test facility together with two tonnes Rock-stop safety nets and found to be able to hold two tonnes mass when installed at a standard spacing of 1.5 m x 1.5 m. This indicated that components of the temporary support systems other than the two tonnes Rock-stop safety net were not considered during the roll out. These components include 12 mm diameter flexible G-hooks, roof bolt face plates with a thickness of 4.5 mm, and square headboard mechanical props with welded 12 mm U-hooks and headboard dimensions of 130 mm x 130 mm.

Therefore, it was decided to conduct a study to test the temporary support systems holistically using installation scenarios as practiced at Thembelani Mine as opposed to testing each of the constituents of the systems individually. The aim of the tests was to assess if all components fulfil the requirements of the two tonnes temporary support systems from system test point of view.

While conducting the study, it was found that the safety nets were introduced without considering all aspects of the temporary support systems, such as safety net deflection parameters, hooks, mechanical props, and roof bolt face plates. Moreover, it is necessary to maintain a safe working height within a specific stoping width, which is the vertical distance between the footwall and the safety net in the hangingwall after holding a falling rock. This is to ensure that the employee underneath the net does not get struck by the FOG which deflected with the safety net.

The study aimed to identify the items that did not meet the two tonnes systems' requirements and recommend improvements to ensure they function as expected. The study was conducted at available drop test facilities such as NCM and Videx, simulating the installation scenarios as practiced at Thembelani Mine.

The study revealed that the two tonnes Rock-stop safety nets, along with 6 mm face plates, 14 mm Carbon steel S-hooks, or 14.5 mm Spring steel G-hooks, fulfilled the requirements for the two tonnes systems. The two tonnes Rock-stop safety nets and T-shaped Grease box mechanical props with flexible 16 mm G-hooks also fulfilled the two tonnes' requirements. The study determined that the systems that fulfilled the two tonnes' requirements were effective for all stopes at Thembelani Mine with heights of 1.2 m and 1.4 m and flat excavation ends with a height of 3.2 m, with deflection limits of 0.35 m, 0.55 m and 1.3 m respectively.

In 2022, an alternative to the safety nets, the MINAX 80/3 Blast-on Mesh (BOM) with 8 mm blast-on cable, was introduced. The BOM underwent a similar study to the Rock-stop safety net, and the drop tests showed that the deflections obtained with the BOM in various scenarios as installed at Thembelani Mine were all above 0.35 m but less than 0.55 m. Hence, BOM can be used in stopes and flat excavations with heights of 1.4 m and 3.2 m, respectively.

# PUBLICATIONS AS PART OF THIS RESEARCH

No publications have emanated from this research yet.

# ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Sibanye-Stillwater SA PGM section for providing me with the time, resources and opportunity to conduct this study. I also want to give a special thanks to Mr Vusi Zulu the former Mine Manager at Thembelani Mine, who encouraged me to carry out this study for compliance with regulation 14.1.6 of the Mine Health and Safety Act 29 of 1996 in RSA. Furthermore, I would like to acknowledge the Thembelani Mine Rock Engineering team, along with its former members, who participated in the drop tests, conducted trials and rolled out the two tonnes temporary support system. Their dedication and hard work helped make this study a success. I am thankful to Mike Strong and Dane Bishop from M-props for providing props to be tested and assisting with technical knowledge of the mechanical props. Their assistance is truly appreciated throughout the study is truly appreciated. I would also like to express my gratitude to Billy Flanagan (Sales Manager at NCM) and Leon le Roux (Managing Director at Videx) for allowing me to conduct drop tests at their facilities. My project supervisor, Professor Nielen Van der Merwe deserves a special mention for providing me with guidance throughout the study. Lastly, I am grateful for the supervision provided by Doctor Mpoyi Jacques Kanda, who provided his valuable time and guidance in correcting the thesis following the examiners' reviews. His kind and passionate supervision restored my confidence and encouraged me to get back on track and conduct the required additional work.

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# LIST OF ABBREVIATIONS AND SYMBOLS

| Abbreviation | Description |
|---|---|
| ASG | Advance Strike Gully |
| BOM | Blast-on Mesh |
| FCGs | Full Column Grouted Tendons |
| FOG | Fall of Ground |
| FOS | Factor of Safety |
| HAZ | Heat Affected Zone |
| kJ | Killo Joules |
| MHSA | Mine Health and Safety Act |
| OEM | Original Equipment Manufacturer |
| PPE | Personal Protective Equipment |
| RDO | Rock Drill Operator |
| RSA | Republic of South Africa |
| SABS | South African Bureau of Standards |
| SA PGM | South African Platinum Group Metals |
| SIMRAC | Safety in Mines Research Advisory Committee |
| UG2 | Upper Group Two |
| UK | United Kingdom |
| UHTSSM | Ultra-High Tensile Strength Steel Mesh |

| Symbol | Description | Units |
|---|---|---|
| $F_i$ | Impact Force | kN |
| $F_t$ | Total Force | kN |
| $F_w$ | Weight | kN |
| $G$ | Gravitational Acceleration | m / $s^2$ |
| GPa | Giga Pascals | 1000 000 000 Pa |
| Kg | Kilogram | 1000 g |
| kN | Kilo Newtons | 1000 N |
| M | Metres | 1000 mm |
| Mm | Millimetres | 0.001 m |
| MPa | Mega Pascals | 1000 000 Pa |
| N | Newtons | Kg m / $s^2$ |
| Pa | Pascals | Kg m / $s^2$ / $m^2$ |
| T | Tonne | 1000 kg |
| $V$ | Velocity | m / s |

# 1 INTRODUCTION

In 2019, three fatalities occurred at Thembelani Mine due to falls of ground (FOGs). Two fatalities took place in the stope panel face area, while the other occurred on a haulage face area. In response, mine management launched a safety campaign to raise awareness among employees about the dangers of FOGs. The campaign included demonstrations and awareness sessions at mass meetings, as well as coaching sessions on measures to control and prevent FOGs. These sessions were conducted by supervisors, management, labour representatives and health and safety representatives in the underground workings. Due to this campaign, employees were able to identify and remove loose rocks from the workplace, thereby preventing potential FOGs from injuring them. As a result, employees were able to return to a safety-conscious mindset and avoid further FOG accidents. As a part of the campaign, the management together with the Rock Engineering department introduced safety nets with a capacity of two tonnes (generally referred to as two tonnes Rock-stop safety nets) as part of temporary support systems to hold FOGs caused by unidentified loose rocks in the face area. Despite the use of these safety nets, a tragic accident occurred in 2020 during a drilling shift when a mass of 1.65 tonnes (t) of rock fell, leading to the death of an employee. This prompted a study to examine the effectiveness of the temporary support systems implemented in the face area. This chapter aims to outline the following:

- Mine background and support standards for Thembelani Mine;
- The purpose of the study;
- Characteristics of FOGs at Thembelani Mine;
- Research background and context;
- Problem statement;
- Justification of research;
- Application of the engineering design to temporary support systems;
- Research objectives;
- Research methods;
- Source of data;
- Research validation; and
- Structure of the report.

## 1.1 Mine Background and Support Standards for Thembelani Mine

Thembelani Mine is a conventional narrow reef mine that is relatively shallow, with a depth of up to 936 m below the surface. It is a part of the Sibanye-Stillwater South African (SA) Platinum Group Metals (PGM) section. Figure 1-1 shows a map that indicates the location of Thembelani Mine relative to other Sibanye-Stillwater African mining operations.

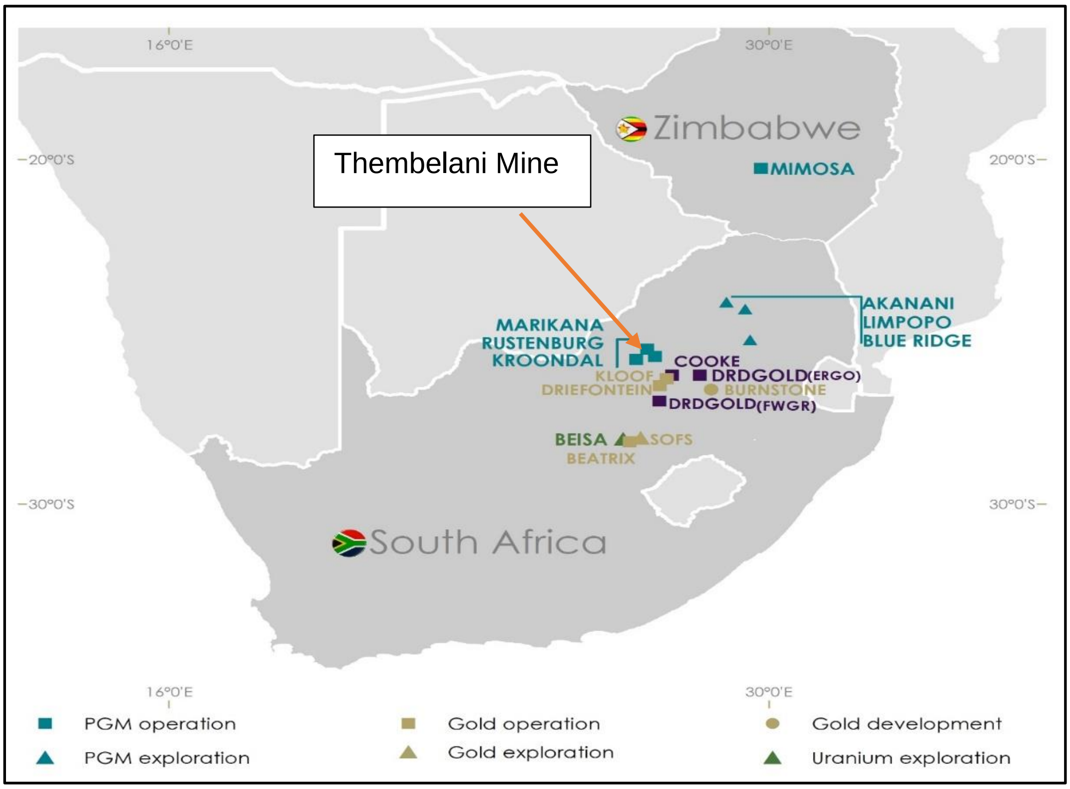



*Figure 1-1: Location of Thembelani Mine (Heera, 2024)*

Thembelani Mine is located in the Northwest Province of South Africa, to the east of Rustenburg town. Its latitude and longitude are 25°42' South and 27°20' East respectively, as shown in Figure 1-1. Thembelani Mine is part of Sibanye-Stillwater's Rustenburg section, which lies between the Kroondal and Marikana operations (Heera, 2024).

Thembelani Mine accesses two types of reefs namely Merensky and Upper Group 2 (UG2), through a vertical shaft and decline system for economic exploitation (Heera, 2024). Both reefs lie on a dip of 9° and are accessed using flat off-reef excavations such as haulages and crosscuts developed from the vertical shaft and decline system. Thembelani Mine uses conventional breast stope panels that advance outwards on strike from central gullies to extract the reef. The off-reef excavations have wider dimensions (3 m in width and 3.2 m in height) for easy access by both employees and machinery. However, a narrow stoping width of 1.2 to 1.4 m is used to extract the reef to minimize dilution from the surrounding waste rock. A typical layout that shows accesses and stoping excavations for Thembelani Mine is illustrated in Figure 1-2.

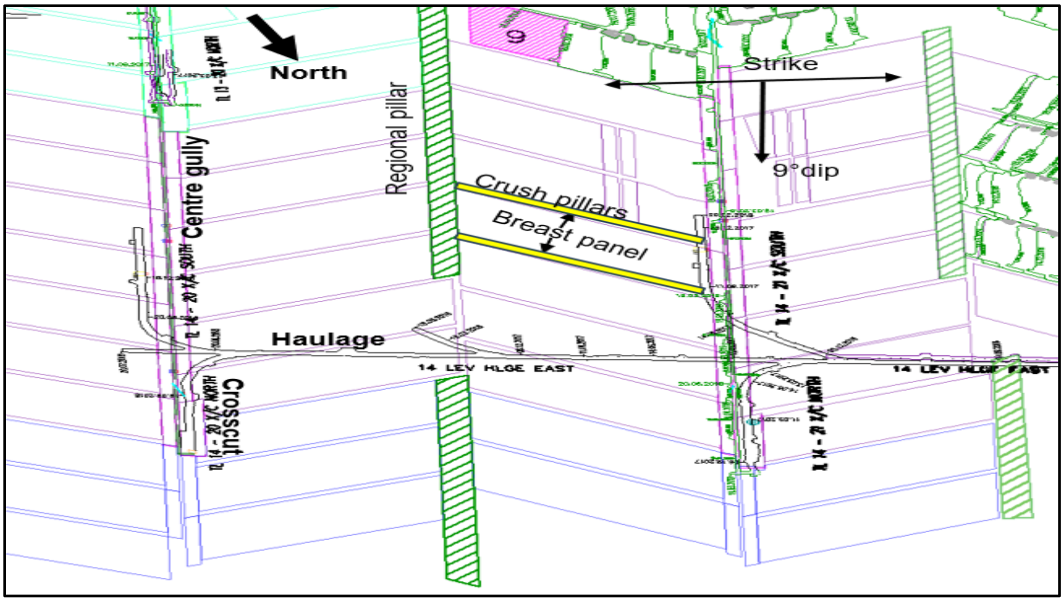



*Figure 1-2: Typical plan view of the accesses and stoping excavations for Thembelani Mine*

The diagram in Figure 1-2 shows various underground mining structures such as haulages, crosscuts, centre gullies and stope panels. The two reefs mined, namely the UG2 and Merensky, have a dip of 9° towards the northeast direction. The stope areas are supported by regional pillars, which are placed 200 m apart on strike. Multiple stope panels make up the stope areas. Crush pillars, spaced 32 m apart for UG2 reef and 35 m apart for the Merensky reef, support the area between the regional pillars. To ensure stability within a stope panel, artificial support such as grout packs, timber elongates, roof bolts, mechanical props, and safety nets are used. Different support standards are applied for stoping horizon and flat development excavations due to their size, shape and purpose. These standards are found in sections 1.1.1 and 1.1.2.

### 1.1.1 Stoping support standard

The stope support systems are designed to cater only to the localized ground conditions within a stope panel. Figure 1-3 shows a typical support layout for a stope panel at Thembelani Mine.

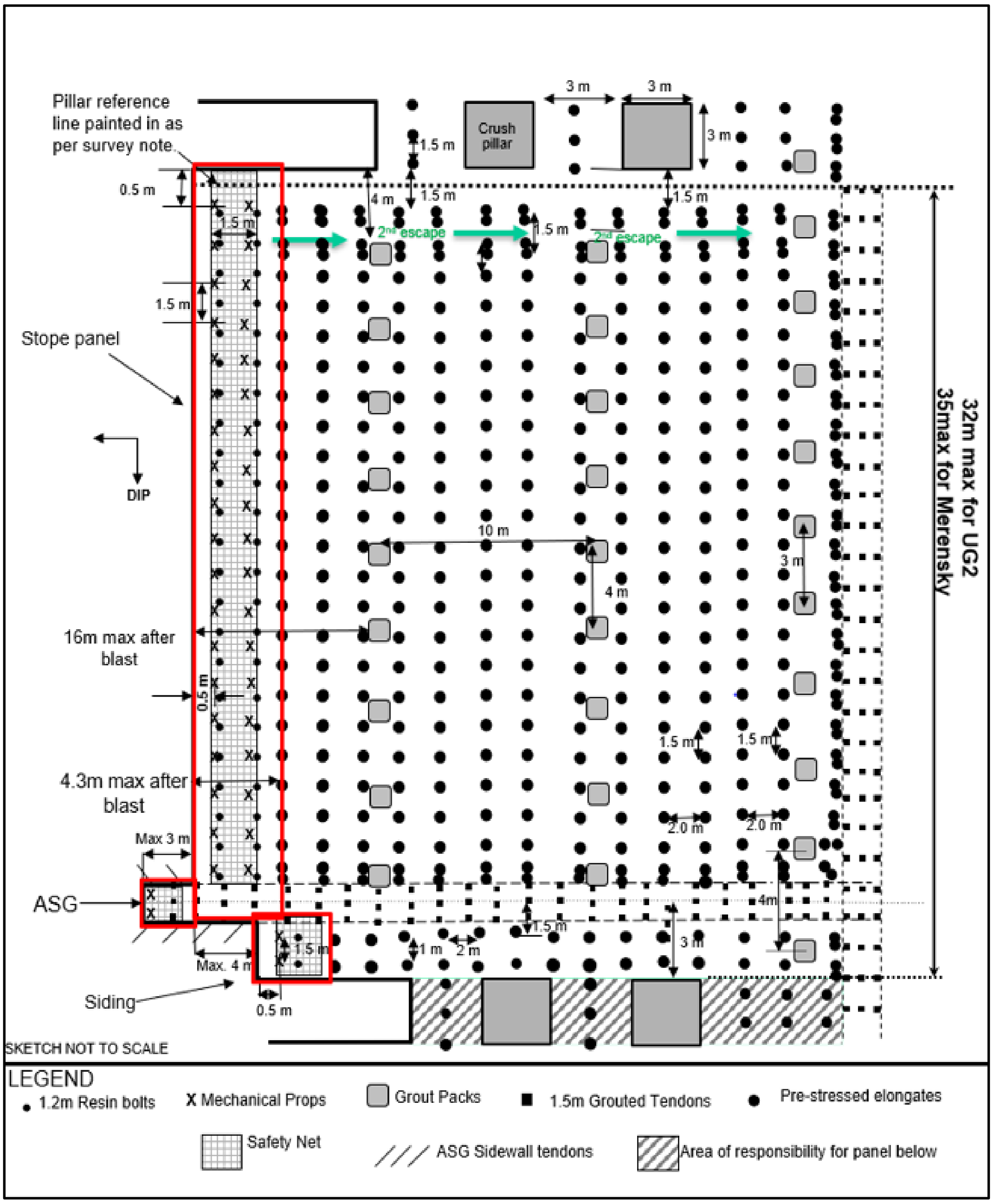



*Figure 1-3: Breast stope panel support layout for Thembelani Mine (Mutsvanga, 2018)*

In Figure 1-3, the face area of the stope panel, advance strike gully (ASG), and siding are highlighted. To support the face area, 1.2 m long Resin bolts, mechanical props, and safety nets are used in the stope panel and siding. The safety net is attached with hooks on mechanical props or roof bolts' face plates. Mechanical props are spaced 1.5 m x 1.5 m and are placed no more than 0.5 m from the face. Resin bolts are also installed at a spacing of 1.5 m x 1.5m and are placed no more than 0.2 m from the face before the blast.

In the ASG, the face area is supported with mechanical props and safety nets. Permanent support elements, such as pre-stressed timber elongates and grout packs, are installed at distances not exceeding 4.3 m and 16 m from the panel face, respectively. Full-column grouted tendons (FCGs) with a length of 1.5 m are installed in the ASG and centre gully at spacings of 1.5 m and 0.7 m along and across these excavations. Mechanical props and safety nets are installed only during the drilling shift when employees work on the face area. These support units are then removed at the end of the drilling shift before the blast.

After the blast, employees are prohibited from entering the panel and siding face areas, and only the ASG face is examined for the rigging of the scrapers. The cleaning process takes place with winch scrapers while employees are away from the face area.

### 1.1.2 Flat development excavation support standard

At Thembelani Mine, flat development excavations called haulages are created from the access shaft at a depth of 32 to 35 m below the reefs. These haulages are developed parallel to the strike of the reef and crosscuts are created from them to access the reef parallel to its dip. The dimensions of both crosscuts and haulages are typically 3 m wide and 3.2 m high. Drill rigs are used for drill production and support holes. FCGs with a length of 1.8 m are installed every 1.5 m across and 1.2 m along the excavations for permanent support. Temporary support is provided by safety nets and mechanical props. The flat off-reef excavation support layout is illustrated in Figure 1-4.

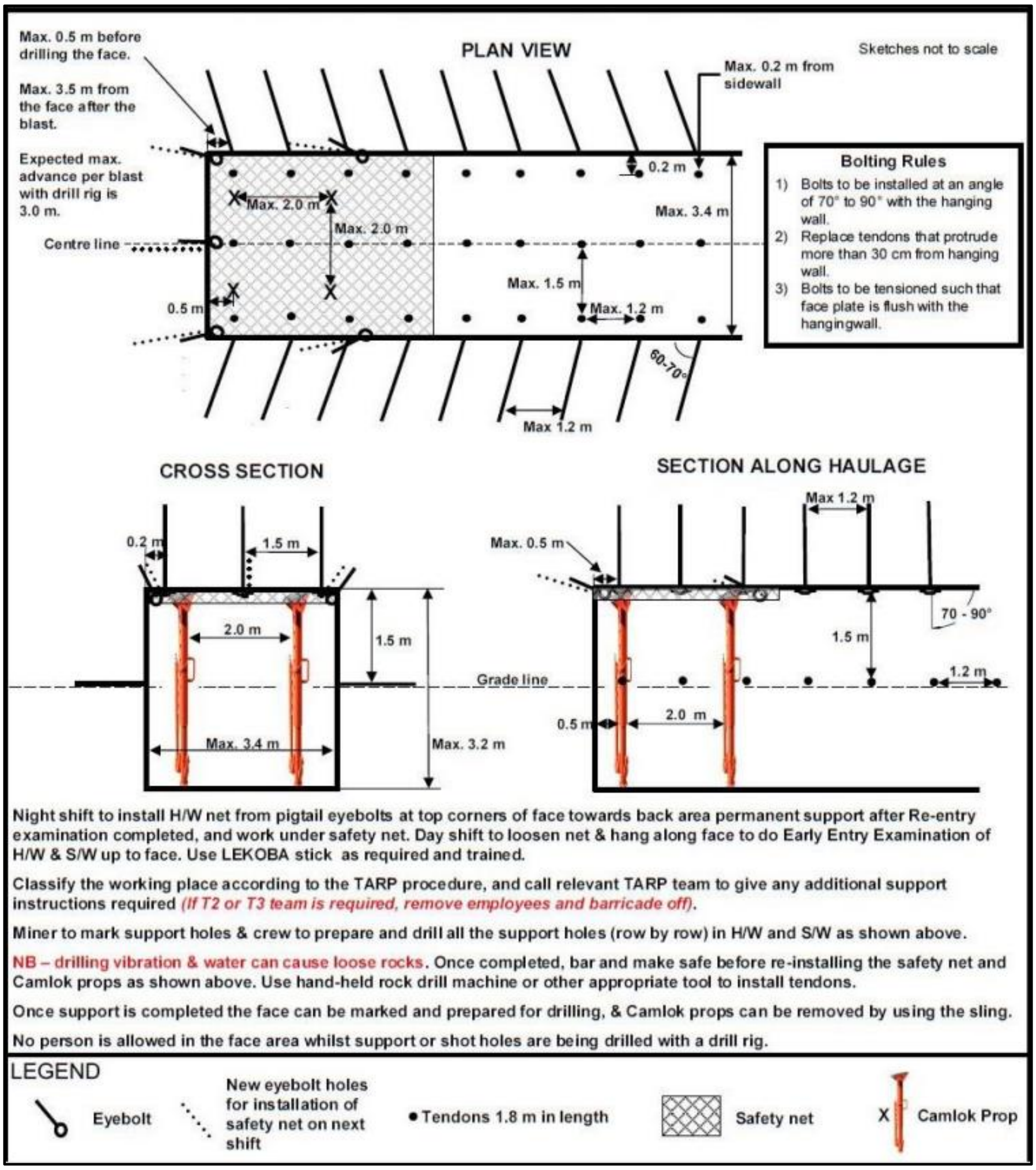



*Figure 1-4: Flat development excavations support standard for Thembelani Mine (Mutsvanga, 2018)*

Figure 1-4 depicts the installation of temporary support elements, such as safety nets and mechanical props, in the face area, which is the region between the face and FCGs installed within 3.5 m from the face after the blast. During the cleaning shift, loose rocks are removed by barring. Thereafter, three pigtail eyebolts are installed on the face at a spacing of 1.5 m across the excavation, closer to the hangingwall. Then, the safety net is attached with hooks to pigtail eye bolts and face plates of FCGs installed within 3.5 m from the face. After the safety net is installed, the cleaning operations are performed using mechanical loaders.

At the end of the cleaning shift, the installed safety net is not removed. When the drilling shift begins, the safety net is detached from the line of FCGs and hung downwards from pigtail eyebolts against the face. The face is then examined and secured by barring. After securing the face, a drill rig is used to drill support holes while everyone is away from the face area. The face area is then re-examined and secured again by means of barring. Thereafter, the safety net is reattached to the face plates on the last line of FCGs with hooks. This is followed by the installation of four mechanical props at a spacing of 2 m x 2 m apart at 0.5 m from the face. After that, the 1.8 m long FCGs are installed up to 0.5m from the face. Finally, the mechanical props are removed, allowing a double boom drill rig to drill the face.

### 1.2 Purpose of the Study

In 2019, Thembelani Mine experienced a high number of injuries caused by FOGs in the face area. To address this issue, safety nets with a capacity of two tonnes were urgently introduced. The two tonnes safety nets were intended to hold FOGs with a maximum mass of 1.78 tonnes, thereby providing a factor of safety of 1.1. However, in 2020 a FOG accident occurred during a drilling shift when a rock with a mass of 1.65 tonnes fell, leading to the death of an employee. The square headboard mechanical props with headboard dimensions of 130 mm x 130 mm, which were supposed to hold the safety net, were pulled out by the FOG, thereby allowing the safety net to collapse with the FOG. The pulling out of the square headboard mechanical props was due to a smaller headboard surface area of 130 mm x 130 mm in contact with hangingwall and a prestressing load of 0.86 tonnes to 1.43 tonnes which could not sustain a falling rock with a mass of 1.65 tonnes. This indicated that components of the temporary support systems other than the two tonnes Rock-stop safety net were not considered during the roll out. These components include 12 mm diameter flexible G-hooks, roof bolt face plates with a thickness of 4.5 mm, and square headboard mechanical props with welded 12 mm U-hooks and headboard dimensions of 130 mm x 130 mm. As a safety measure, the square headboard supports were replaced with T-shaped Grease box mechanical props that have an average pretension load of 2.23 tonnes. Additionally, the headboards were made larger and longer, measuring 370 mm x 100 mm, to increase resistance to slipping out. A flexible 16mm G-hook was also attached to the headboard.

To ensure that the newly introduced temporary support system meets the requirements of the two-tonne temporary support systems from a system test perspective, it was decided to conduct a study. The study will test the temporary support systems, using installation scenarios practiced at Thembelani Mine, rather than testing each component of the system separately.

### 1.3 Characteristics of FOGs at Thembelani Mine

According to Part C of the Guideline for Compilation of Mandatory Code of Practice to Combat Rockfall and Rock-burst Accidents for Tabular Metalliferous Mines, a FOG database is mandatory for every mine. This database must show a graphical representation of casualty and non-casualty incidents (Kotze et al., 2002). At Thembelani Mine, all FOGs are recorded on the dedicated FOG database in adherence to the guidelines. The FOG database is helpful for record-keeping and trend analysis, and it also assists in reviewing the support design. Figure 1-5 shows a five-year history of FOGs that occurred on stoping panel faces and flat development ends during the drilling shift at Thembelani Mine.

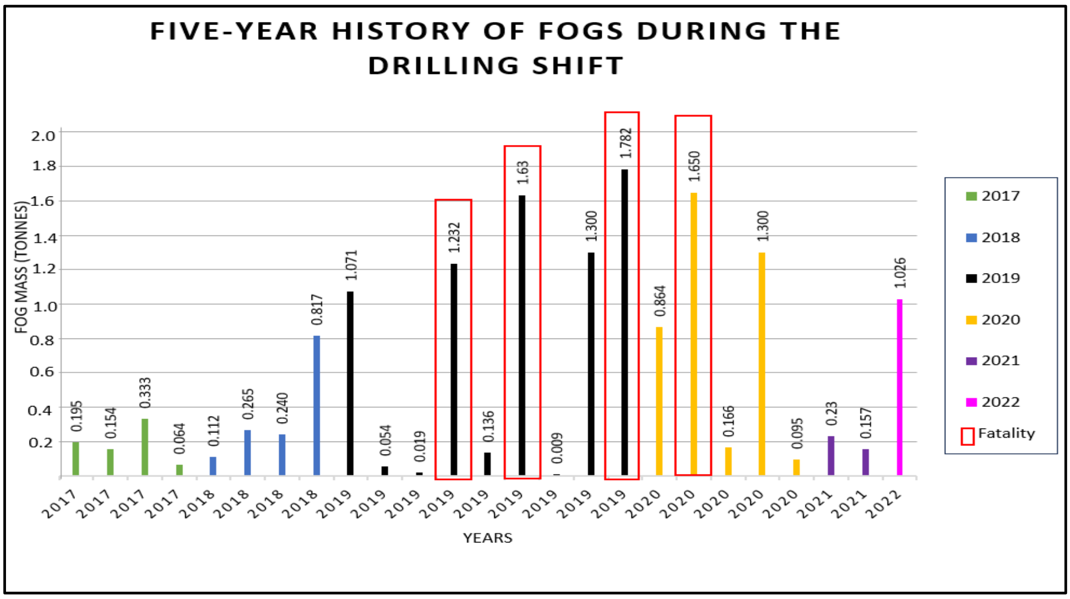



*Figure 1-5: FOGs which occurred during the drilling shift on the stope panel face and development ends from 2017 to 2022*

The graph in Figure 1-5 illustrates how the mass of FOGs increased from 0.33 t in 2017 to 1.78 t in 2019 but then decreased to 1.03 t in 2022. The three FOGs that caused fatalities in 2019 had masses of 1.23 t, 1.63 t, and 1.78 t, as highlighted in red. Two of the FOG fatalities (1.23 t and 1.63 t) occurred on the face of stope panels and one fatality (1.78 t) occurred on the face of a flat development excavation. These FOGs occurred when temporary support units were installed, and safety nets with a capacity of 450 kg were used in the stope panels and flat development excavations. However, it was found that the temporary support system failed, as its capacity was less than the mass of the FOGs. Based on this, two tonnes safety nets with a 1.1 Factor of Safety (FOS) were introduced. This rollout took place between November 2019 and February 2020.

The design of the two tonnes safety nets was done quickly address the occurrence of FOG fatalities. In March 2020, another FOG fatality occurred in a stope panel where the new support system had been installed. The FOG had a mass of 1.65 t, which was significantly smaller than the capacity of the two tonnes safety net. In this case the mechanical props slipped out and allowed the safety net to collapse with the FOG. The incident indicated that the temporary support system was not performing as expected. As a result, a study was conducted to assess the entire temporary support system. The investigation included the safety nets, mechanical props, safety net hooks and roof bolt face plates. The study aimed to identify items that did not fulfil the requirements of the two tonnes temporary support system. Improvements will be made to the system based on the study's findings to ensure that it performs as expected. Figure 1-6 shows the location where the 1.65 t FOG occurred.

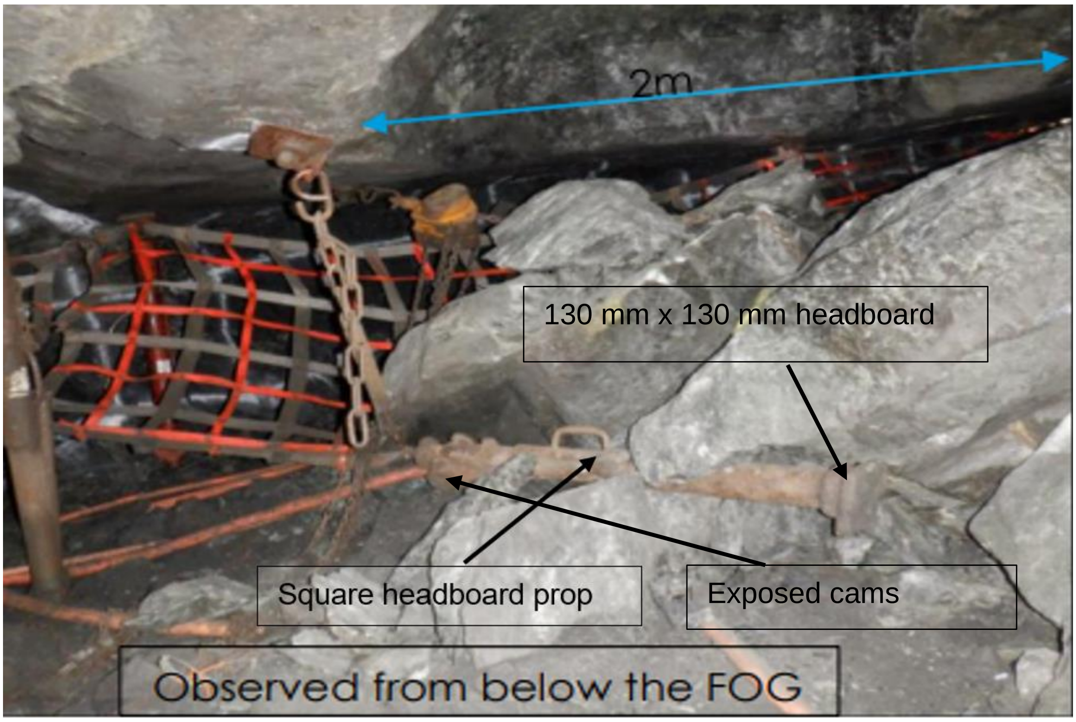



*Figure 1-6: The scene of the 1.65 tonnes FOG*

During the mining operation, a 1.65 t piece of rock fell and struck the Rock Drill Operator (RDO) while he was starting to drill the panel face. This happened after the safety checks and measures such as entry examination and safe declaration had already been taken. The FOG was 1.8 m long and 0.72 m wide with an average thickness of 0.39 m. The hangingwall Pyroxenite, which is the material of the FOG, has a density of 3258 kg/m³, from which the mass of the FOG was calculated. The square headboard mechanical props, which were supposed to hold the safety net, were pulled out by the FOG, causing it to hit the RDO. However, the two tonnes rock stop safety net remained intact and undamaged. The temporary support system was designed to hold a load of two tonnes, which offered a FOS of 1.2. Although other factors like poor barring practice also contributed to the incident, the temporary support system should have held the FOG since a FOS of more than one generally provides stability.

## 1.4 Research Background and Context

Between 2019 and 2020, there were four fatal incidents involving the collapse of temporary support systems during mining. This prompted a study to investigate the causes of temporary support system failure in holding FOGs, and improvements were subsequently made to the system. The improved temporary support system should be capable of holding FOGs weighing up to two tonnes.

The investigation revealed that the primary cause of the fatal incidents was the failure to identify loose rocks and remove them during the entry examination process. However, in all cases, the temporary support system was the last line of defence and subsequently collapsed.

The temporary support system at Thembelani Mine's stope panel face area initially comprised 450 kg capacity safety nets, 12 mm diameter G-hooks, roof bolt face plates with a thickness of 4.5 mm, and mechanical props with welded 12 mm diameter U-hooks. The square headboard props had headboard dimensions of 130 mm x 130 mm. On off-reef flat development excavations, 450 kg safety nets, 8 mm diameter S-hooks, and mechanical props with 12 mm diameter welded U-hooks were used. An example of the typical temporary support system used at Thembelani Mine before the introduction of the two tonnes temporary support system is indicated in Figure 1-7.

*Figure 1-7: Typical temporary support on a stope panel face area (Mutsvanga, 2018)*

In Figure 1-7, the safety net is installed on the hangingwall of a stope panel and hooked to the face plates of roof bolts and mechanical props. The mechanical props used in this configuration had welded C-hooks attached to square 130 mm x 130 mm headboards on which the nets were hooked.

Strong (2016) indicated that the square headboard mechanical props provided a pre-stressed load of 0.86 tonnes for old square headboard props (older than six months in use) and 1.43 tonnes for new square headboard props when input an force of 0.05 tonnes equivalent to installation with a hand in underground workings is applied. This gives an indication that the pre-stressing abilities of square headboard props decreased with time over which the prop is used. The loss of pre-stressing abilities over time resulting in pre-stressing load which are less than the FOG mass and poor installation of the props (prop installation at less than 90° to hangingwall and at a spacing of more than 1.5 m) contributed to slipping out of the props.

An analysis of the FOGs that caused fatalities between 2019 and 2020 was conducted to identify the major causes of the failure of the temporary support system. The onset of the system failure was categorized as follows:

- The flexible hooks attached to the face plates of roof bolts stretched open and allowed the rocks to fall with the safety nets;
- The welded hooks on mechanical props stretched open and allowed the rocks to fall with the safety nets;
- The safety net strands broke, and the FOG penetrated past it to the footwall;
- The safety nets deflected to the footwall and;
- The safety nets held to the hangingwall by square headboard mechanical props slipped out and fell with the rocks.

The temporary support system, comprising safety nets and mechanical props, was not able to hold FOGs ranging from 1.23 t to 1.78 t, which resulted in fatalities. These FOGs occurred between resin bolts in the stope face area and dislodged as a single slab bounded by geological features. An example of the FOGs that collapsed with a safety net is indicated in Figure 1-8.


*Figure 1-8: Typical rocks which fell with temporary support*

As shown in Figure 1-8, there was an incident where a FOG was caught by a safety net, but eventually fell when the net collapsed due to slipping out of mechanical props on the second line from the face. The safety net had a capacity of 450 kg and the mechanical props had a square headboard with 12 mm hooks welded on. The FOG occurred 0.2 m from the face between Resin bolts that were spaced 1.5 m apart on dip and 1.2 m apart on strike. This FOG weighed twice the capacity of the safety net, which was not able to hold it. Fortunately, an employee drilling on the face was able to escape with only minor injuries.

## 1.5 Problem Statement

The introduction of two tonnes safety nets to hold FOGs with a maximum mass of 1.78 tonnes was rushed due to the urgent need to prevent the high number of injuries that occurred at Thembelani Mine in 2019. This approach was taken because two tonnes safety nets are stronger than the heaviest FOG, which weighs 1.78 tonnes, providing a FOS of 1.1. However, this design did not consider all aspects of the temporary support system, such as safety net deflection parameters, hooks, mechanical props, and roof bolts' face plates. Even though the safety net can hold a FOG up to two tonnes, it should not deflect excessively, posing a risk to mine employees. This means that there needs to be a safe working height within a specific stoping width, which is the vertical distance between the footwall and the safety net in the hangingwall after holding a falling rock. For normal ground conditions, the safe working height should account for a stoping width of 1.2 m, while higher areas in adverse ground conditions require a stoping width of 1.4 m, and flat development excavations require a stoping width of 3.2 m. This study aims to identify which items do not fulfil the two tonnes system and apply improvements for the system to perform as expected.

### 1.6 Justification for Research

According to Regulation 14.1(6) in chapter 14 of part 2 of the Mine Health and Safety Act (MHSA) 29 of 1996 in the Republic of South Africa (RSA), it is the employer's responsibility to ensure that the support products used in a mine are suitable for the ground conditions specific to that mine. Chapter 2 of this act also indicates that manufacturers and suppliers of products and equipment to the mine must ensure that their products do not pose health and safety risks to the employees (Department of Mineral Resource and Energy (DMRE), 2018). As a result, a mine must provide proper specifications to the supplier to ensure that the products supplied are fit for purpose.

In accordance with regulation 14.1(6), management identified that the temporary support system on the face area did not adequately cater to the potential fall-of-ground (FOG) risks that caused fatalities in 2019. The temporary support system was not strong enough to handle the three FOGs that occurred. Therefore, management provided the supplier with specifications to supply two tonnes capacity safety nets to address the FOG fatalities. These actions were necessary and appropriate since the problem was identified, and solutions were given.

However, in 2020, a FOG with a mass of 1.65 t collapsed with the temporary support installed in the face area, indicating that the temporary support was not performing as expected. On this basis, it was discovered that the decision to introduce the two tonnes safety nets was rushed and did not consider all aspects that could have led to the temporary support failure.

## 1.7 Application of the Engineering Design to Temporary Support Systems

To ensure an effective engineering design, it is essential to follow an iterative step-by-step process. The process should aim to achieve well-stated objectives while keeping in mind the cost, safety, and ergonomics. The design should be based on the application of basic mathematics, engineering mathematics, and basic science principles to meet the objectives. It is also crucial to consider environmental and legal implications while designing. The design must follow a risk-based approach, in line with corporate policies set as per international standards (Stacey, 2023). In the context of this study, legal implications align with the MHSA 29 of 1996. Figure 1-9 illustrates Stacey's ten-step engineering wheel of design.

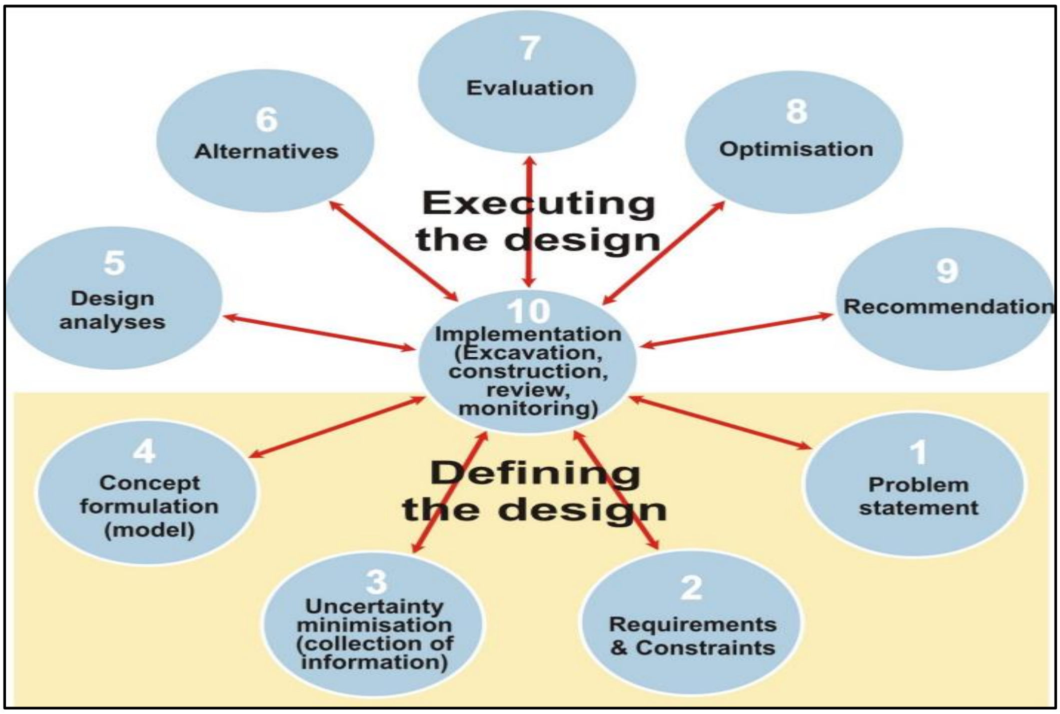



*Figure 1-9: 10-step engineering wheel of design (Stacey, 2009)*

The design process can be divided into two main phases: defining the design and executing it. During the defining phase, it is important to identify and clearly state the problem, list requirements and constraint and gather significant data to minimize uncertainty. The more data you have, the less conservative your design needs to be. Once these steps are completed, you can formulate a concept. The next phase is executing the design, during which you analyse the design, consider alternatives, evaluate options, apply optimization, and make recommendations. At the centre of the design process is implementation, where you construct the design, monitor its progress, and continuously improve through reviews. It is important to note that the process is iterative, as indicated by the arrows pointing inwards and outwards from the centre of the wheel (Stacey, 2023). Figure 1-10 provides an example of a successful engineering project across multiple stages of the design process.

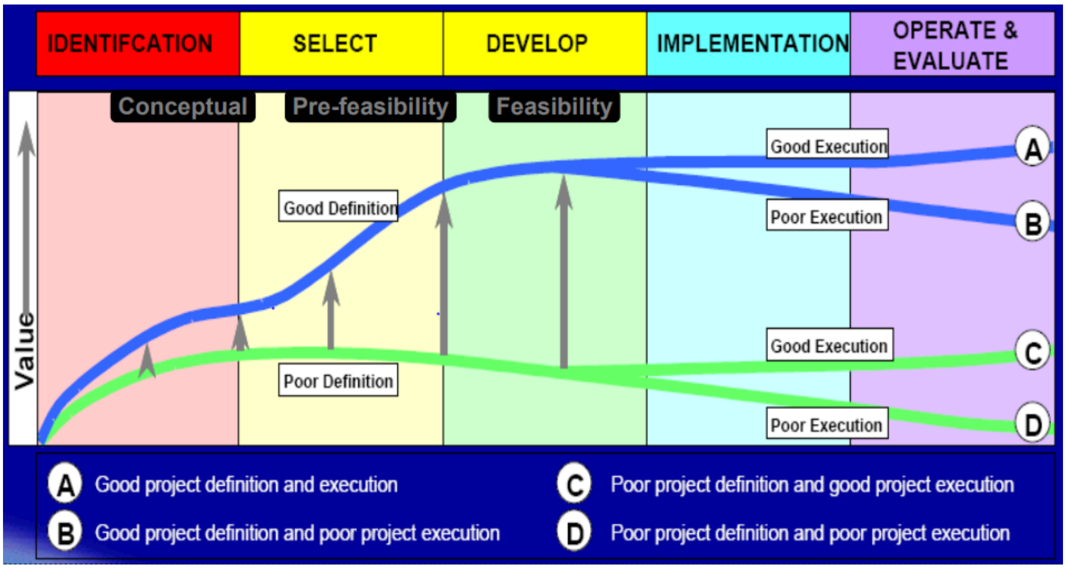



*Figure 1-10: Engineering project value versus design stages (Stacey, 2023)*

Figure 1-10 shows the importance of problem definition and execution in project management. According to Stacey (2023), good problem definition adds greater value to a project and should not be overlooked. Figure 1-10 indicates the impact that poor problem definition and execution can have on the value of a project. It shows that a good problem definition and execution can result in a higher value of the project, whereas poor execution may result in a slight drop in value. However, poor problem definition can lead to a significant drop in value, as shown by lines C and D in the text. Line C provides a higher value than Line D due to good execution for C. Therefore, it is essential to spend more time defining the problem to set the project up for success.

When two tonnes safety nets were rolled out, only the strength of the safety nets was considered, and other elements contributing towards face area support systems were not assessed. This indicates poor problem definition as the constraints were not thoroughly evaluated. Information regarding accessories of temporary support elements other than the safety net was not acquired, which created uncertainty. The design was not well formulated, and consequently, it was not well-defined. To avoid such problems, it is crucial to carry out a holistic temporary support system test that can simulate standard underground installations. This would help in identifying accessories that require improvements and therefore minimize uncertainty before executing the design.

The safety net attachment spacing is another essential factor that should be considered during testing. The attachments refer to the safety net hooks that attach the safety net to the roof bolt face plates. These hooks must be strong enough to hold two tonnes of mass without opening and allowing the safety net to slip out. The roof bolt's face plates on which the safety net is hooked should also be strong enough to hold two tonnes without tearing and allowing the safety net to collapse with the FOG. Mechanical prop hooks should also not open or tear off and allow the safety net to slip out. Mechanical props headboards must not slip out and allow the safety net to collapse with the FOG. Therefore, the entire temporary support system must be tested together to simulate actual underground conditions.

### 1.8 Inclusion of Blast-on Mesh in the Study

During the study of a two tonnes temporary support system, Sibanye-Stillwater executives adopted blast-on mesh (BOM), which is a new industry-leading practice in South African mining. BOM provides an alternative to safety nets to hold face area FOGs. Therefore, this study included the testing of BOM in a similar manner to safety nets. According to Mulenga et al. (2016), BOM, also known as ultra-high tensile strength steel mesh (UHTSSM), is a blast-resistant mesh that is pinned onto the hangingwall with roof bolts and left in place permanently to provide support in the face area. Observations at Thembelani Mine showed that the installation of BOM reduces the area that needs to be examined and made safe. If BOM is installed at 0.2 m from the face before the blast and the face advances for 1m, only a 1.2m strike length must be examined and made safe.

### 1.9 Research Objectives

The main objective of this study is to determine if the temporary support system meets the two tonnes system specification in all aspects. If any aspects do not meet the specifications, they should be identified and improved. The following objectives must be fulfilled:

- Test the temporary support system with a two tonnes capacity, including safety nets, mechanical temporary steel props, face plates, and attachment hooks;
- Test the BOM in the same way as the safety nets;
- Identify the elements that do not perform according to the specification and understand the conditions under which they fail;
- Measure the deflection or deformation of the safety net and BOM when subjected to the design load using the design specification, and evaluate their compliance with the specification;
- Assess the impact of the load and the safety net deflection or deformation on the temporary mechanical props;
- Assess the survival height relative to the working height or stoping width at the face of a working panel;
- Consider design specification adjustments;
- Suggest improvements to those components that fail, so that the support system can meet the design specifications;
- Based on the investigation, recommend a more effective, efficient, safe, and robust two tonnes temporary support system for use at the working face and;
- Describe the conditions under which this support system would perform optimally.

These objectives follow the 10-step design process in Figure 1-8. The data collection process through drop tests on mechanical props, safety nets, BOM, hooks, and face plates falls under defining the process. Whereas the analysis of the drop test results and recommendation of a change in some items fall under executing the design. Implementation of the design is represented by the rollout of the entire two tonnes temporary support system with a safety net or BOM. Routine underground observations conducted by the supplier's facilitators and members of the rock engineering department constitute monitoring. During the routine observations, items that do not perform as required are identified, and solutions are provided for continuous improvements. The whole process is iterative from an implementation point of view.

## 1.10 Research Methods

This study included both qualitative and quantitative research methods.

### 1.10.1 Qualitative research

A literature review was carried out to gain an understanding of the components of temporary support systems used in underground mining environments. The review also covered an evaluation of drop tests conducted on safety netting used in the European construction industry. The insights gained from these net tests in the construction industry can be applied to test the mine safety nets. Physical observations were conducted underground to better understand the practical implementation of the two tonnes system. During these observations, employees were interviewed to share their experiences with the temporary support system and suggest improvements. Additionally, discussions were held with management, labour representatives, the training department, full-time health and safety representatives, and the rock engineering department to ensure all stakeholders were involved in the project. The involvement of these parties was aimed at facilitating the smooth rollout of the temporary support system and acquiring suggestions for improvements from all parties involved.

### 1.10.2 Quantitative research

The impact of FOGs on temporary support systems was analysed using the database of Thembelani Mine. Following this, drop tests were carried out on the temporary support systems. All elements of the system, including the safety net, hooks, mechanical props, and face plates of roof bolts to which the hooks are attached, were tested at a drop test facility. Additionally, an alternative face area support, such as BOM, was also tested similarly to safety nets at the drop test facility. It is important to note that drop impact strength and tensile strength testing of hooks are different. For this study, the New Concept Mining (NCM) and Videx drop test facilities were used.

## 1.11 Sources of Data

The study relied on the FOG database, which is continuously updated with information on new FOGs. The database provided a detailed log of every FOG. The author also participated in some of the FOG investigations underground, where a two tonnes temporary support system was used. The components of this system, such as safety nets, hooks, mechanical props, and roof bolt face plates, were tested at the drop test facilities owned by NCM and Videx Mining Supplies. The study drew on learning acquired from net testing in the construction industry, the Savuka drop test set-up, and the Western Australian School of Mines (WASM) drop test on BOM.

### 1.12 Research Validation

In 2019, Thembelani Mine implemented a temporary support system to address an increase in FOG incidents in conventional tabular stopes and flat excavation face areas. The system involved using two tonnes Rock-stop safety nets to hold FOGs weighing up to 1.78 tonnes, with a FOS of 1.1. However, this approach did not account for all the structural properties required in the temporary support system, such as the safety net deflection parameters, hook shape and diameter, mechanical props headboard size, and the thickness of the face plates.

In 2020, the temporary support system failed to hold a 1.65 tonnes FOG leading to the collapse of the mechanical props. The safety net did not fail or get damaged by the FOG but slipped out from the headboard attachments. As a result, a study was conducted to assess the temporary support system, including the safety nets, mechanical props, safety net hooks, and roof bolt face plates. BOM was added to the study to be tested similarly to safety nets. The temporary support system could be said to be two tonnes full proof with confidence after all items fulfil the two tonnes' requirements.

### 1.13 Structure of the Research Report

The report is divided into six chapters. The first chapter is an introduction, and it covers the research topic's background, problem statement, justification for the research, and research objectives. The research methodologies for this study and the sources of information are also introduced. The chapter discusses the research validation criteria and contribution to knowledge. Chapters 2 to 6 are discussed below:

- Chapter 2 reviews the literature on temporary support systems and BOM for the face area. It also covers drop test facilities for testing safety nets and BOM;

- Chapter 3 establishes the criteria that temporary support units and BOM must meet to fulfil the two tonnes requirement;
- Chapter 4 includes details on temporary support characteristics, design requirements, and testing procedures. It outlines the manufacturer specifications for temporary support system units and BOM used at Thembelani Mine, as well as the installation standards.
- Chapter 5 discusses the findings and analyses based on the criteria that each constituent of the temporary support system must fulfil. It lists the drop test results and;
- Chapter 6 is the conclusion and recommendation. It summarizes the chapters, research observations, research contributions, research limitations and recommendations for future research work.

# 2 LITERATURE REVIEW

A review of the literature was carried out to gain an understanding of the temporary support system components utilized in the underground mines of RSA. This chapter presents an overview of the face area support used in these mines. The review of face area support reveals the previously used methods and their effectiveness. The set-up for the drop test of temporary support systems and its expected outcomes have also been detailed in this chapter. The primary objective of this chapter is to analyse and learn from historical practices. The purpose of the study is to determine if there is an existing solution to the problem available elsewhere. If there is no such solution, the study will use historical knowledge to produce results for the temporary support systems at Thembelani Mine that can handle up to two tonnes of weight.

## 2.1 Face Area Support

According to Van der Merwe et al. (2001), most fatalities due to FOGs in the RSA mining industry occur in the immediate face area of the Gold and Platinum sectors. Therefore, employees need robust support in the face area to protect them from FOGs during all work shifts, including cleaning, making safe, face preparation, drilling and charging. The most crucial requirement for immediate face area support is to preserve fractured rock around the excavation and prevent the displacement of key blocks in the first place. This need is more critical in shallow mining environments where there are minimal horizontal clamping stresses, and failure may occur by separation from parting planes or dislodgement of individual key blocks. Consequently, immediate face area support must cater for the smallest key blocks (Daehnke et al, 2000). This is determined by the areal coverage of the support system, which is the surface of a hangingwall in direct contact with the support units (Ryder and Jager, 2001).

In a typical conventional narrow reef stope supported with timber elongates and mechanical props, the contact surface of these support units with the rock is less than 1% (Jager and Ryder, 1999). Tendons are used as face area support in shallow mining environments with a stoping width as narrow as 0.9 m to clamp parting planes and key blocks (Daehnke et al, 2000). To prevent the dislodgement of individual key blocks effectively, tendons should be at a distance less than the smallest key block size (Daehnke et al, 2000). Hoek and Wood (1987) suggest that the distance between tendon face plates should be three times the average spacing of discontinuities. In this respect, the tendon spacing is less practical with the decrease in discontinuity spacing. For instance, a discontinuity spacing of 0.5 m would result in a practical tendon spacing of 1.5 m. Conversely, a narrower discontinuity spacing of 0.1 m would result in an impractical tendon spacing of 0.3 m. Therefore, the use of areal support together with tendons is necessary to cater to the smallest key blocks (Hoek and Wood, 1987).

When it comes to supporting the face area in mining operations, it is crucial to ensure that the support system does not interfere with drilling, charging, blasting and cleaning activities. Historically, wire mesh with tendons has been a popular method of providing support on the face area, as it prevents small rocks from falling and causing injuries (Daehnke et al, 2000). This support system was least affected by cleaning operations since it was installed on the hangingwall and not in the path of the scraper. However, it took longer to install in narrow stopes and incurred blast damage (Daehnke et al, 2000).

Another approach is to use safety nets alongside temporary support units. In RSA, safety nets were trialled by installing them between the first and second rows of elongates from the face. The nets did not need to be pinned to the hangingwall, but they were hooked onto permanent support elements, such as timber support. However, the nets were found to get damaged by the scraper after withstanding 13 blasts (Daehnke et al, 2000).

Safety nets were introduced in the Platinum sector of RSA in 2004 at Impala Mines, according to Gardner and Fernandes (2008). Safety nets with a claimed capacity of 750 kg were installed with two rows of mechanical props at the beginning of the morning shift on the face area. Both mechanical props and safety nets were removed after drilling and charging the face to prevent damage during blasting and cleaning operations. This rollout resulted in significant improvements in terms of holding small FOGs during the drilling shift. Tendons were not used in the face area for this purpose (Gardner and Fernandes, 2008).

## 2.2 Wire Mesh, Safety Nets, Hooks, and Roof Bolt Face Plates

This section describes the typical support elements used in the face area of South African underground mines.

### 2.2.1 Chain-linked mesh and welded mesh

Wire mesh has been used to provide support for mining operations since the 1950s (Morton et al., 2007). Wire mesh is made up of steel wires that are woven or welded into a specific pattern to form a design that is strong enough to hold smaller pieces of rock that may fall between support units. Wire mesh is loaded in tension when used for mining applications (Mulenga, 2018). The strength of the mesh is determined by the diameter of the wire, the wire's tensile strength, and the aperture size. In the South African mining industry, mesh is typically supplied with tensile steel strengths ranging from 500 MPa to 750 MPa for welded mesh and 500 MPa to 700 MPa for chain-linked mesh. However, there are cases where wire mesh is made with ultra-high tensile strength steel of up to 1.8 GPa. The stiffness and strength of the wire mesh increase proportionally with the increase in tensile strength and wire diameter. Conversely, an increase in aperture size decreases the stiffness and strength of the mesh. Chain-linked mesh and welded mesh are the two types of wire mesh commonly used for mining applications, as shown in Figure 2-1 and Figure 2-2 (Mulenga, 2018).

*Figure 2-1: Chain-linked mesh (Mulenga, 2018)*

Chain-linked mesh, also known as diamond mesh, is a flexible material that consists of diamond-shaped openings. The mesh most used for mining applications comes in two aperture sizes of 100 mm x 100 mm and 75 mm x 75 mm and has wire diameters that range from 3 to 4 mm. The user can choose the appropriate specifications based on their strength and stiffness requirements (Mulenga, 2018).

*Figure 2-2: Welded wire mesh*

The welded mesh is made up of square welded apertures that are fixed in place. Depending on the strength and stiffness requirements of the end user, welded mesh is typically supplied with apertures of 100 mm x 100 mm, 75 mm x 75 mm, and 50 mm x 50 mm. In the South African mining industry, the wire diameter for welded mesh usually ranges from 3.7 mm to 4.9 mm (Mulenga, 2018).

Wire mesh that is used for wire mesh and lacing is manufactured using low-strength chain-link mesh. This type of mesh has low initial stiffness, but a higher yielding capacity. It also has a low load-bearing capacity. Alternatively, welded mesh offers a higher initial stiffness and load-bearing capacity, with less deformation (Mulenga, 2018).

### 2.2.2 Blast-on mesh

A case study conducted by Mulenga et al. (2016) at a conventional narrow reef mine showed that an ultra-high tensile strength chain-linked steel mesh (UHTSSM), also known as BOM, can be used in conjunction with roof bolts up to the face of the conventional stope and resist blast damage. This type of mesh has a high breaking strength of 12.5 kN and a wire diameter of 3mm (Mulenga et al., 2016). BOM wires are coated with Aluminium Zinc to resist corrosion three to four times better than normal Zinc galvanized wires. These results are based on salt spray tests. Various types of BOM are listed in Table 2-1 (Brändle et al., 2017).

*Table 2-1: Types of ultra-high tensile strength steel mesh (Brändle et al., 2017)*

| Material | MINAX® 65/4 | MINAX® 80/4 | MINAX® 80/3 |
|---|---|---|---|
| Mesh width | 63 mm | 80 mm | 80 mm |
| Diagonal | 83 × 138 mm | 102 × 177 mm | 103 × 180 mm |
| Wire diameter | 4 mm | 4 mm | 3 mm |
| Wire strength | 1,770 MPa | 1,770 MPa | 1,770 MPa |
| Breaking load – single wire | 22 kN | 22 kN | 12.5 kN |
| Tensile strength | 250 kN/m | 190 kN/m | 110 kN/m |
| Weight | 3.3 kg/m$^2$ | 2.6 kg/m$^2$ | 1.45 kg/m$^2$ |

Table 2-1 displays three types of BOM: MINAX 65/4, MINAX 80/4, and MINAX 80/3. All of them are made from a wire strength of 1770 MPa. The breaking load increases with the increase in wire diameter, as 4 mm wire breaks at a load of 22 kN while 3 mm wire breaks at 12.5 kN. When the wire diameter decreases, and the mesh width and diagonal lengths increase, both the tensile strength of the mesh and the weight decrease. Lightweight mesh is easier to handle, but stronger mesh has higher stiffness and load-carrying capacity (Brändle et al., 2017). MINAX 80/3 is currently available for supply in the South African market (Mathews, 2023).

BOM can only be rolled in one direction, making it easier to handle and install in comparison to welded mesh. However, BOM is prone to damage from cleaning equipment, which is its major drawback. Owing to its high-yielding capacity, BOM may deflect when holding a FOG, which could potentially cause injuries to employees. Another factor to consider is that the cost of BOM is relatively higher than that of normal mesh and safety nets, which may negatively impact its rollout in mines (Mulenga et al., 2016).

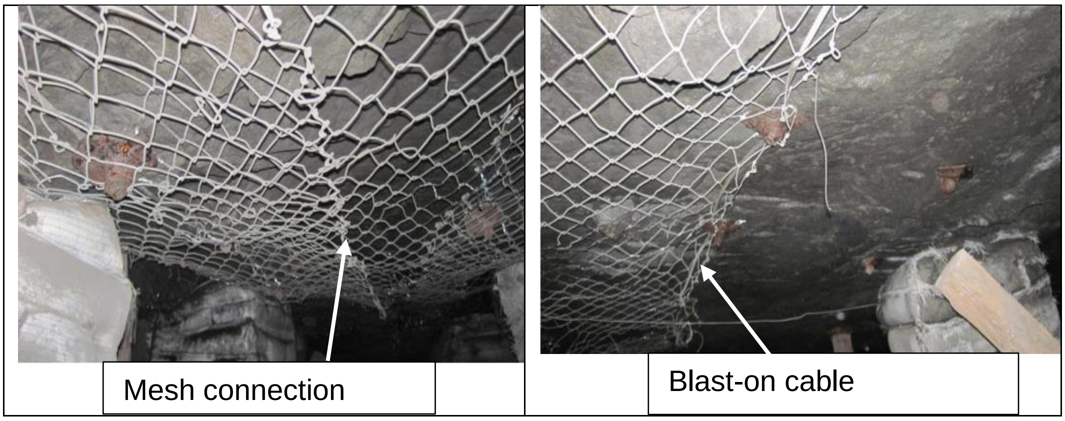



*Figure 2-3: BOM installed in a conventional narrow reef stope (Mulenga et al., 2016)*

To provide areal support, BOM is secured to the hangingwall with roof bolts and remains in place permanently. Individual mesh rolls are connected with clips to form a continuous support structure. Additionally, BOM is equipped with a cable attached to the perimeter on the side closer to the face, which helps resist blast damage, as noted by Mulenga et al. (2016).

### 2.2.3 Safety nets

Safety nets are used alongside other support units such as elongates, mechanical props, tendons, and hydraulic props. They provide temporary coverage between these units. The installation of safety nets should be as close as possible to the hangingwall, ensuring about 85% coverage upon installation. Specific safety nets with a 4 t perimeter webbing and a 2 t inside webbing were tested at the stope panel face area. The inside webbing comprised of multiple 2 t straps attached to the outside webbing in a continuous system is designed to hold two tonnes of rock. The perimeter webbing had hooks on every corner used to attach the net to other support units. These nets can also be designed based on specific site requirements. Safety nets are installed manually, and the gap between the hangingwall and the net must be minimized (Van der Merwe et al., 2001). This is the most suitable description for the webbing safety nets currently used at Thembelani Mine as shown in Figure 2-4.

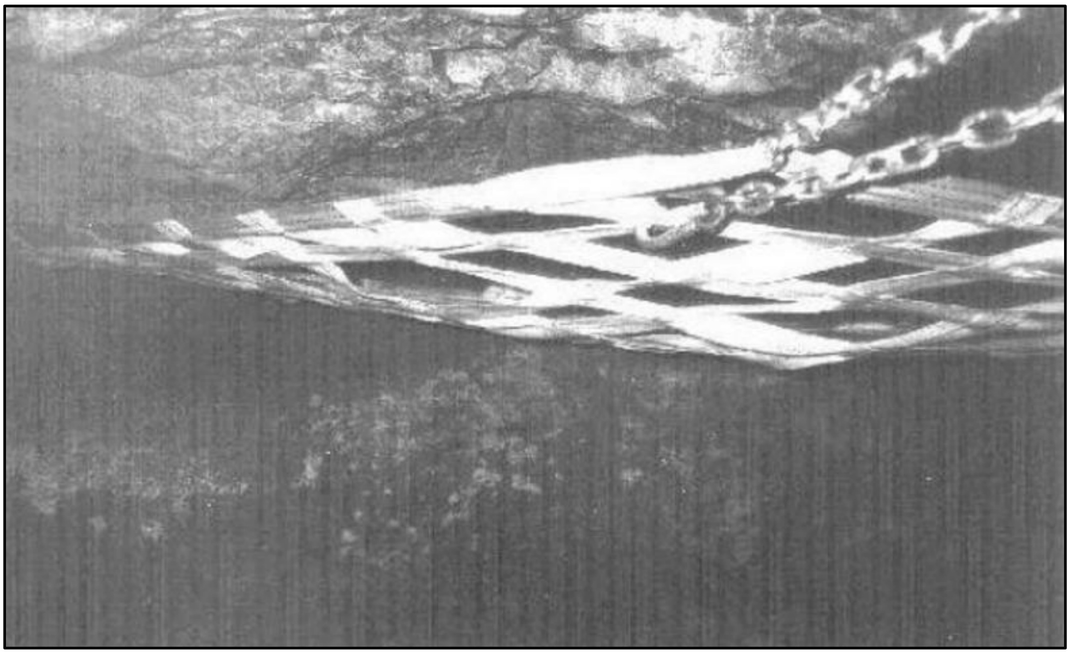


*Figure 2-4: Two tonnes safety net installed underground with hooks and tensioners (Van der Merwe et al., 2001)*

The gap between the hangingwall and the safety net can be reduced by stretching the net with chain tensioners. Safety nets are used as additional support to the existing temporary and permanent support. They are passive and cover the area between support units. Safety nets can be easily installed and reused. However, since they have multiple uses, they can be easily stolen and utilized elsewhere outside the mines. When used in a narrow stope environment, cleaning equipment such as winch scrapers can damage safety nets (Van der Merwe et al., 2001).

There are other types of safety nets available to the mining industry, such as Nylon rope nets and cable nets. Nylon nets were discontinued at Thembelani Mine after one of them deflected to the footwall while holding a FOG. Nylon nets are braided and twisted into ropes, knotted at specific intervals to form a grid of apertures of equal size. The rope diameter usually ranges from 10 mm to 20 mm, depending on the required strength. The thicker the rope, the stronger the net. Thicker or multiple ropes are used on the perimeter of the net to make it stronger (Zaayman, 2020). Nylon nets coated with latex are used as blast-on safety nets as practiced at Sibanye-Stillwater Hlanganani Gold, as shown in Figure 2-5 (Zaayman, 2023).

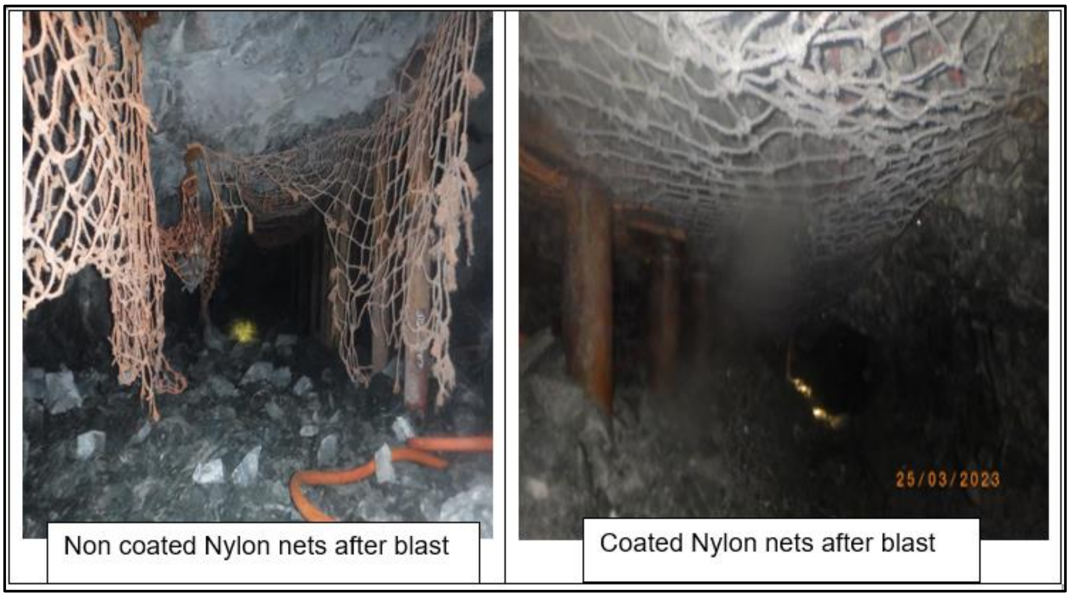



*Figure 2-5: Non-coated and coated Nylon safety nets after the blast (Zaayman, 2023)*

Figure 2-5 depicts the severe damage incurred by a non-coated Nylon safety net due to a blast. However, coating the Nylon nets makes them more resistant to blast damage. It is worth noting that these nets are still undergoing their first underground trials at Sibanye-Stillwater Hlanganani Mine, with conventional stope panels being mined at a stoping width of 1.4 m (Zaayman, 2023). The effect of equipment damage on the coated Nylon nets has not yet been established.

BOM and cable nets are becoming more popular in the South African mining industry, as the industry moves towards permanent areal support on the immediate face area of the workings. Durapraj (2023) indicated that cable nets may serve a dual function of being removable after drilling due to their flexibility and light weight. Cable nets also offer the option of being pinned to the hangingwall with bolts and left in place permanently owing to their ability to resist blast (Durapraj, 2023).

The Blast-on cable nets, such as those manufactured by New Concept Mining powered by Epiroc (NCM PBE), have a modular design that consists of rectangular nets that are subdivided by apertures of equal dimensions. The cable is made up of six strands, each of which comprises seven galvanized wires weaved together, resulting in a total uncoated diameter of 3 mm. After coating, the diameter increases to 5 mm, and the cable is then covered with plastic Polyvinyl Chloride

(PVC) to prevent corrosion (Flanagan, 2020). The mesh's ends are covered with black caps to protect the woven wires from water and moisture (Flanagan, 2023).

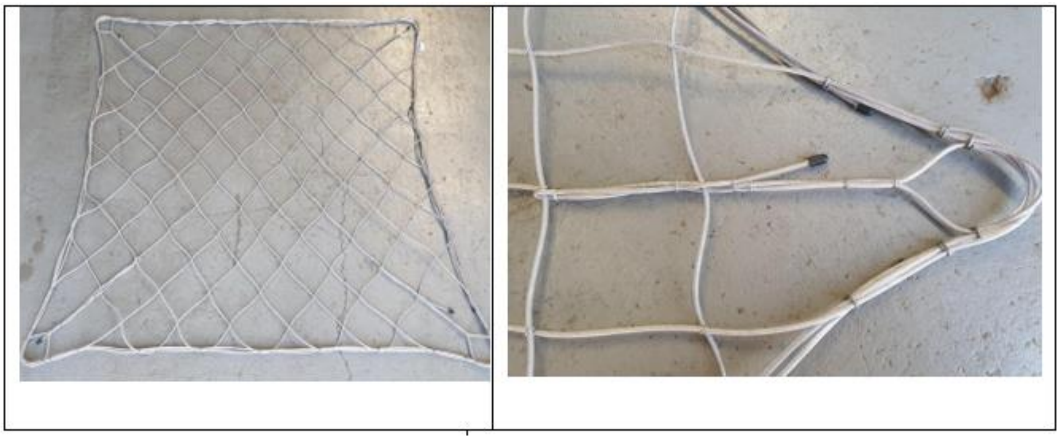


*Figure 2-6: Bast on cable net (Flanagan, 2020)*

The nets shown in Figure 2-6 are created with various aperture sizes, such as 70 mm x 70 mm, 100 mm x 100 mm, 130 mm x 130 mm, and 150 mm x 150 mm. However, these sizes can be increased or decreased according to the end user's preference. The nets' wire ropes have a tensile strength of 4.9 kN and weigh 1.1 kg/$m^2$. They are designed to hold two tonnes of rock with minimal deflection (Flanagan, 2020). The Zinc Aluminium C-rings are used to crimp the nets into the apertures and reinforce the nets' bodies and edges. Reducing the aperture size increases the nets' load-bearing capacity and decreases deflection (Flanagan, 2023). These nets have undergone corrosion resistance testing at SANAS metallurgical labs, where salt was sprayed on uncoated and coated samples with plastic PVC casing. The results after 100 hours showed that 80 to 90% of the length of uncoated samples was covered in red rust, while plastic-coated samples only had corrosion on the edges. The crimping rings were partially affected by corrosion. Plastic PVC-coated net samples with caps at the ends did not undergo noticeable corrosion change after 100 hours of salt spray (Seoka and Van Niekerk, 2020).

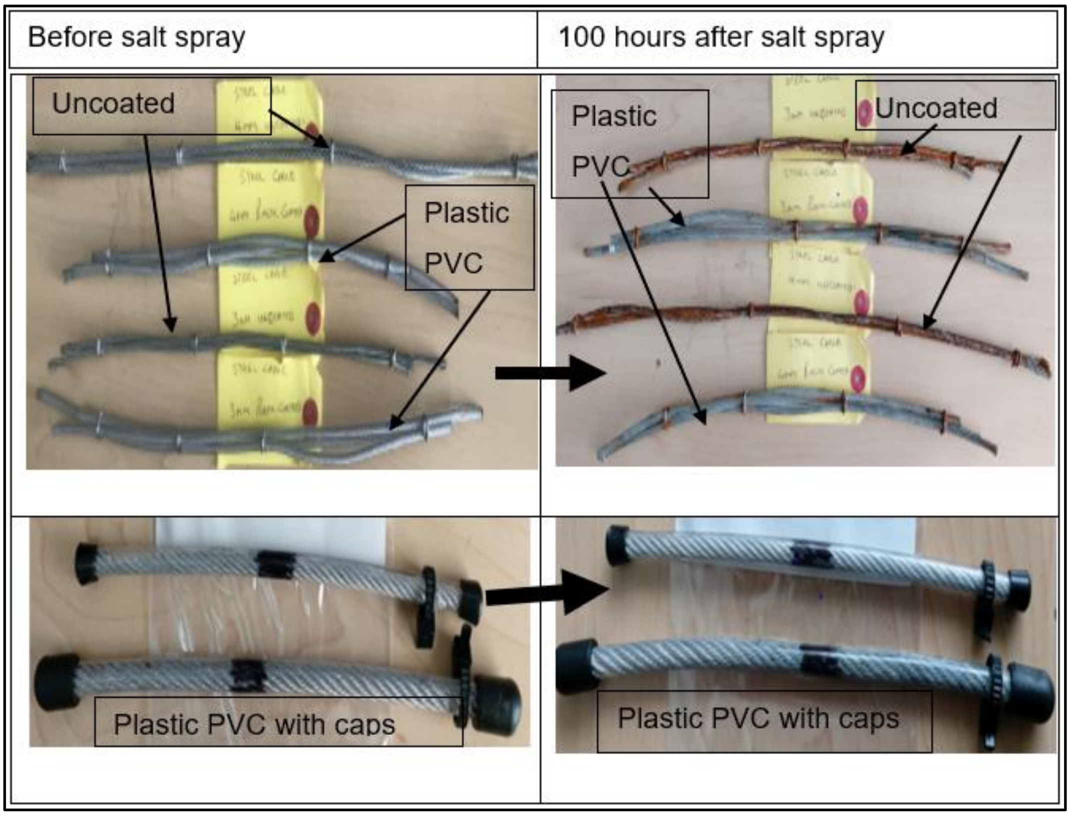



*Figure 2-7: Corrosion test on the coated and non-coated cable nets (Seoka and Van Niekerk, 2020)*

The moist underground environment can easily corrode uncoated samples, which may eventually affect the load-bearing capacity of the net. Coated nets that lack caps may get corroded at the edges. Therefore, capped-coated nets are considered the ideal option (Flanagan, 2023). These nets have not yet been tested in an underground environment. However, the manufacturer claims that they are suitable for use as removal nets or blast-on mesh, making them a dual-function solution.

### 2.2.4 Hooks and roof bolt face plates

Safety net hooks are made of steel rods that can be twisted into any shape required by the user. The material, diameter, and shape of the hook can all have an impact on its strength when holding a certain weight. By increasing the steel strength or thickness of the hook, its holding capacity can also be increased (le Roux, 2020). Typically, underground safety net hooks come in S, G, and U shapes as shown in Figure 2-8.


*Figure 2-8: Typical safety net hooks used in the South African underground mines*

In Figure 2-8, the U-hook is welded to a mechanical prop headboard, while the G-hook and S-hook are flexibly attached to the face plates of the roof bolts. These hooks are used to suspend the safety net by attaching it to the roof bolt face plate, mechanical prop headboard, or timber elongate headboard.

The face plates, which are made of steel and are typically square-shaped, act as washers and are attached to the bottom end of the roof bolt. Each face plate may have a hole punched into it for the attachment of the hook, according to the end user's discretion. The strength of the face plate can be increased by increasing the steel strength or thickness of the face plate itself (le Roux, 2020).

According to Haile (1999), face plates help in tensioning roof bolts between the anchor of the roof bolt at the top of the hole and the rock surface. Figure 2-9 shows an assembly of the face plate and hook on the roof bolt.


*Figure 2-9: Assembly of face plate and hook on the roof bolt*

The image on the left side of Figure 2-9 depicts a resin roof bolt assembly utilized in the stope panels at Thembelani Mine. This assembly includes a flexible G-hook and a face plate. On the other hand, the image on the right side shows a spike plate that is also attached to the Resin bolt along with the face plate. According to Mathews (2023), spike plates are utilized in areas where BOM is installed to secure the BOM wires to the hangingwall using spikes on the edge of the plate. In an underground mining environment, it is important to position the face plates or spike plates flush against the hangingwall to effectively prevent key block fallout.

## 2.3 Mechanical Props

Temporary support is required on the face area before installing permanent support. Mechanical props are commonly used for this purpose, as they can be pretensioned to act as active support when installed. At the end of the shift, the props are released with a releasing tool from a remote, safe supported area to prevent any injuries during removal, especially if there is a dead weight supported by the prop that may fall due to gravity upon removal of the props. Mechanical props are a cost-effective choice of support as they can be reused (Botha, 2010). Figure 2-10 shows a typical underground installation of mechanical props.

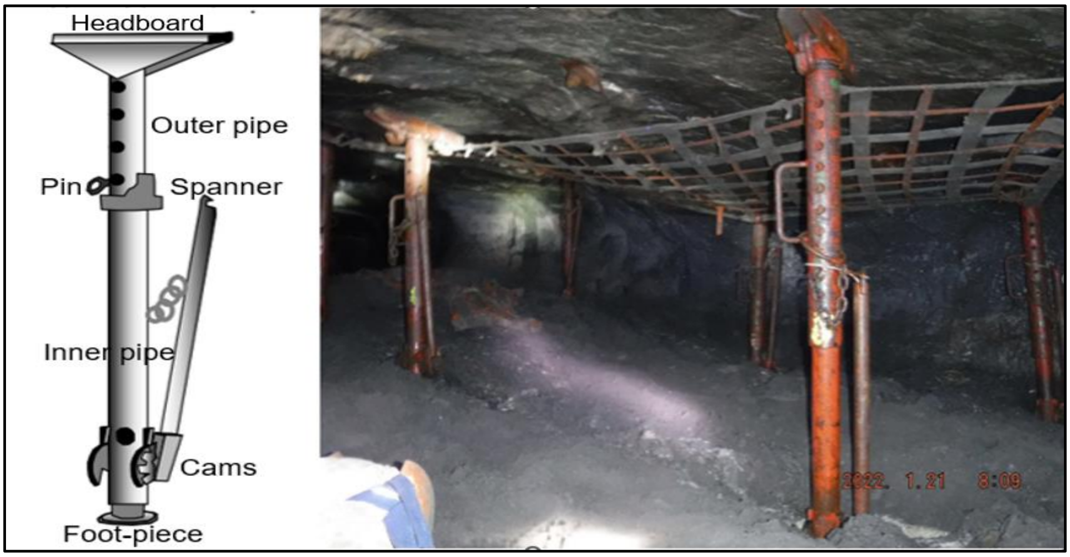



*Figure 2-10: Mechanical props installed underground (Botha, 2010)*

A mechanical prop is comprised of a headboard, outer pipe, inner pipe, cams and a tensioning spanner. During installation, the props are extended upwards and fixed to a specific height that fits the stoping width. The cams are then tensioned with a spanner. When properly tensioned, the prop becomes an active support at a certain applied pre-load. To remove the prop, a releasing sling is attached to the pin and the hook of the tensioning spanner. The sling is then pulled from a safe supported side. The headboard of the prop is typically equipped with hooks that allow for the suspension of a safety net, as shown on the right side of Figure 2-10 (Botha, 2010).

## 2.4 Typical Drop Tests on Safety nets

This section outlines drop tests conducted on safety nets for the construction industry, temporary support for mines and BOM.

### 2.4.1 European standard for safety net test

In 2005, a new European standard was implemented to improve safety and reduce injuries in the construction industry. The standard focussed on working at heights and resulted in the creation of a safety net drop testing facility. This facility enabled the study of safety nets' behaviour when holding falling objects and employees working at heights. The study focussed on several factors, including the type of nets, attachment spacing, sag, repeated loading on the same position, the effect of defects on the net, aging of the net and the effect of items falling on different positions along the net. The European standard specified a drop height of 2 m and an attachment capacity of 6 kN. Additionally, the standard specified that wastage (the gap between the net and attachments) should not exceed 225 mm, and a recommended gap of 100 mm is easily achievable, as shown in Figure 2-11 (McCann, 2011).

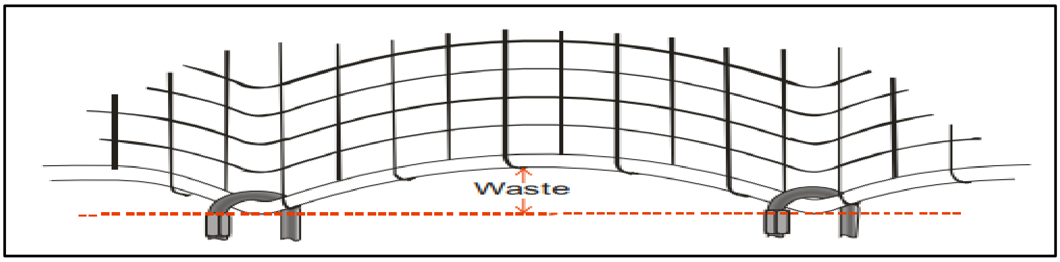



*Figure 2-11: Wastage between the net and attachments (McCann, 2011)*

Figure 2-11 shows a plan view of the safety net and its attachments, where the maximum wastage is recorded midway between attachments. The relevant safety standards stated that the attachments should not take the form of drilled objects onto the steel frame of the drop test facility. Instead, flexible attachments must be used to attach the safety net to the frame, as illustrated in Figure 2-12 (McCann, 2011).

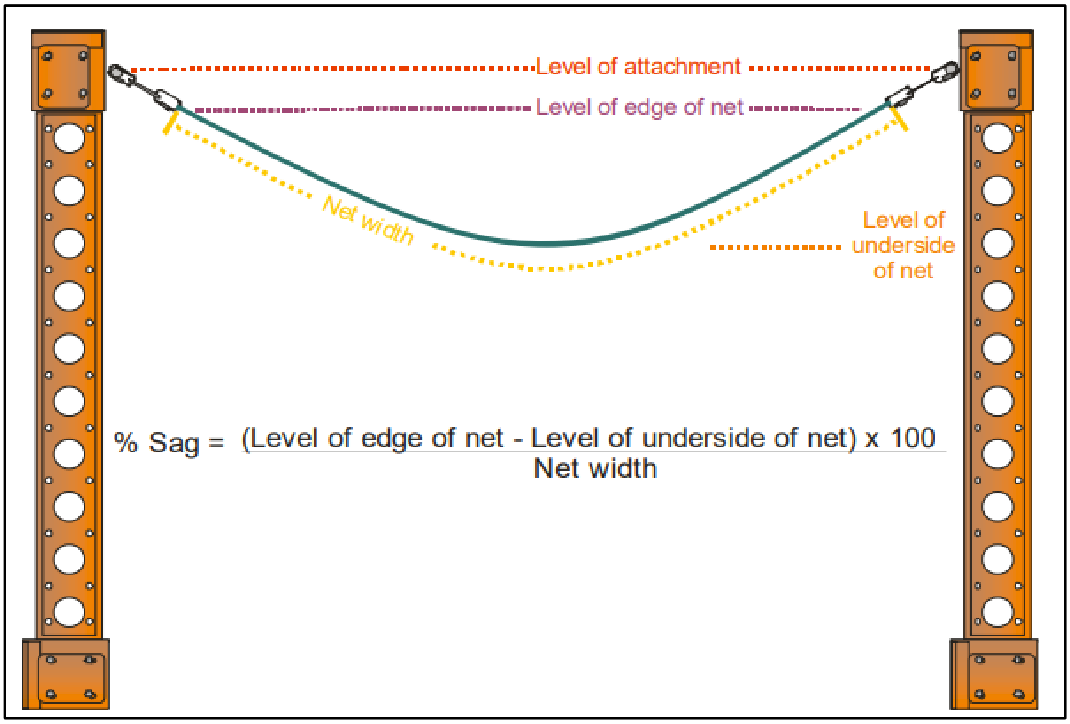



*Figure 2-12: Attachments position and determination of sag (McCann, 2011)*

Figure 2-12 illustrates a typical set-up of the drop test facility with flexible attachments and a safety net. The equation for calculating sag is also presented. According to European construction industry standards, the initial sag during installation should not exceed 10% of the net width (McCann, 2011).

The European drop test facility conducted tests on four net options available in the United Kingdom (UK), namely knotted Polypropylene, knotless Polypropylene, knotted Nylon, and used knotless Polypropylene. For each net, attachment spacing tests were performed with spacings of 0.1 m, 0.5 m, 1 m, and 2 m (McCann, 2011). Figure 2-13 shows the dynamic drop test facility that was developed for testing safety nets.

*Figure 2-13: Dynamic drop test facility for construction industry safety nets situated in the United Kingdom (McCann, 2011)*

The drop test facility consisted of a crane located on a tower. The drop height could be adjusted up to 20 m above the net. A horizontal rigid steel base, measuring 8 m by 6 m, was positioned below the crane. The steel base allowed for the suspension of nets and the installation of instruments. The opening area of the base could be adjusted to accommodate nets of smaller dimensions. The horizontal rigid frame was supported by steel structures. The facility was used to drop various objects onto the nets, such as a spherical ball weighing 100 kg with a diameter of 500 mm, a human dummy weighing 100 kg, or a cylinder weighing 100 kg with a diameter of 200 mm. Drops were made at different positions on the net and the results were recorded through attached load cells (McCann, 2011). Figure 2-14 and Figure 2-15 show the drop masses and attachments with load cell positions, respectively.

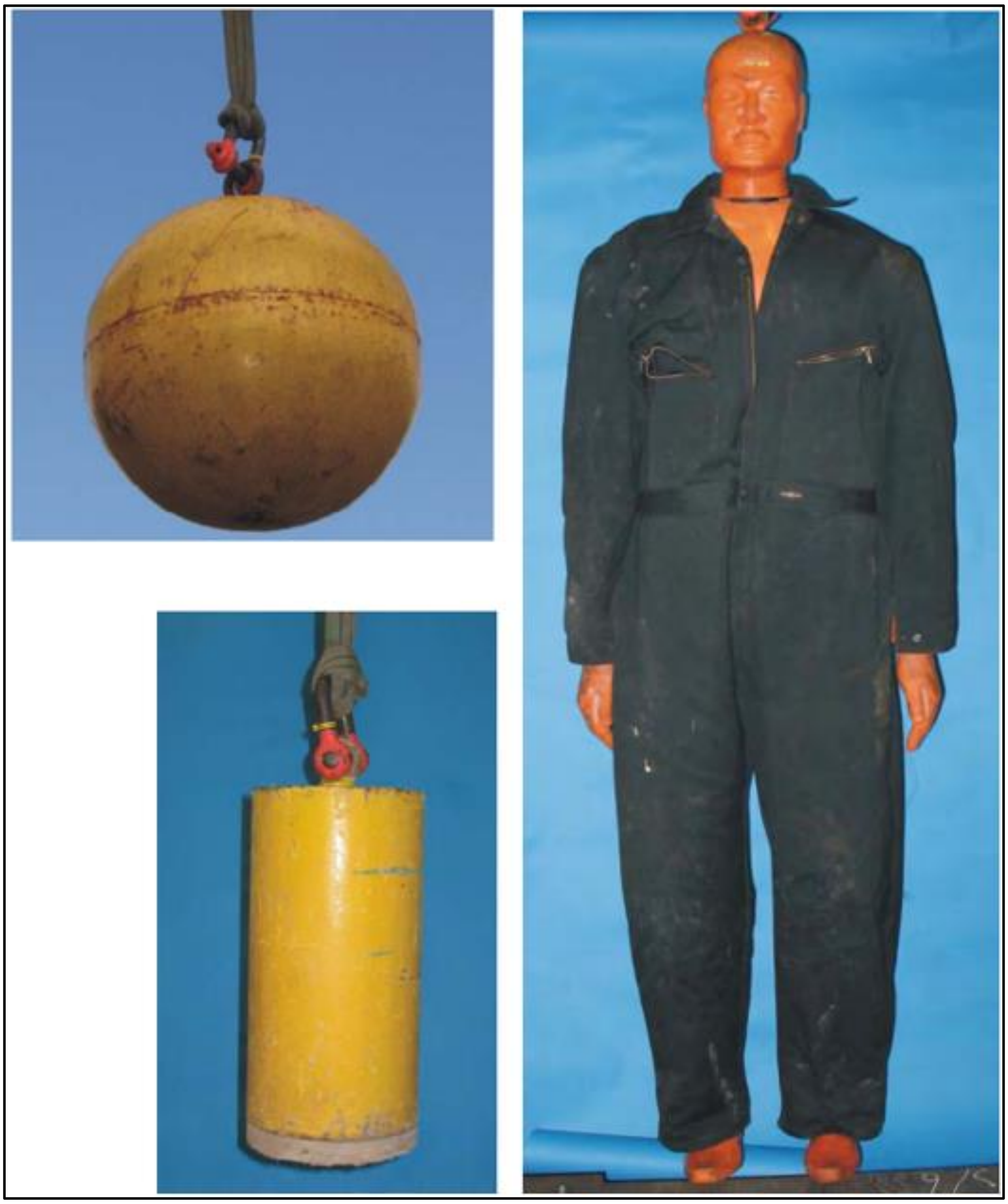


*Figure 2-14: Drop masses (McCann, 2011)*

To simulate the effects of possible objects falling on safety nets, each item shown in Figure 2-14 was dropped separately and the results were recorded. Drop tests were conducted from a height of 2m above the safety net to establish standards for testing, in accordance with the maximum fall height set by the construction industry. The sag and wastage of the net were measured before each test, as per McCann (2011).

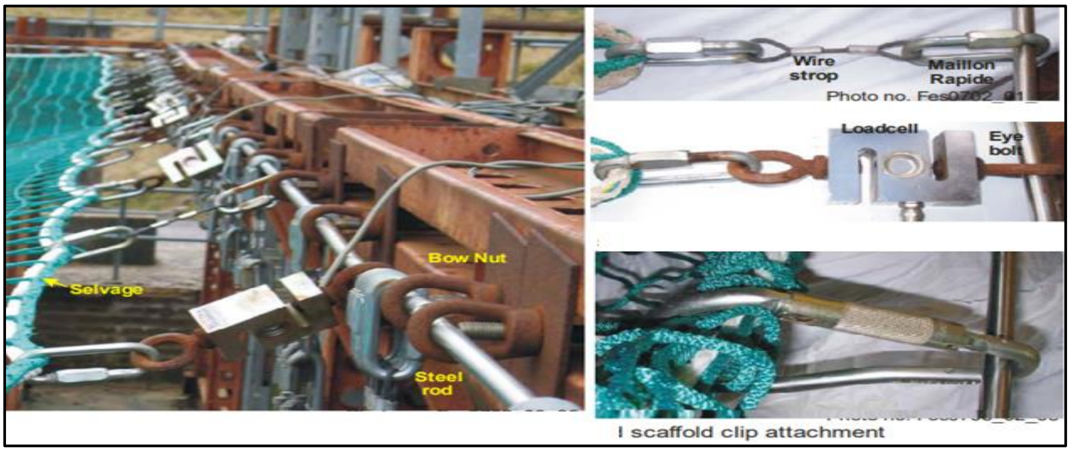



*Figure 2-15: Load cell and attachments position on the testing facility (McCann, 2011)*

To capture the results during the drop tests, 14 load cells were attached to the equipment as shown in Figure 2-15. The results were then transferred to a storage and read-out device located in the building adjacent to the test facility. The weather monitoring station installed in the test facility helped in indicating the environmental conditions during the tests. The mass was dropped from an adjustable crane, which had the flexibility to drop the mass at any point along the safety net. The schematic plan view of the drop test facility as shown in Figure 2-16, depicts the crane, drop point positions, weather station and load cell positions (McCann, 2011).

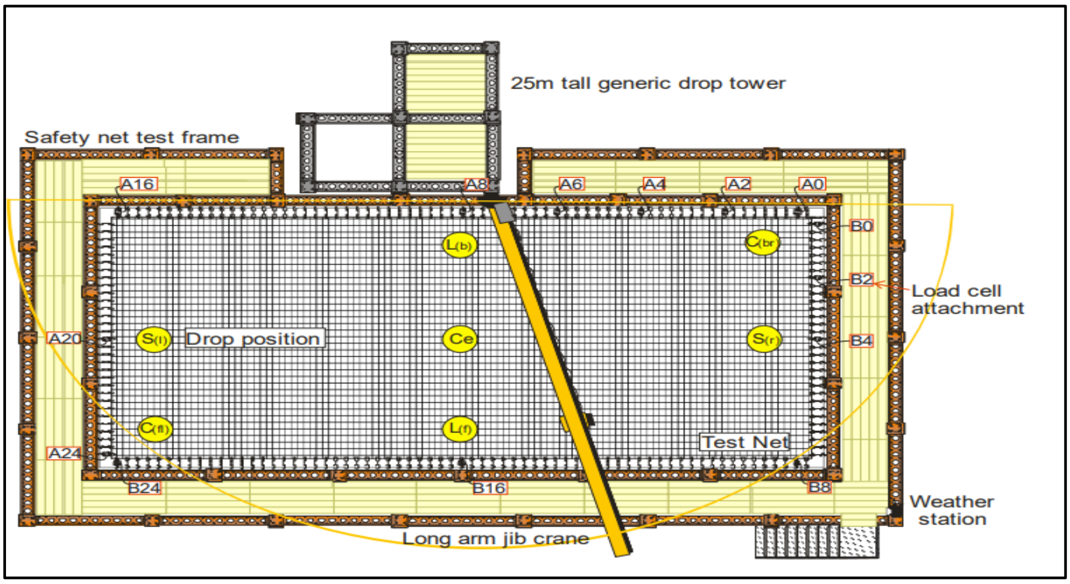



*Figure 2-16: Schematic plan view of the drop test facility (McCann, 2011)*

Figure 2-16 shows the positions of 14 load cells labelled as As and Bs around the perimeter of the safety net, along with various drop positions labelled as Cs and Ls. The orange arc indicates that the crane can rotate radially for 180° along the safety net test frame (McCann, 2011).

To set the testing standard, seven drops were conducted on each net at different positions as shown in Figure 2-16. After that, additional five drops were repeated at the same previous positions, resulting in a total of 12 drops per net. Care was taken to avoid damaging the load cells by placing the outer drop positions no closer than 1 m from the test frame, and to decrease the test frame's effect on the results (McCann, 2011).

The tests revealed that the initial sag during the installation increased with an increase in attachment spacing for the four types of nets tested. The used Knotless Propylene net at 2 m attachment spacing recorded the highest sag of 13%. All the other nets had an approximately 8% sag at 2 m attachment spacing. However, the facility conducted tests to assess the effect of the initial sag on net performance by varying the sag from 6% to 20%. These tests revealed that increasing sag to above 10% resulted in a higher displacement, which required more clearance between the ground and the net. On the other hand, decreasing sag to below 10% resulted in an increased loading on attachments (McCann, 2011).

An increase in the spacing between attachments caused higher loads on the attachments. The displacement also increased when the attachment spacing increased. The highest load recorded on attachments was 4.48 kN which was less than the 6 kN limit set by the European safety net standard. The elasticity of the nets decreased significantly after repeated drops. According to the European standard, nets should be discarded and not used after they have been loaded with a mass. Broken strands resulted in a source of failure when located closer to the drop points, while defects located towards the attachments resulted in higher displacements. All tested masses tended to move toward the centre of the net. The dummy resulted in higher loads on the attachments than the sphere. Safety nets could not retain the cylinder, which penetrated past the nets, possibly due to sharp edges that cut the nets. The nets retained their shape even closer to defects and only deteriorated when significant obvious damage was present (McCann, 2011).

### 2.4.2 South African standard for testing of safety nets

Safety nets used in mines are designed with specifications that match the area of use, such as gullies, the stope face area and development ends. The design criteria should ensure that the safety net deflects less while sustaining the load from fallen rocks. In RSA, due to area-specific design, there was no standard for testing safety nets. The testing facilities in RSA such as the CSIR and the South African Bureau of Standards (SABS), do not conduct standard tests on safety nets (Skarbøvig et al. 2011).

The Safety in Mines Research Advisory Committee (SIMRAC) established Savuka facility in 2007 to test safety nets and establish a standard for testing safety nets. The facility was operated by SRK Consulting and Norsenet, who conducted 200 tests on different types of safety nets to create a testing standard. Analysis of the data collected from the tests showed that safety net performance was affected by several factors, including the type of strands, mesh size, and interaction between the safety net strands, net ropes and net attachments. All these elements work together to form a system that absorbs energy from falling rocks and transfers it through the ropes to the attachment points, net perimeter and mechanical props. If one element failed, the system was compromised, and the onset of failure occurred on the weakest element before propagating throughout the entire system. (Skarbøvig et al., 2011). This indicates that it is well known that temporary support systems must be tested holistically.

The test facility at Savuka was designed such that a 1.2 m high stope was built with concrete blocks, and it could be opened and closed in the centre with concrete blocks suspended on the crane. The set-up could also be arranged with an opening in the middle where blocks of concrete would be dropped from the crane onto the support elements to be tested (Skarbøvig et al., 2011). The set-up could be arranged to simulate both dynamic tests and static tests (Humans and Fernandes, 2004). Figure 2-17 and Figure 2-18 show dynamic test set-ups at the Savuka facility.

*Figure 2-17: Savuka drop test facility set-up simulating gravity-induced FOGs (dynamic testing) (Skarbøvig et al., 2011).*

To test the safety net, a set-up was created according to Figure 2-17. Four mechanical props were placed under the concrete stope block, spaced 1.5 m x 1.5 m apart. The safety net was attached to the mechanical props on the headboards. A 450 kg mass was dropped repeatedly, until either the net failed or a crane lifting limit of 2 m above the net was reached. The first drop was done slowly to simulate a static performance, and with each subsequent drop, the height above the net was increased by 0.1 m from 0 m to 2 m. The safety net's condition was assessed after each drop to record failure, and measurements and pictures were taken before and after the tests. The drop tests were also recorded on video (Skarbøvig et al., 2011).

In a similar simulation conducted by Humans and Fernandes (2004), a FOG comprised of key blocks was tested. The Savuka set-up used eight concrete blocks weighing 250 kg each, dropped onto the net until a total mass of two tonnes was reached. This set-up is illustrated in Figure 2-18.

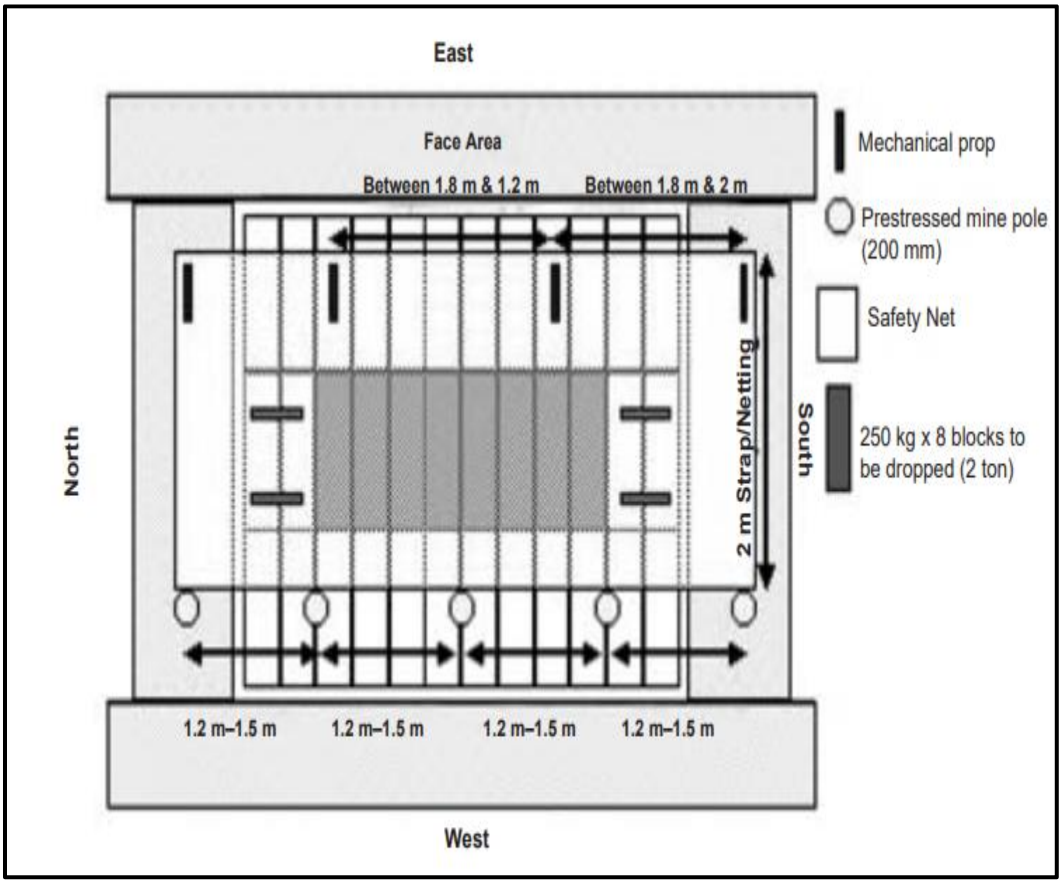



*Figure 2-18: Savuka test facility simulating two tonnes cumulative FOGs onto safety nets and mechanical props (Humans and Fernandes, 2004)*

As shown in Figure 2-18, the concrete blocks were dropped onto a safety net that was suspended from the roof using mechanical props installed at a 2 m by 2 m spacing. The simulation revealed that the net should be installed as close to the hangingwall as possible to prevent the FOG from gaining momentum before hitting the net. The momentum gain of the object could cause the net to fail. To avoid the common failure of slipping out of the props from the hangingwall and collapsing with the FOG, the mechanical props must have sufficient pretension load (Humans and Fernandes, 2004).

## 2.5 Test Set-up for Wire Mesh

In 2002, the Western Australian School of Mines (WASM) developed a significant mesh testing facility for dynamic testing. Later, in 2005, the facility was upgraded to account for static testing of mesh samples, as described by Player et al. (2008). The static testing facility is indicated in Figure 2-19.

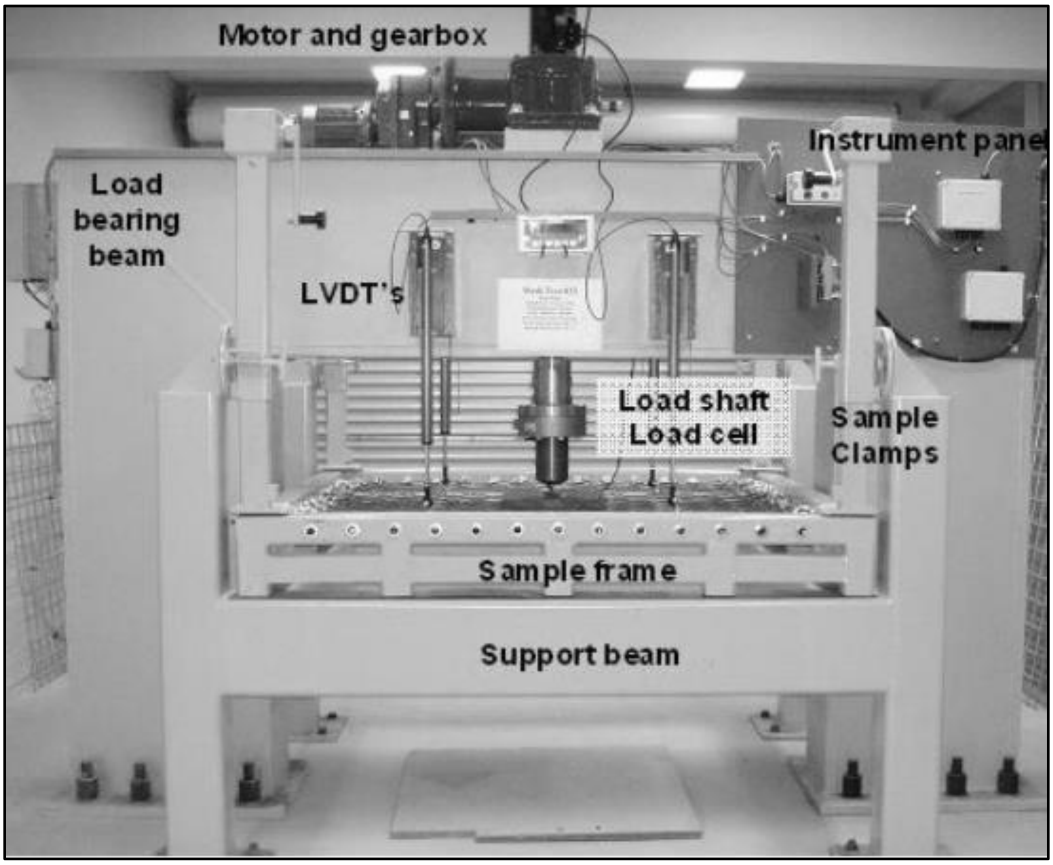



*Figure 2-19: Static mesh testing facility (Player et al., 2008)*

A rectangular rigid steel frame was used to suspend the mesh on top of the supporting beam. The load-bearing beam was erected above the sample frame with its leg structures sitting on either side of it, allowing for easy movement of a screw feed jack around the mesh sample. The screw feed jack was driven by a motor and gearbox located at the top of the load-bearing beam. The load was applied at a constant rate of 4 mm per minute through a screw feed jack on the 300 mm square plate, which was placed on top of the mesh sample. Load cells capable of measuring up to 50 tonnes were mounted between the screw feed and the loading point. One sample could be tested in one hour (Player et al., 2008).

Dynamic mesh testing involved dropping a mass from a specific height onto the mesh suspended on a rigid steel frame. The test was conducted based on a momentum transfer concept, whereby the momentum of the falling mass was transferred to the mesh (Player et al., 2008). Figure 2-20 shows a dynamic test facility.

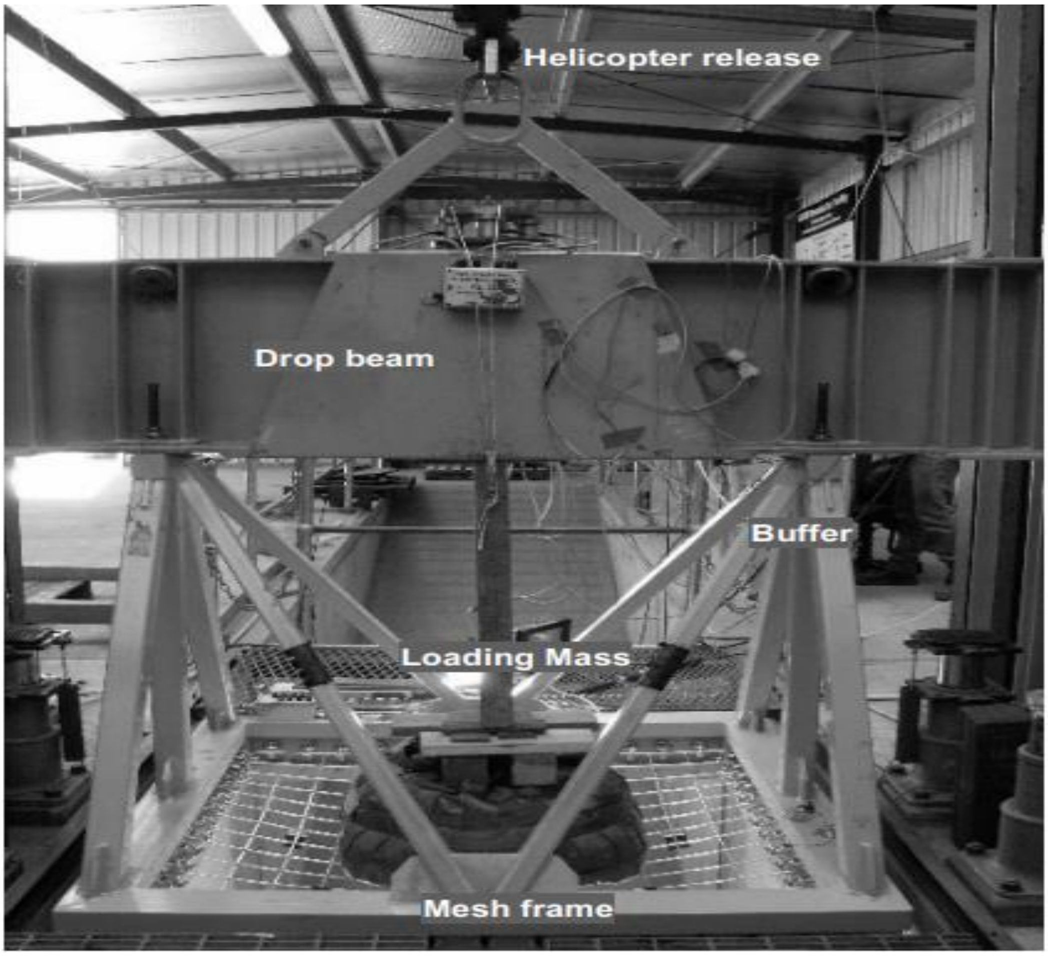



*Figure 2-20: Dynamic testing of wire mesh (Player et al., 2008)*

During the experiment, a mass of either 0.5 or 1 tonne with a surface area of 650 $mm^2$ was dropped from a height through a guiding wooden prop onto a mesh. The wooden prop was used to reduce the swing during the free-fall. The experiment lasted less than a second, and the output was recorded and analysed using sophisticated computer software. The data was used to determine the dynamic performance of the mesh after testing (Player et al., 2008).

Both static and dynamic test displacement, force and energy absorption capacity were considered in analysing the results. Energy absorption was calculated as the product of force and displacement. Higher energy absorption capacity indicated a higher displacement. If some mesh strands were broken upon impact of the mass onto the mesh, displacement was likely to increase. Therefore, tests were stopped at rupture, which was the point at which a component of the mesh broke. It was indicated that the rupture force was not equal to the peak strength of the mesh.

After rupture, an element of variability was introduced, which inhibited detailed analysis (Player et al., 2008).

Two types of wire mesh were tested at the WASM facilities: welded mesh with a 5.6 mm wire diameter and apertures of 100 mm², and high tensile strength Geobrugg chain-linked mesh (BOM) with a wire diameter of 4 mm. Mesh samples of 1.3 m² were tested for both static and dynamic tests. The static results for welded mesh and BOM are shown in Figure 2-21 (Player et al., 2008).

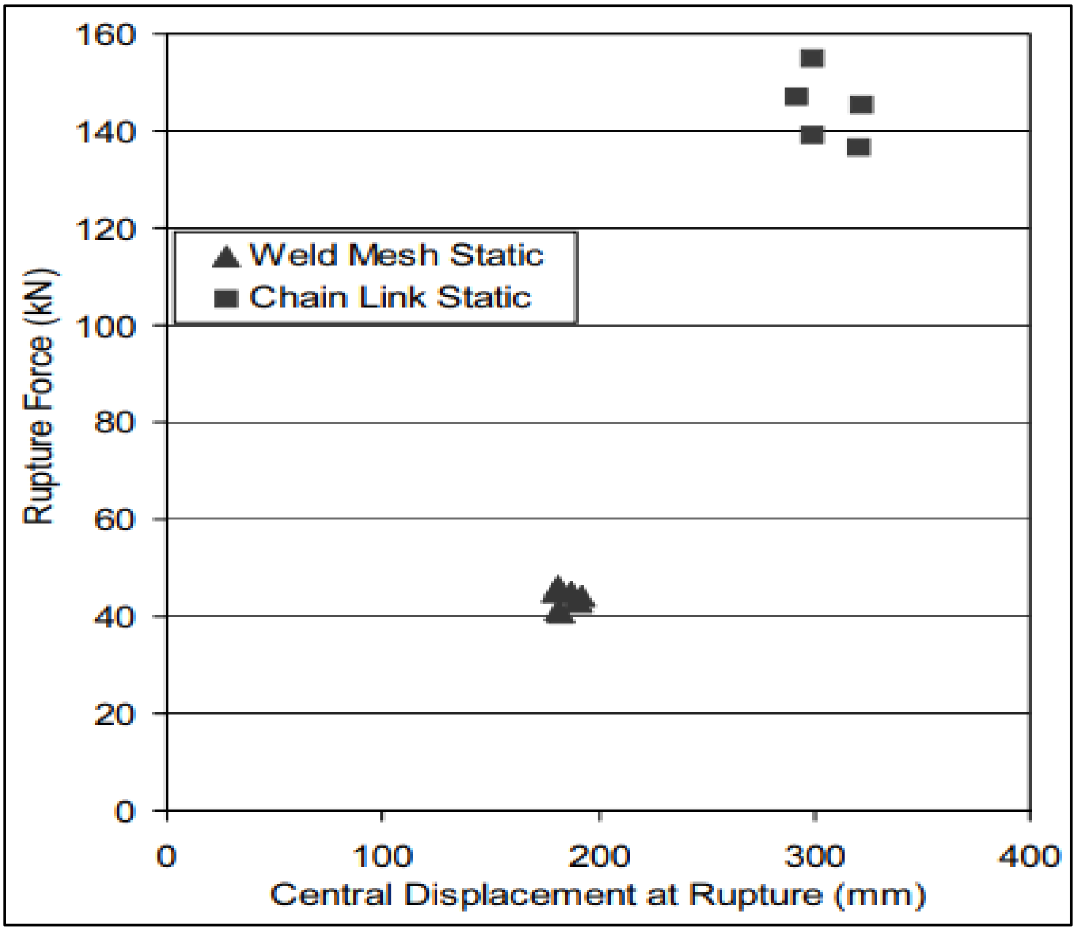



*Figure 2-21: Rupture force versus central displacement for static mesh test (Player et al., 2008)*

According to Player et al. (2008), static testing showed that chain link mesh had an average central displacement at rupture of 307 mm and an average static rupture force of 145 kN, while welded mesh had an average central displacement at rupture of 186 mm and an average static rupture force of 44 kN. On the other hand, dynamic testing revealed that chain link mesh had an average rupture force of 185 kN at a displacement of 306 mm, while welded mesh had an average rupture force of 55 kN at a displacement of 203 mm. The average dynamic energy at rupture was found to be 9 kJ for chain link mesh and 2 kJ for welded mesh, as shown in Figure 2-22 (Player et al., 2008).

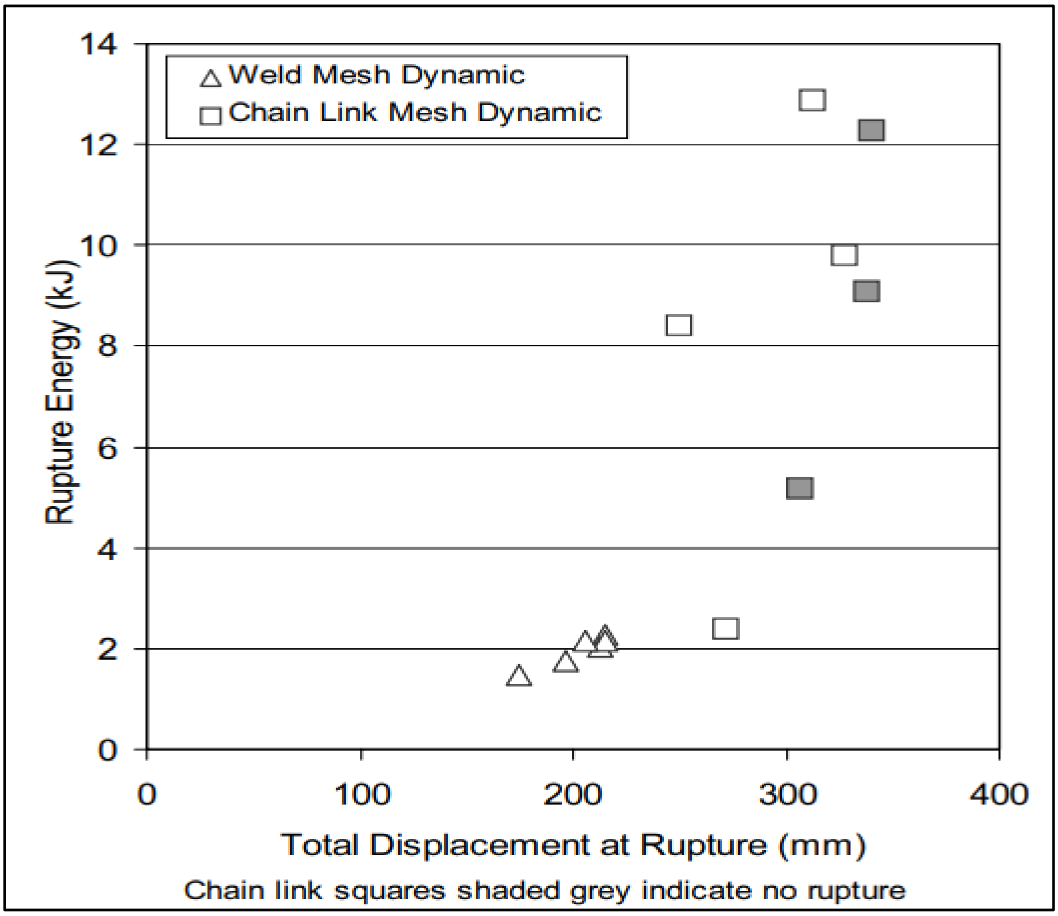



*Figure 2-22: Rupture energy versus displacement for welded mesh and chain-linked mesh (Player et al., 2008)*

During the dynamic testing, rupture was not observed on three samples of 4 mm BOM. The impact strength was measured and depicted as shaded square boxes in Figure 2-22 (Player et al., 2008). The welded mesh exhibited three failure mechanisms, including tensile breaking of the wire when its strength is exceeded, breaking of the welded points, and failure of the wire through the heat-affected zone (HAZ). The failure mechanisms of the welded mesh were similar for both dynamic and static tests. For the 4 mm BOM, the failure mechanism involved cutting off the wires with the steel loading plate during static loading and breaking of wires along the links during dynamic loading (Player et al., 2008). Figure 2-23 and Figure 2-24 illustrate the failure mechanisms for welded mesh and chain link mesh.

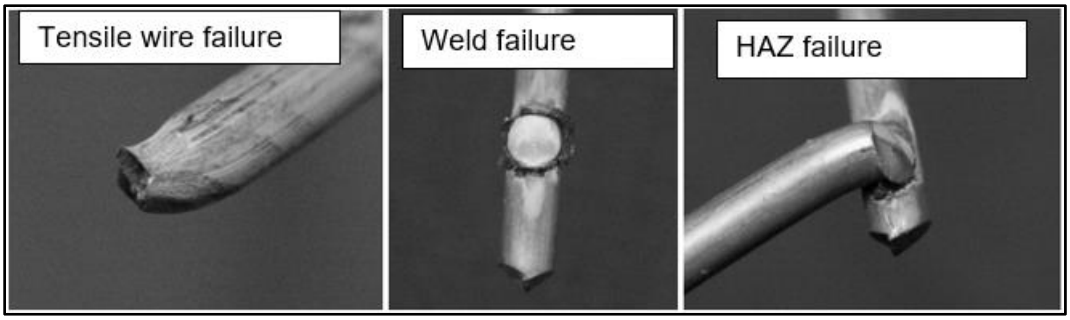



*Figure 2-23: Failure mechanisms for welded mesh (Player et al., 2008)*

Generally, failure for welded mesh occurred at the centre and propagated towards the corners (Player et al., 2008).

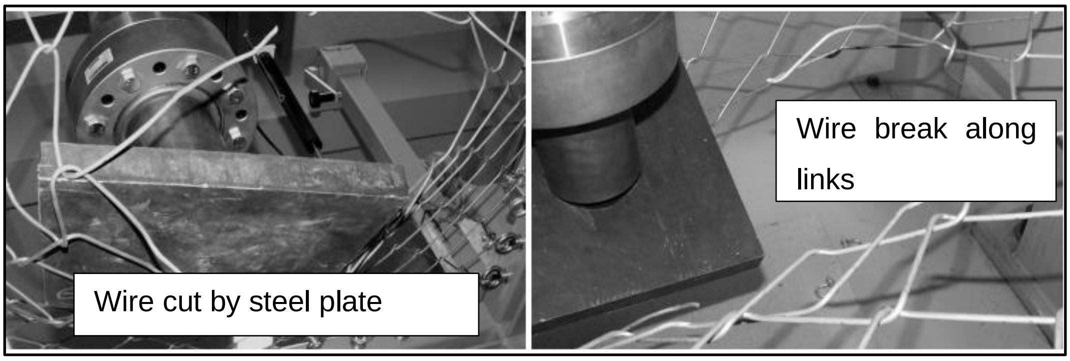



*Figure 2-24: Failure mechanisms for chain-linked mesh (Player et al., 2008)*

During the test, one or two wires broke, and the load dropped completely to the ground due to plate movement, leading to the test being stopped. The failure position varied as some samples failed towards the boundary of the chain-linked mesh sample, while others failed at the edge of the loading plate (Player et al., 2008).

When comparing results for welded mesh, it was deduced that dynamic displacement and dynamic force are 8% and 20% higher than static tests, respectively. For chain-linked mesh, the average rupture displacement was relatively similar for both dynamic and static loading, while the average dynamic rupture force was 21% higher than the static force. The higher forces during dynamic loading could be attributed to the larger loading area of 650 $mm^2$ resulting in more wires being loaded compared to a smaller loading area of 300 $mm^2$ for static loading (Player et al., 2008).

BOM with 4 mm wires performed better than welded mesh as it provided higher rupture force and higher energy absorption (Player et al., 2008).

## 2.6 Key Debates and Controversies

The study by McCann (2011) focused more on safety net performance as it was performed for construction industry nets. Conversely, the studies done by Humans and Fernandes (2004) and Skarbøvig et al. (2011) assessed the temporary support items for mining applications considering safety nets, mechanical props and attachment spacing. All these studies did not assess the impact of attachment thickness, face plate thickness and mechanical prop hooks on temporary support performance.

This project aims to identify the impact of each temporary support component on the two tonnes temporary support systems. The suppliers normally specify the compressive strength of mechanical props, hook opening tensile strength and hole-breaking shear strength on the face plate. The strength parameter under the drop test may differ from those that are specified.

The study conducted by Player et al. (2008) at WASM focussed on the rupture force and displacement on 4 mm wire diameter BOM for mesh dimensions of 1.3 $m^2$ without the use of face plates. Geobrugg currently supplies 3 mm BOM used with spike plates to the South African mining industry. Mathews (2023) indicated that the 4 mm diameter BOM is more costly with a cost of R 590 / $m^2$ owing to its higher strength and less displacement compared to the 3 mm diameter BOM with a cost of R 290 / $m^2$. This makes the 4 mm BOM only preferred in special cases like seismically active mining environments such as the El Teniente Mine in Chile (Brändle et al., 2017). Mulenga (2018) also indicated that BOM is more costly, and this may deter its rollout in the South African mining industry.

Thembelani Mine falls under a shallow mining environment with a depth of less than 1000 m and it is considered less seismically active. Therefore, the 3 mm BOM may suffice pending drop test results. For a conventional stope mining application, BOM is pinned to a hangingwall with two lines of mechanical props and thereafter pinned with roof bolts. The drop tests should be set up to reflect the underground application.

Player et al. (2008) indicated that the test was stopped when a rupture of the mesh occurred. In the case of Thembelani Mine BOM with broken strands may not be used. When some strands are damaged by equipment or blast, that portion of the mesh is replaced. The rupture force and rupture displacement acquired with the 4 mm BOM may not be used for Thembelani Mine application as a 3 mm BOM is available for use. Therefore, drop tests should be conducted on a 3 mm BOM to evaluate if it can hold two tonnes with acceptable deflections.

## 2.7 Chapter Summary

Two studies were historically conducted in terms of safety net performance (one in Europe and one in RSA). Some learnings were acquired from the European construction industry in terms of the construction of a drop test facility for safety nets and conducting drop tests. From these studies, it was deduced that safety nets designed to hold free-falling objects must be tested from a drop tests facility. These kinds of tests are called dynamic drop tests.

Dynamic tests were conducted at WASM on 4 mm BOM for mining applications whereby the rupture force and rupture displacements were measured. The drop test facilities for testing of safety nets in Europe and testing of BOM at WASM both had load cells to accurately measure the force and displacement. There was no mention of load cells at the Savuka drop test facility.

The drop tests conducted in the European construction industry focussed only on safety nets and attachment points. The attachment points for the European construction industry are far different from hooks and face plates used in the South African mining industry.

The drop tests conducted at Savuka focused on pressing the safety nets with mechanical props onto the test frames. Consequently, roof bolt face plates, safety hooks and mechanical props hooks were not accounted for by Savuka drop tests.

The WASM study on BOM only focussed on 4 mm diameter UHTSM. The 3 mm diameter mesh was not accounted for.

The previous studies did not account for all items of temporary support elements used at Thembelani Mine. The installation scenarios used at Thembelani Mine were also not accounted for in the previous studies. This study aims to address all temporary support elements used at Thembelani Mine and the 3 mm diameter BOM not tested at WASM.

Thembelani Mine with a depth of less than 1000m is characterized by shallow mining environment behaviour whereby FOGs are gravity-induced. The history of FOGs at Thembelani Mine from 2017 to 2022 agrees with gravity-induced FOGs. Therefore, dynamic drop tests whereby a specific mass is dropped vertically from a small distance above the net are more representative of the Thembelani Mine FOGs.

# 3 GUIDELINE FOR SAFETY NETS AND DESCRIPTION OF TEST FACILITIES

This chapter describes the design requirements that the Thembelani Mine temporary support system must meet. A summary of the lessons learned from the historical drop testing is outlined. The drop test facilities (NCM and Videx) that were utilized for this investigation are then discussed, along with their drop testing protocols. The drop test results validation process, the data analysis methodology, and the study's underlying assumptions are all covered in detail in the final section of the chapter.

## 3.1 Guideline for Safety Nets Used at Thembelani Mine

### 3.1.1 Initial sag on safety nets

The European construction industry's drop test study revealed that the initial sag, attachment spacing, repeated drops, drop position and net defects all have an impact on safety net performance. The net performance was affected by the shape of the drop mass since sharp-edged, cylindrical masses tended to cut the nets. According to this study, during installation, the initial sag should be kept at roughly 10% (McCann, 2011). According to research by Skarbøvig et al. (2011), to prevent the FOG from gaining momentum before it strikes the net, the net needs to be installed as close to the hangingwall as feasible. The FOG's increased motion tended to fail the net. To minimize any sag, tensioners are placed at the end of a safety net for use in mining applications, and hooks are positioned throughout the net's body to provide maximum tension against the hangingwall. In a stope panel at Thembelani Mine, a sag range of 0 m to 0.05 m was commonly seen between the hangingwall and the net. A 0.05 m to 0.1 m sag range was noted for haulages and crosscuts.

### 3.1.2 Safe working height

The safe working height in this context is the vertical distance between the foot wall and the safety net suspended on the hangingwall after holding a falling rock. In this regard, the stoping width is 1.2 m for normal ground conditions, 1.4 m for higher areas in adverse ground conditions and for flat development end is 3.2 m. Therefore, if a FOG weighing less than two tonnes occurs, an employee drilling in these stopping widths should not sustain any injuries.

According to McCann (2011), to prevent undue loading on attachments and greater displacements (also referred to as deflection) on the safety net, attachments should not be placed too far apart. Less ground clearance beneath the net (sometimes referred to as survival height) is the result of higher safety net deflection. A survival height of 0.6 m or above is advised by Ryder and Jager (2001) as sufficient clearance to permit employee mobility within a stope panel. The support design must therefore account for a maximum closure of 0.3 m (0.1 m from quasi-static closure and 0.2 m from dynamic closure) in a dynamic loading environment, based on a conventional stoping panel with a stoping width of 0.9 m (Ryder and Jager, 2001).

For Thembelani Mine, a specific safety net deflection as a function of survival height should be determined and used as a design criterion. Rock drill operators (RDOs) are the group of workers at Thembelani Mine who spend most of their time drilling in the face area. Onsite measurements revealed that the RDO kneeling height during drilling is between 0.7 m and 0.8 m. The safety net should not be allowed to be deflected by the falling rock to the point where it strikes the RDO who is kneeling and drilling beneath the net. Table 3-1 shows how the maximum allowable deflection on the safety net and BOM was determined.

*Table 3-1: Criterion for deflection on safety net or BOM at Thembelani Mine*

| Excavation type | Stoping width (m) | Working height (m) | Acceptable vertical displacement of the rock from Hangingwall (m) | Initial Sag on the net(m) | Maximum net deflection(m) |
|---|---|---|---|---|---|
| **Normal Conventional stope panel** | 1.200 | 0.800 | 0.400 | 0.050 | 0.350 |
| **Adverse ground conditions stope panel** | 1.400 | 0.800 | 0.600 | 0.050 | 0.550 |
| **Haulage and crosscut** | 3.200 | 1.800 | 1.400 | 0.100 | 1.300 |

Safety nets and BOM at Thembelani Mine should be able to hold two tonnes rock at deflections of no more than 0.35 m and 0.55 m, respectively, for stope widths of 1.2 m and 1.4 m. The safety nets and BOM for haulages and crosscuts should not deflect more than 1.3 m. As a result, the design criteria for deflection on safety nets and BOM are based on these values. This criterion is valid provided the hooks, face plates, mechanical props hooks and mechanical props headboard do not fail and give way for the safety net to deflect with the fallen rock.

Additionally, McCann (2011) found that, except for evident damage, net defects did not affect the net performance. There is a discard criterion on defects for safety nets used in the mines. At Thembelani Mine, a safety net is disposed of in accordance with the manufacturer's specification if any of the perimeter, outside, or two inside webbing straps break. The entire BOM sheet is thrown away if any wires are broken or corrosion is found. Therefore, this study considers safety nets and BOM sheets free of flaws.

## 3.2 Learnings from Historic Drop Tests on Safety Nets and Blast-on Mesh

The performance of safety net tests was the subject of two studies, one in Europe and the other in RSA, as reported in chapter 2 of this study. A few lessons about building a drop test facility and performing drop tests for safety nets were learned from the European construction sector. These investigations led to the conclusion that safety nets intended to catch free-falling objects need to undergo testing at a drop test facility. To measure the force of the loading mass and the net's deflection, an object with a specific mass is dropped onto the net at the drop test facility.

Load cells were utilized by the safety net testing facility in Europe as well as the BOM testing facility at WASM to accurately measure the force and displacement during drop tests. This study aims to address all temporary support elements used at Thembelani Mine, as well as the 3 mm strand diameter BOM that was not tested at WASM, as explained in Chapters 1 and 2.

## 3.3 New Concept Mining Drop Test Facility

The NCM drop test facility is situated at Kroondal farms near the town of Rustenburg in the Northwest Province of RSA. It is specifically designed to test safety nets that are supplied by NCM to the mines. The NCM drop test facility comprises two base frames for testing of nets and mechanical props. An overhead crane extends over the two base frames. The overhead crane has rails on which the mass is moved between the two base frames. Steel slabs with a mass of up to three tonnes may be dropped above the steel base frame up to a safe distance of 1 m above the frame. The facility is also equipped with an accelerometer attached to the centre of the mass to measure the velocity, impact force, and displacement during the test. The output goes into a laptop whereby the software is used to calculate impact velocity, kinetic energy, total energy, final deformation, maximum deflection, maximum force, and survival height.  A camera stand is also in place to capture videos during the drop test. A schematic plan view of the NCM drop test facility is indicated in Figure 3-1.

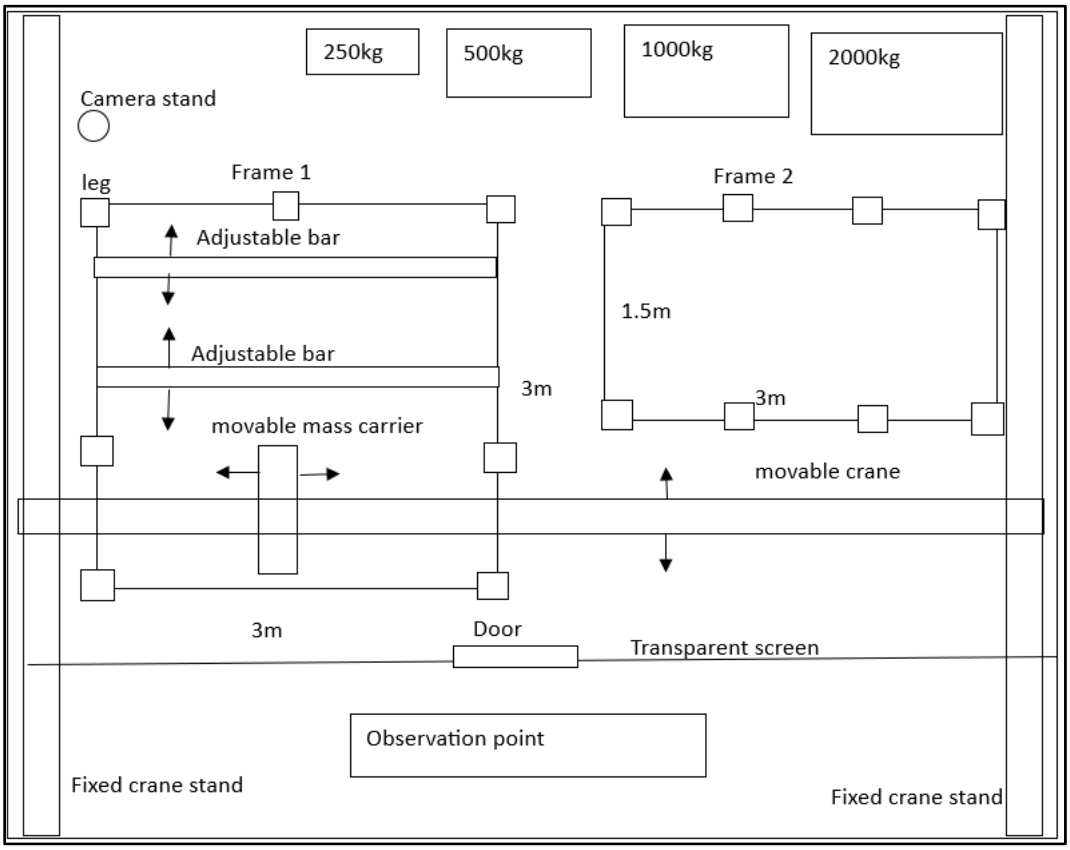



*Figure 3-1: Schematic plan view of NCM dynamic drop test facility*

Within the NCM facility, square-shaped steel slabs weighing 250 kg, 450 kg, 500 kg, 1000 kg, and 2000 kg are positioned to be dropped onto safety nets. Two movable arms on Frame 1 allow for safety net fits up to 3 m in length and 3 m in width. In a safer manner, the facility has tested 3.1 m x 1.4 m nets thus far. At Thembelani Mine 10 of the 3.1 m x 1.4 m Rock-stop safety nets are installed to cover 30 m face area length (excluding ASG and siding). The fixed dimensions of Frame 2 are 1.5 m x 3 m.  Safety nets, roof bolt face plates, and hooks are tested using Frame 1, and mechanical props with safety nets are tested using Frame 2. Pictures of the NCM facility are provided in Figures 3-2, 3-3, 3-4, 3-5 and 3-6.


*Figure 3-2: NCM accelerometer attached to a steel block mass hanging on a crane above Frame 1*

The movable three-tonne overhead crane can lower the weight at any point along and across the two frames. It is supported by two fixed stands. The crane lowers the mass onto the safety net from a predetermined height. A pin and shackle fasten the mass to the crane. During the test, the steel block is released using a cable that is fastened to the pin, allowing for free-fall. To measure displacement and velocity during the drop test, an accelerometer is magnetically attached to the drop mass.

*Figure 3-3: NCM Frame 1 for testing of nets, hooks and face plates*

Steel tubes that fit into Frame 1 are designed to hold bolts in place and are fastened with nuts at the top of the tube. The face plates and hooks are fastened to the bolt's bottom using nuts to replicate an underground installation. The safety net is then fastened to the hooks at any interval required by the mine specifications. Face plates are placed 1.2 m above the ground to replicate the width of a typical conventional panel stop. If the tested materials are unable to support the steel blocks, a rubber mat is positioned over a hole in the floor beneath the frame to safely bring the blocks to rest and shield the floor.

*Figure 3-4: NCM Frame 2 for testing of mechanical props with safety nets*

Up to six mechanical props arranged at a fixed 1.5 m spacing can be accommodated by Frame 2. The footplates of the props are fixed on permanent concrete slabs during installation, and the headboard presses square steel blocks against the test frame's base. Like a standard conventional panel stopping width, the space between the bottom of the steel blocks and the concrete blocks is 1.2 m. Frame 2 does not have an accelerometer because it was intended to be used for visual tests to help mines test their mechanical props using NCM nets. If the tested materials are unable to support the steel blocks, plastic nets are positioned beneath Frame 2 to securely bring it to rest and shield the floor.


*Figure 3-5: Transparent observation safety screen*

During the drop tests, the operator and observers stand behind the safety screen to avoid any injury from flying objects. Access to the test area is only allowed before and after the test for setting up and taking measurements after the test. Before everyone else can enter the test area after the test, the operator enters first and re-attaches the shackle to the dropped mass so that in case it continues falling it gets held by the crane. Correct Personal Protective Equipment (PPE) such as safety glasses, gloves, and hard hats are required during the test.

*Figure 3-6: Two tonnes steel slab at NCM drop test facility*

A steel slab measuring 1.99 m in length, 0.75 m in width, and 0.17 m in thickness is dropped on the safety net undergoing the test from a predetermined height above the net.  To avoid sharp edges harming the nets during testing, the slab's edges are smooth.

### 3.4 Videx Drop Test Facility

The Videx dynamic drop test facility is situated in Germiston in the Gauteng Province of RSA. It was built mainly for testing face plates and hooks that Videx Mining Supplies supplied with roof bolts. Furthermore, any supplier or mining company is welcome to use Videx Mining Supplies' facilities to run drop tests on their mining support product line. To assess deflection and determine if they can support a specific mass, face plates, hooks, safety nets, steel mesh, and mechanical props may be put through testing. Figure 3-7 shows the Videx drop test facility.

*Figure 3-7: Videx dynamic impact drop test facility*

The facility comprises of the drop rig, base test frame for attaching material to be tested, and screen mesh to contain falling objects within the confines of the test area. A steel slab of a certain mass is attached to a chain using two shackles and a round pole. The chain is rolled upwards and downwards by a winch at the top of the rig to lift or lower the mass of up to two tonnes to a specific distance above base frame. Drop heights extend up to 1m above the test frame. To reduce swing during the drop test, the steel slab is dropped using a round pole after the shackles are removed. In the event that the tested materials are unable to support the steel slab, a tractor tire is positioned beneath the test frame to safely bring it to rest and shield the floor. There are currently no accelerometers or load cells in the facility. Physical measurements are taken both before and following the drop test. Before and after the test, visual observations are also made of the products under examination. Images and videos may be captured while conducting the test. Figure 3-8 displays an image of the base frame.

*Figure 3-8: Videx drop test base frame*

Two steel arms that are fixed and two steel arms that are adjustable make up the basic test frame. The movable arms can be extended up to 2 m apart, while the fixed arms are spaced 3 m apart. The movable arms feature holes that allow face plates and roof bolts to be attached. The test frame's bottom and floor are separated vertically by 1.2 m distance, simulating a traditional stope panel in a narrow reef environment. In the centre of the test frame, a two tonnes steel slab as depicted in Figure 3-9, is dropped vertically onto the test area.

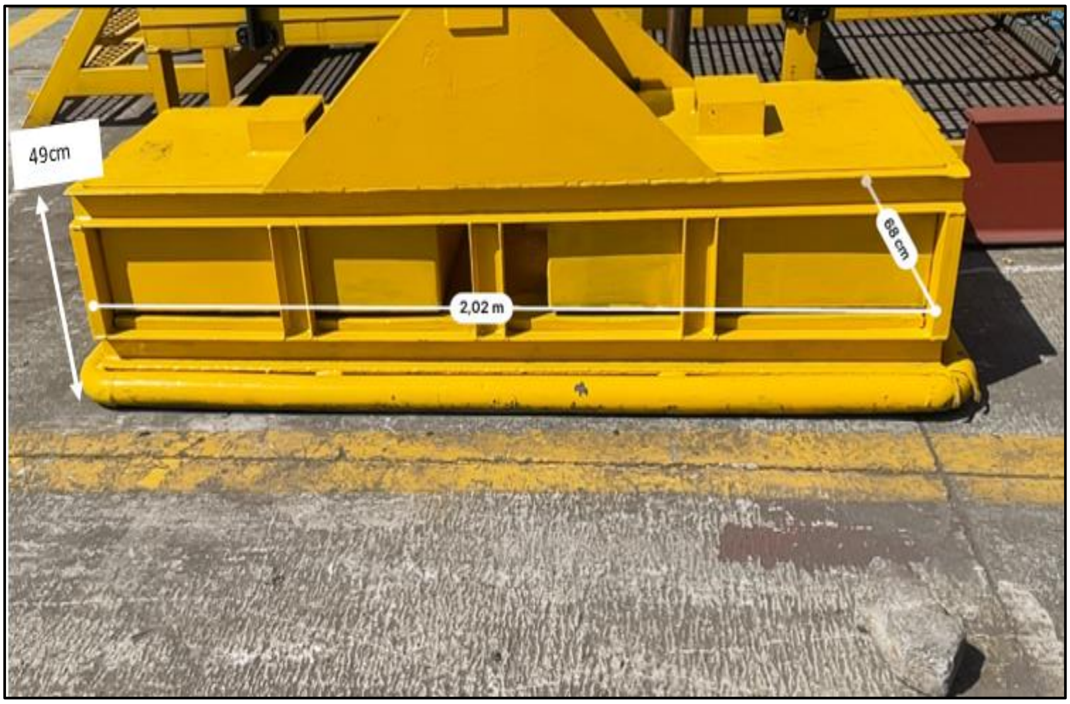


*Figure 3-9: Two tonnes steel slab used at Videx drop test facility*

For two tonnes drop test, a steel slab with length of 2.02 m, width of 0.68 m and thickness of 0.49 m is dropped on the materials being tested from a specific distance above the net. The slab is smooth on the edges to prevent sharp points from damaging the nets during the test.

## 3.5 Alignment of NCM and Videx Facilities with the European, Savuka and Western Australian School of Mines Test Facilities

### 3.5.1 Sag and wastage

This investigation made use of two dynamic drop test facilities. The NCM was used for testing safety nets, and Videx was used for testing BOM. Both Videx and NCM's attachment points permit flexible hook attachments to be placed on the face plates during testing, which complies with European drop test regulations. Savuka did not take into consideration the 225 mm (recommended 100 mm) of waste that was indicated by the European standard for safety nets between the net and hooks. The effect of waste is lessened in the mines by using tensioners to drape the net against the hangingwall. Waste was therefore not considered in this investigation.

### 3.5.2 Drop mass

Both NCM and Videx drop test facilities, to an extent, perform dynamic drop tests in a similar manner to both the European net testing facilities, the Savuka drop test facility and WASM for BOM. It is noted that only a single slab is dropped for a single test on both the NCM and Videx drop test facilities. This is different from the two tonnes drop test conducted at Savuka, which consisted of eight blocks with a mass of 250 kg each dropped onto the net. The FOG database for Thembelani Mine indicated that FOGs that caused casualties occurred as larger slabs with a length of 1 m to 1.8 m, a width of 0.5 m to 1 m, and a thickness of 0.2 m to 0.4 m. The two tonnes steel slab dimensions of 1.99 m x 0.75 m x 0.25 m and 2.02 m x 0.68 m x 0.49 m for NCM and Videx, respectively, are more representative of FOGs that resulted in casualties at Thembelani Mine. A pole attached to the steel slab dropped onto the materials to be tested at Videx reduces the effect of the swing to conform to the WASM dynamic drop test facility.

### 3.5.3 Drop height

While drop heights at the European test facility and Savuka were conducted at 2 m and 0 m to 2 m above the net, respectively, at NCM and Videx, drop heights can be adjusted up to 1 m above the net. For this exercise, the drop height ranged from 0 m to 0.3 m above the safety net and 0 m to 0.1 m above the BOM to accommodate all possible installations underground. The ideal situation would have the safety net or BOM draping against the hangingwall, which is denoted by a drop height of 0 m above it. In the case of safety net installation, tensioners are installed to ensure that the net completely drapes the hangingwall. A drop height of 0 m above the net or mesh will be conducted to simulate static performance along a smooth hangingwall in a similar manner to Savuka dynamic drop tests on mine safety nets.

### 3.5.4 Number of drops conducted per safety net or Blast-on mesh

While at Savuka, a mass was dropped repeatedly until the safety net broke, at NCM, a mass is dropped once on each safety net. Whether or not they are damaged, the safety net and mechanical props at Thembelani Mine are disposed of after holding the FOG. This explains why single drops are used. Attachments such as face plates and hooks are changed after holding a FOG. Every sample was exposed to a single drop mass during the dynamic testing of the steel mesh at WASM, and the outcomes were noted at the time the wires ruptured. This therefore sets the standard for testing of BOM in the South African drop test facilities, as the mesh is expected to hold a rock falling under gravity.

### 3.6 Data Collection Process

The two tonnes temporary support system's primary goal is to hold two tonnes without unduly deflecting and exposing the worker beneath to injury from the FOG. To create a standard for allowable deflection on the temporary support system, measurements were made onsite. Additionally, a review of the temporary support standard was conducted at Thembelani Mine to conduct drop tests in a manner that simulated it. Original equipment manufacturers (OEMs) provided specifications for temporary support elements, including safety nets, mechanical props, hooks, face plates, BOM and spike plates. Calculations of strength against structural properties were made on some of the specifications. For instance, a direct proportionality between the hooks' diameter and strength was noted. Deflections from the drop tests were measured and compared to the maximum permitted deflections found for underground environments. During the drop tests, the temporary support units' deformation, failure, and deflection were noted.

### 3.7 Data Validation and Analyses Approach

This study utilizes the physics of falling objects, as explained in chapter 4, to establish a correlation between the total force on temporary support and the drop height at various deflections. By comparing the accelerometer data obtained from NCM with this correlation, it can be determined whether there is alignment or not. If there is alignment, it can be concluded that the accelerometer measurements obtained from the NCM drop test facility are accurate and can be used for analysis and decision-making purposes. To evaluate deformation and failure on support units, measurements and physical observations were made both before and after the drop test. To help with the comparison of the physical conditions prior to, during and following the tests, photos and videos were taken during the test. Failure Mechanisms were assessed based on physical observations and measurements taken during the tests. Results from drop tests were compared with the direct proportional relationship between hook diameter and hook strength derived from OEM supplied information.

## 3.8 Chapter Summary

For the study of temporary support at Thembelani Mine, two tonnes drop tests were conducted using the drop test facilities at NCM and Videx. These facilities were designed to simulate dynamic drop tests for free-falling objects and assess the deflection on safety nets as well as the deformation on attachments. The structural construction of both facilities is in accordance with the standards set for European and Savuka test facilities. Additionally, the Videx drop test facility complies with the WASM dynamic drop test facility for BOM.

# 4 CHARACTERISTICS OF TEMPORARY SUPPORT, DESIGN REQUIREMENTS AND TEST PROCEDURES

This section provides a detailed description of the specifications of the temporary support units used at Thembelani Mine. It also highlights the design requirements that the temporary support systems must fulfil. Furthermore, it explains the test protocols replicating the standard underground installations at Thembelani Mine.

## 4.1 Safety Nets Used at Thembelani Mine

Rock-stop safety nets, with a capacity of two tonnes and a deflection of 0.3 m, are employed in the stope panels and off-reef excavations at Thembelani Mine. These nets can be customized to fit any excavation size, based on the user's preference. Refer to section 1.2 for the installation procedure of safety nets at Thembelani Mine. Figure 4-1 shows the Rock-stop safety net used at the Mine.

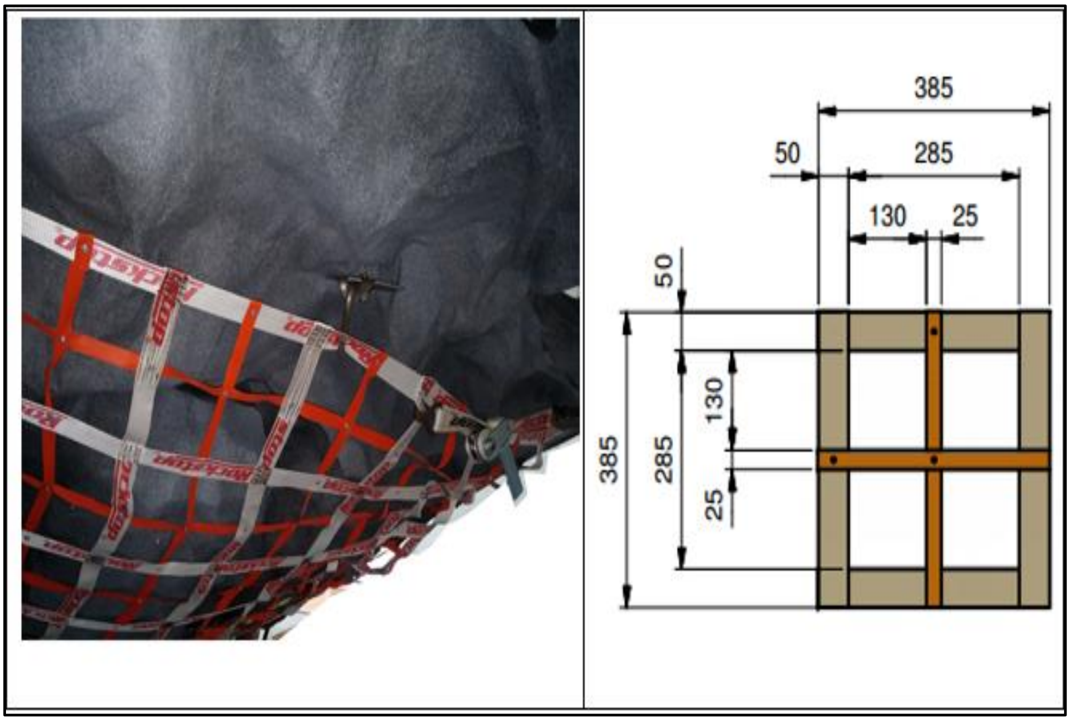



*Figure 4-1: Two tonnes Rock-stop safety net used at Thembelani Mine (Steyn et al., 2018)*

The Rock-Stop safety net is designed with white perimeter webbing, white outer webbing, and orange inner webbing. The outer webbing has a width of 50 mm and is made up of apertures that measure 285 mm x 285 mm. The orange inner webbing reduces the overall size of the apertures to 130 mm x 130 mm with a width of 25 mm. The individual straps of the inner webbing are connected to each other and to the outer webbing using rivet pins. The corners of the outer webbing are looped around the perimeter webbing and stitched together. The perimeter, outer and inner webbings are all made of Polyester material, and their strengths are provided in Table 4-1 (Steyn et al., 2018).

*Table 4-1: Two tonnes Rock-stop safety net webbing strength (Steyn et al., 2018)*

| **Webbing type** | **Tensile Strength (kN)** |
| --- | --- |
| White Polyester (Perimeter webbing) | 58.900 |
| White Polyester (outside webbing) | 39.300 |
| 100% Polyester Orange (inside webbing). | 7.500 |

The Rock-stop safety net features a distinct white webbing along its perimeter, which possesses superior tensile strength compared to the remaining outer white webbing, despite their identical appearance. To facilitate energy absorption, the orange, white webbing exhibits the lowest tensile strength. As per the manufacturer's specifications, it is anticipated that the safety net will fail at its weakest point, which corresponds to the inner webbing. The manufacture's specifications indicate that the Rock-stop safety net is designed to hold two tonnes at an attachment spacing of 1.5 m x 1.5 m (Flanagan, 2023).

## 4.2 Mechanical Props Used at Thembelani Mine

The mechanical props with a square headboard area of 130 mm x 130 mm and exposed Cams were replaced with T-shaped long headboard props after a fatal incident in 2020 due to FOG with a mass 1.65 tonnes. Tests conducted by M props indicated the square headboard props provide a pre-stressed load of 0.86 tonnes for old square headboard props and 1.43 tonnes for new square headboard props when input force of 0.05 tonnes equivalent to installation with a hand in an underground workings is applied(Strong, 2016) . The pulling out of the square headboard mechanical props was due to a smaller headboard surface area of 130 mm x 130 mm in contact with hangingwall and a pretensioned load of 0.86 tonnes to 1.43 tonnes which could not sustain a falling rock with a mass of 1.65 tonnes headboard prop with exposed cams is already indicated in Figure 1-6.

The T-shaped props, also known as medium duty Camlok grease box props, have a longer headboard of 370 mm x 100 mm and come in various lengths. Tests conducted by M props indicated the Camlok grease box props provide a pre-stressed load of 2.07 tonnes for used square props and 2.38 tonnes for new square headboard props when input force of 0.05 tonnes equivalent to installation with a hand in underground workings is applied. The pretension load of over 2 tonnes provide resistance to slip when the props are installed with two tonnes safety nets to hold mass of up to two tonnes (Strong, 2016). Strong (2023) indicated that these props have a compressive strength of 6.62 tonnes to 14.68 kN and are equipped with a load indicator to ensure they can hold up to two tonnes when installed with a safety net at a spacing of 1.5 m x 1.5 m. The props are secured in place with a detachable tensioning spanner as shown in Figure 4-2.

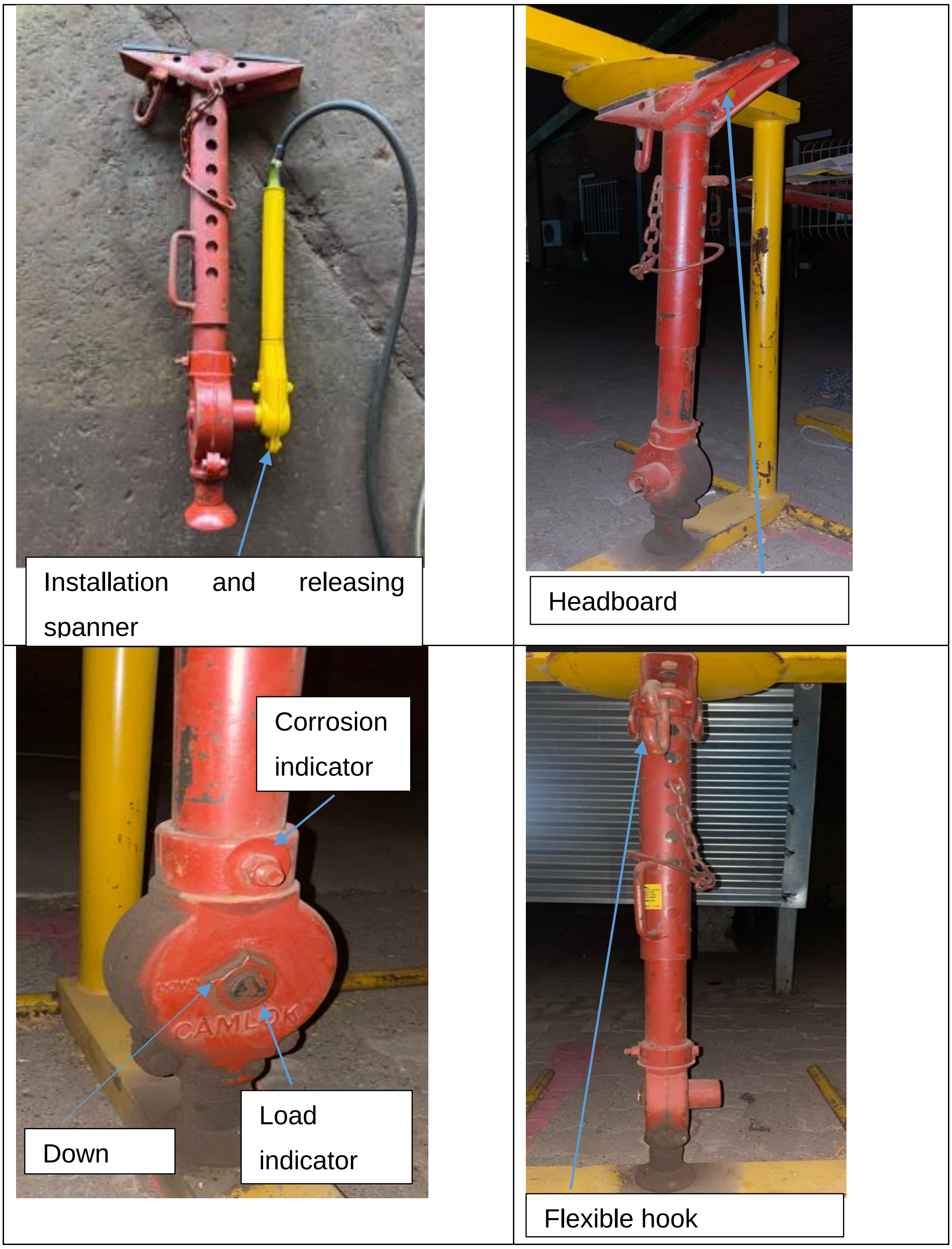



*Figure 4-2: T-shaped long headboard Grease box mechanical prop used at Thembelani Mine*

The headboard's rubber material enhances slip resistance when holding a FOG, and its greater area reduces the likelihood of slippage. A 16 mm diameter flexible G-shaped hook is affixed to the headboard via a welded 16 mm diameter rod. To achieve sufficient tension, the load indicator must rotate approximately 90°

counterclockwise from the Down-arrow to the Up-arrow. The headboard's hook attaches the safety net to the prop. In case of BOM the headboard presses the mesh against the hangingwall thereby securing it tightly in place. The props are designed to support two tonnes of rock when installed at a spacing of 1.5 m x 1.5 m (Strong, 2023).

### 4.3 Blast-on Mesh Used at Thembelani Mine

The UHTSSM that is available in the South African market is MINAX 80/3, which has been previously discussed in section 2.2.1. According to Mathews (2023), MINAX 80/4 is not used in the South African market due to its higher price. MINAX 80/3 is priced at an average of R 290 / $m^2$, whereas MINAX 80/4 is priced at an average of R 590 / $m^2$. The cost of MINAX 80/3, including spike plates, has been determined to be R 352 / $m^2$ at Thembelani Mine for the year 2023. The literature review in section 2.2.1 has indicated that MINAX 80/4 is both stiffer and stronger than MINAX 80/3. However, MINAX 80/4 is more suitable for seismically active mines. The only specifications provided by the OEM to Thembelani Mine are those listed in column 4 of Table 2-1. These specifications do not include information about the net's deflection during the process of holding a FOG with a certain mass. Therefore, the drop test should be conducted on MINAX 80/3 to establish if it is strong enough to hold two tonnes at acceptable deflections. Figure 4-3 shows an installed MINAX 80/3 BOM at Thembelani Mine.

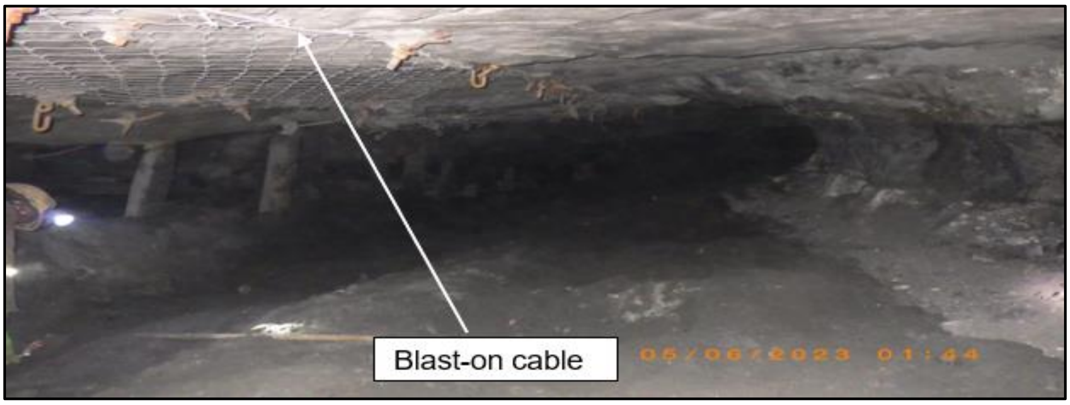



*Figure 4-3: MINAX 80/3 BOM as installed at Thembelani Mine*

MINAX 80/3 BOM is secured to the hangingwall using roof bolts and spike plates, as well as face plates. The spike plates firmly grip the mesh to the hangingwall, while the face plates offer the option to install a hook. This hooking option may be necessary for attachment of safety nets in situations where larger brows are present, and the mesh cannot be fully installed and draped against the rock. To ensure a secure attachment, round steel spike plates with a thickness of 3 mm and a bolt hole diameter of 30 mm are utilized in conjunction with MINAX 80/3.

According to Figure 4-3, the average distance that needs to be barred between the mesh and the face is 1.2 m in the direction of advance. This provides an advantage compared to situations where BOM is not employed, as the normal distance to be barred is 4.3m.

At Thembelani Mine, MINAX 80/3 is equipped with an 8 mm diameter blast-on cable, which is positioned on the side closer to the face to prevent any damage caused by blasts. Figure 4-3 demonstrates that there was no damage observed on MINAX 80/3 following the blast.

## 4.4 Hooks and Face Plates Used at Thembelani Mine

Face plates and hooks, which are made from Spring steel, are assembled with Resin bolts for instope bolting. Initially, G-hooks with a diameter of 12 mm and face plates with a surface area of 125 mm x 125 mm and a thickness of 4.5 mm were assembled to the Resin bolts. However, to meet the requirements of two tonnes temporary support systems, the thickness of the face plates was increased to 6 mm and the diameter of the hooks was increased to 14.5 mm (le Roux, 2020). The face plates, spike plates and hooks currently being used at Thembelani Mine are depicted in Figure 2-9. The tensile strength test on a 6 mm face plate pulled with a 14 mm hook at the lab is illustrated in Figure 4-4.


*Figure 4-4: Pull test of face plates and hooks (le Roux, 2020)*

Figure 4-4 shows a face plate being pulled by a hook from the hole on which the hook is attached. The hook is inserted in the hole and the face plate is subsequently pulled out. To ascertain the tensile strength, the load is measured in relation to the elongation as the bolt exerts force on the face plate. Failure occurs when either the hole in the face plate breaks or the hook stretches open. The maximum tensile strength is determined at the point of failure (le Roux, 2020). Table 4-2 represents the maximum tensile load to pull open the face plate hole and/or the hook.

*Table 4-2: Strength of 14.5 mm hooks and 6 mm face plates (le Roux, 2020)*

| **Support element** | **Tensile Load to stretch the hook open or open the face plate hole (kN)** |
|---|---|
| 14.5 mm G-hook | 25.000 |
| 6 mm face plate | 40.000 |

It is important to note that the results pertain specifically to a dog ear face plate with a hook-hole positioned 10 mm from the edge of the corner of the plate and 5 mm from the edges on the other two sides. It is worth noting that even if the tensile strength of the face plate and hook meet the requirements of a two tonnes system, a drop test must still be conducted. This is because impact forces and metal behaviour may be different from the static tests during a drop test.

The Rock-stop safety nets utilised at Thembelani Mine in ASGs, raises, winzes, and flat ends are equipped with S-hooks with a diameter of 14 mm, which are supplied by NCM. These hooks are constructed from Carbon steel with a steel grade of 500 N. The static strength properties of all hooks provided by NCM can be found in Table 4-3.

*Table 4-3: NCM S-hook strength parameter (Steyn et al., 2018)*

| **Diameter (mm)** | **Tensile Load to pull open the S-hooks (kN)** |
|---|---|
| 12 | 13.300 |
| 14 | 22.600 |
| 16 | 30.400 |

The relationship between the diameter of the S-hook and the tensile load required to pull it open is directly proportional. This correlation is illustrated in Figure 4-5, where the hook diameter and corresponding tensile load are plotted.

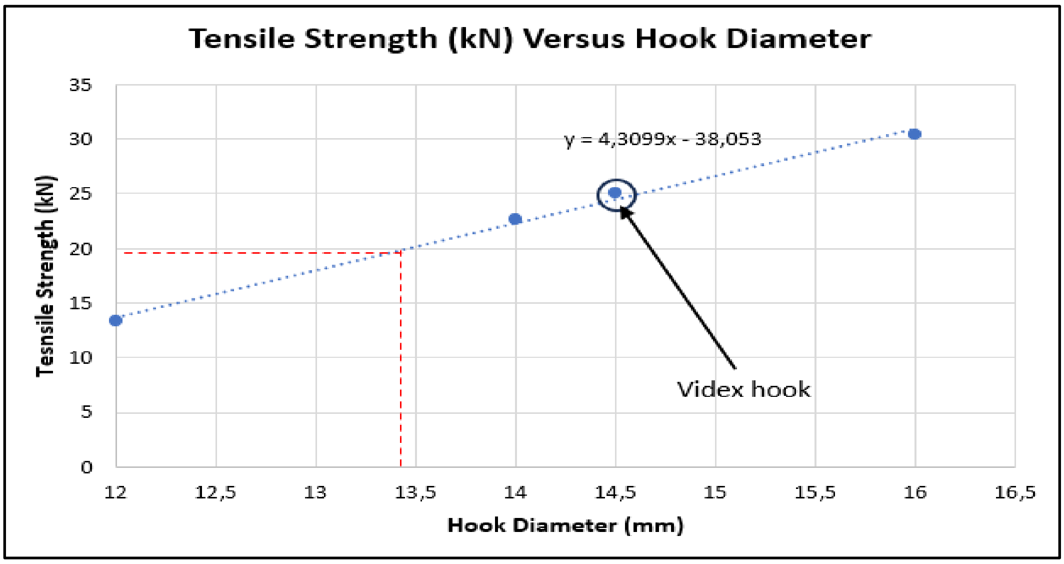



*Figure 4-5: Tensile strength when hook pulls open versus hook diameter*

The tensile strength of three different hook sizes from NCM demonstrates a linear increase as the diameter increases. Using a best-fit straight line, an equation can be derived to calculate the tensile strength for diameters between 12 mm and 16 mm. The Videx G-hook, with a diameter of 14.5 mm, aligns with the best-fit line, regardless of the different types of steel and shape of the hooks used compared to the NCM hooks. The dotted red lines, deduced from the best-fit line, indicate that hooks with a diameter of 13.4 mm provide a tensile strength of 19.6 kN, which is equivalent to two tonnes. Even though Figure 4-5 indicates the expected tensile strength required to pull open the hook, it is still necessary to test the hooks at drop test facilities, with the rest of the temporary support systems, at prescribed spacings and drop heights to assess if they can hold two tonnes from systems test point of view.

## 4.5 Drop Test Set-ups

### 4.5.1 Safety nets

The set-up for conducting drop tests to evaluate the performance of safety nets, using face plates and hooks, was organized in a comparable fashion to underground. Both face plates with hooks and mechanical props with hooks are situated at the identical position, as depicted in Figure 4-6.

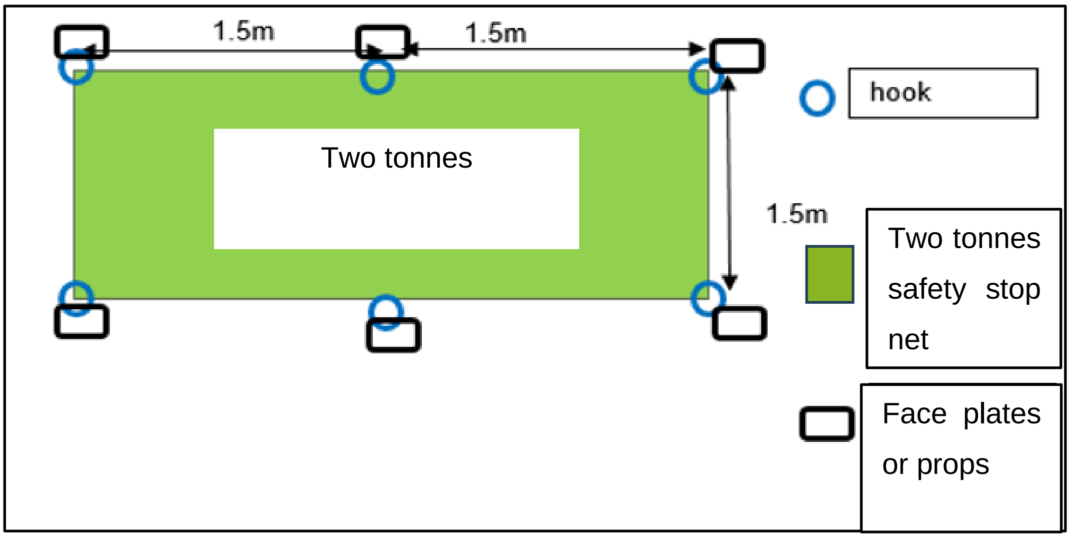



*Figure 4-6: Schematic view of safety net drop test set-up*

The purpose of conducting a drop test on the safety net with hooks was to assess the deflection parameters of the net, as well as the strength of the face plates and hooks that accompany roof bolts. Various hooks and face plates of different thicknesses were tested until the ones that met the two tonnes system requirements were determined based on the results. The Rock-stop safety nets provided were utilized for both tests, including face plates and hooks, as well as mechanical props. To evaluate the prop's hook performance and its ability to withstand slipping out while holding the falling mass, T-shaped mechanical props with flexible hooks of 16 mm G-hooks were employed. According to Strong (2023), the 16 mm hook that comes with the props is made from En8 bright bar high Carbon steel. Although the OEM did not provide the specifications for the hook in terms of tensile strength when the hook pulls open, the tensile strength of a 16 mm diameter hook were estimated to be 30 kN using Figure 4-5. Another set-up was arranged such that the two tonnes mass is dropped away from the centre and much closer to the attachment points to simulate eccentric loading on the Grease box props. This set-up is shown in Figure 4-7.

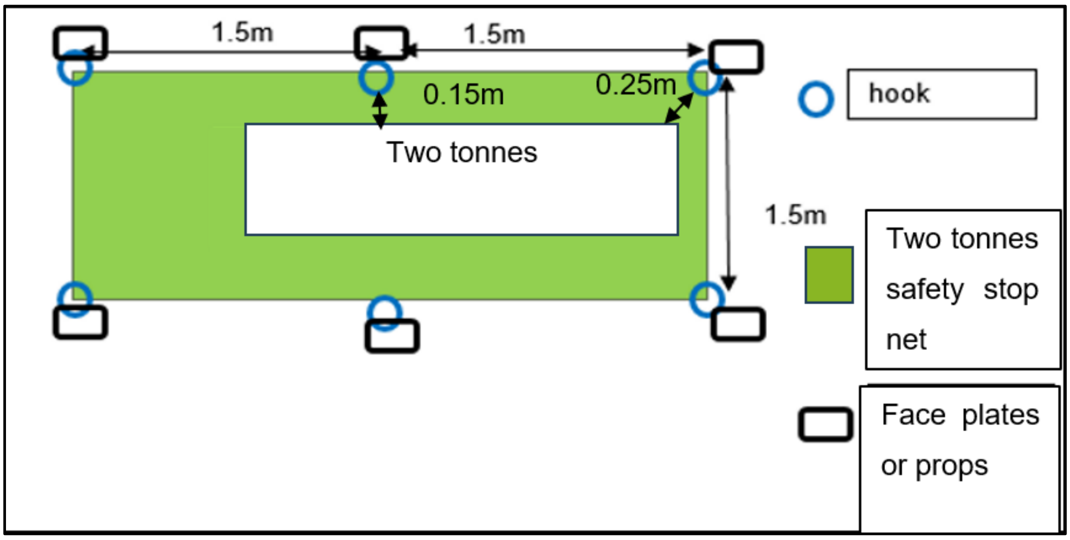



*Figure 4-7: Drop test set-up to simulate eccentric loading mechanical props attachments*

In this set-up, the two tonnes mass is dropped as close as possible to the hooks of the mechanical props. The distance between the mass and the central hook on one side is 0.15 m, and the distance between the mass and the corner attachment on the same side is 0.25 m. The main objective of this set-up is to assess whether the mass falling closer to the attachments will cause attachment failure or slipping out of the prop.

### 4.6 Drop Test Set-up for Blast-on Mesh

The drop test set-up for evaluation of BOM performance was arranged as installed underground. The test set-up aimed to simulate the three underground mesh installation scenarios is shown in Figure 4-8.

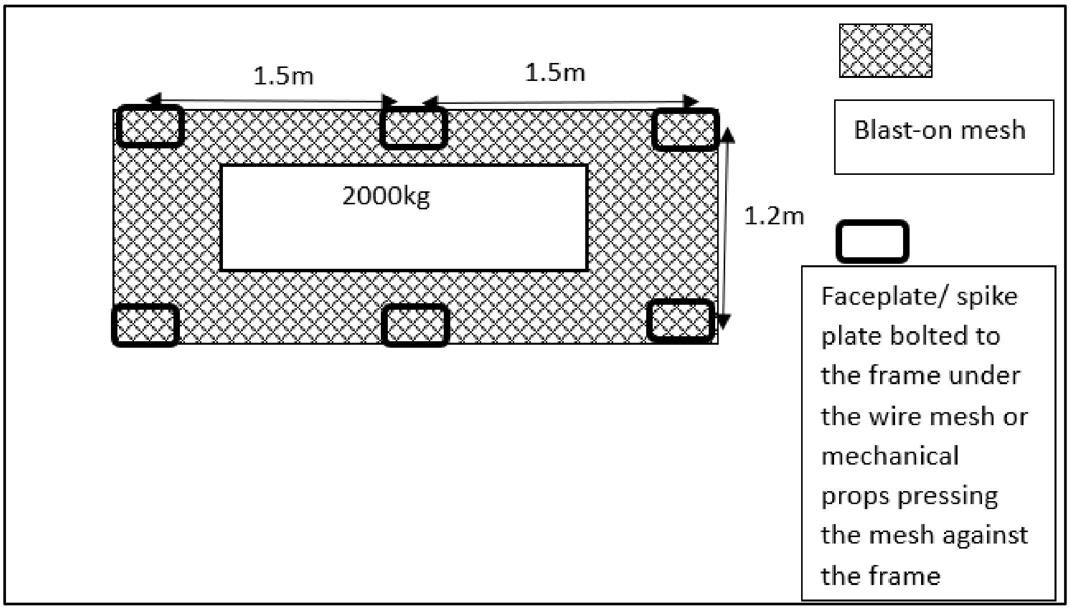



*Figure 4-8: Schematic view of BOM drop test with face plates or spike plates or mechanical props*

The mesh underwent testing in three different scenarios for underground installation. In the first scenario, two tonnes were dropped onto a BOM pinned to the frame by two rows of mechanical props. The spacing across the frame was 1.2 m, while along the frame it was 1.5 m.

In the second and third scenarios, the BOM was placed against a test frame using three mechanical props, which were spaced 1.5 meters apart on one side of the frame. On the other side of the frame, three bolted face plates or spike plates held the BOM at a spacing of 1.5 meters apart. The distance between the mechanical props and the face plates or spike plates was 1.2 meters. This set-up simulated the installation of the BOM in a stope panel, where one side is attached to the previously installed BOM and the other side is pressed against the hangingwall by the mechanical props.

## 4.7 Determining of Strength and Deflection Parameters of Safety Nets and Blast-on Mesh

The physics of objects in a free-fall motion was utilized to assess deflection, impact force and total force experienced by the safety nets and BOM. According to Meriam and Kraige (2012), the force exerted by a falling object in the vertical direction is determined by its mass and the gravitational acceleration. This relationship can be represented by Equation 4-1:

$$F_w = mg \qquad \textit{Equation 4-1}$$

In this equation, $F_w$ represents the weight of the object in kilonewtons (kN), $m$ represents the mass of the falling object in kilograms (kg) or tonnes, and $g$ represents the constant gravitational acceleration of 9.81 in m/s$^2$.

When an object is stationary above the ground, it possesses potential energy which is converted into kinetic energy once it begins to move. The total energy of the object is therefore the sum of its potential and kinetic energy. After impact with the ground, all the energy is converted back into potential energy (Meriam and Kraige, 2012). Ryder and Jager (2001) define the total energy that needs to be absorbed by the support unit as follows:

$$E = \frac{1}{2}\, mv^2 \; + mgh \qquad \textit{Equation 4-2}$$

In Equation 4-2, $E$ represents the total energy that must be absorbed by the support unit, which is the sum of the object's kinetic energy and potential energy. $v$ represents the velocity of the falling object, $m$ represents the mass of the object, $g$ represents the gravitational acceleration of 9.81 m/s$^2$ and $h$ represents the distance the object falls (Ryder and Jager, 2001). Meriam and Kraige (2012) further indicated that when a falling object hits a surface, the surface or the object undergoes deformation or deflection. Therefore, the impact force is determined as a function of the drop height and deformation, or deflection as shown in equation 4-3. The total force acting on a surface after an object has fallen on it is the sum of the weight of the object and the impact force as shown in equation 4-4. Furthermore, the impact velocity is determined as a function of conservation of momentum whereby potential and kinetic energy are equal just before hitting the ground. Therefore, the velocity of impact is deduced as the square root of twice the product of gravitational acceleration and the drop distance as shown in equation 4-5.

$$F_i = \frac{mgh}{d}$$ *Equation 4-3*

$$F_t = F_w + F_i$$ *Equation 4-4*

$$v = \sqrt{2gh}$$ *Equation 4-5*

The determination of the impact force $(F_i)$ on a surface due to a falling object involves several variables. These variables include the mass of the object ($m$), the gravitational acceleration (g), the drop height ($h$), the deflection ($d$), the velocity ($v$), and the total force ($F_t$) required to hold the object on the surface. To investigate this phenomenon, the physics concepts presented in the works of Meriam and Paige (2012) and Ryder and Jager (2001) were utilized. These concepts were employed to calculate the deflection on the net or mesh and to determine the total force, as depicted in Figure 4-9.

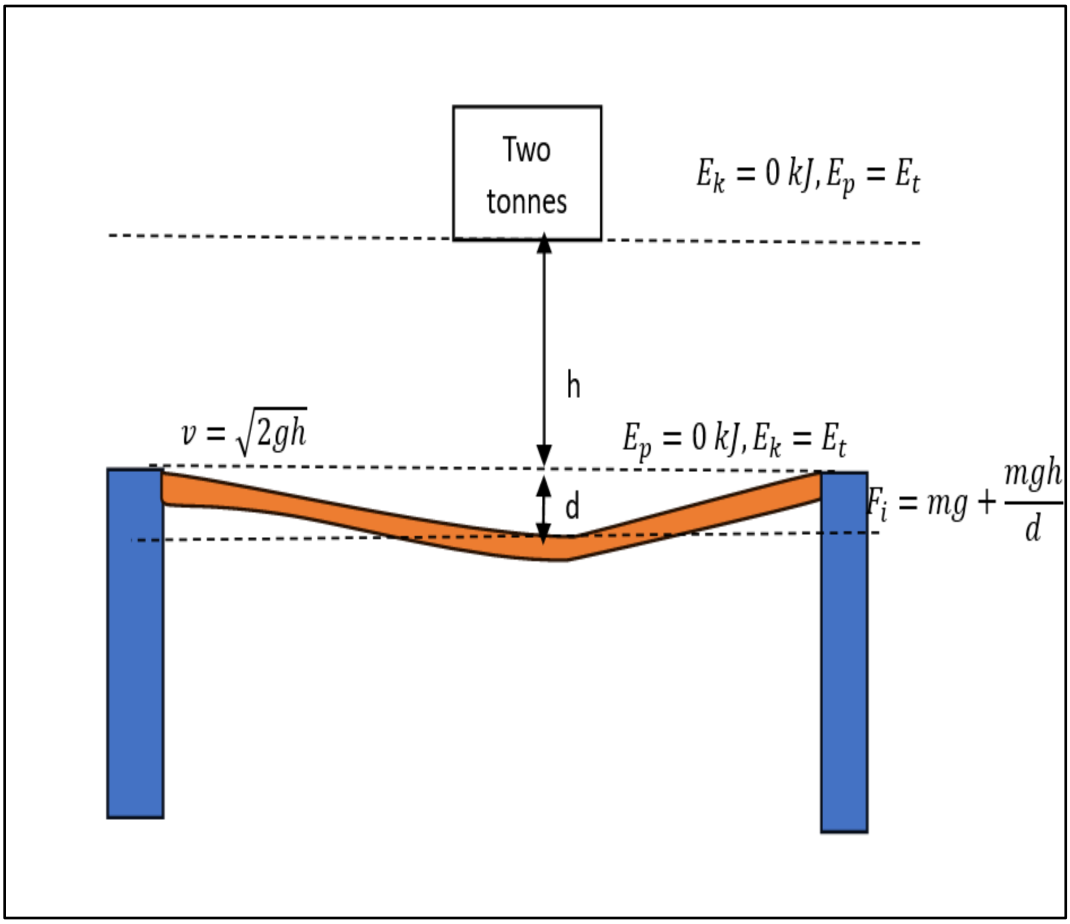



*Figure 4-9: Determination of deflection and impact force from the drop test facilities*

Figure 4-9 illustrates a section view of the drop test facility, where a two tonnes rock is dropped from a specific height above the net or mesh. The symbols $E_p$, $E_k$ and $E_t$ represent the potential, kinetic, and total energies, respectively. Dotted lines indicate the positions at which measurements are taken to determine deflection, total force, and energy absorption.

Equations 4-1, 4-3, and 4-4 were utilized to establish a relationship between total force and drop height at various deflections, considering a mass of two tonnes. The relationships for two tonnes mass dropped onto surfaces such as safety nets and BOM are depicted in Figure 4-10.

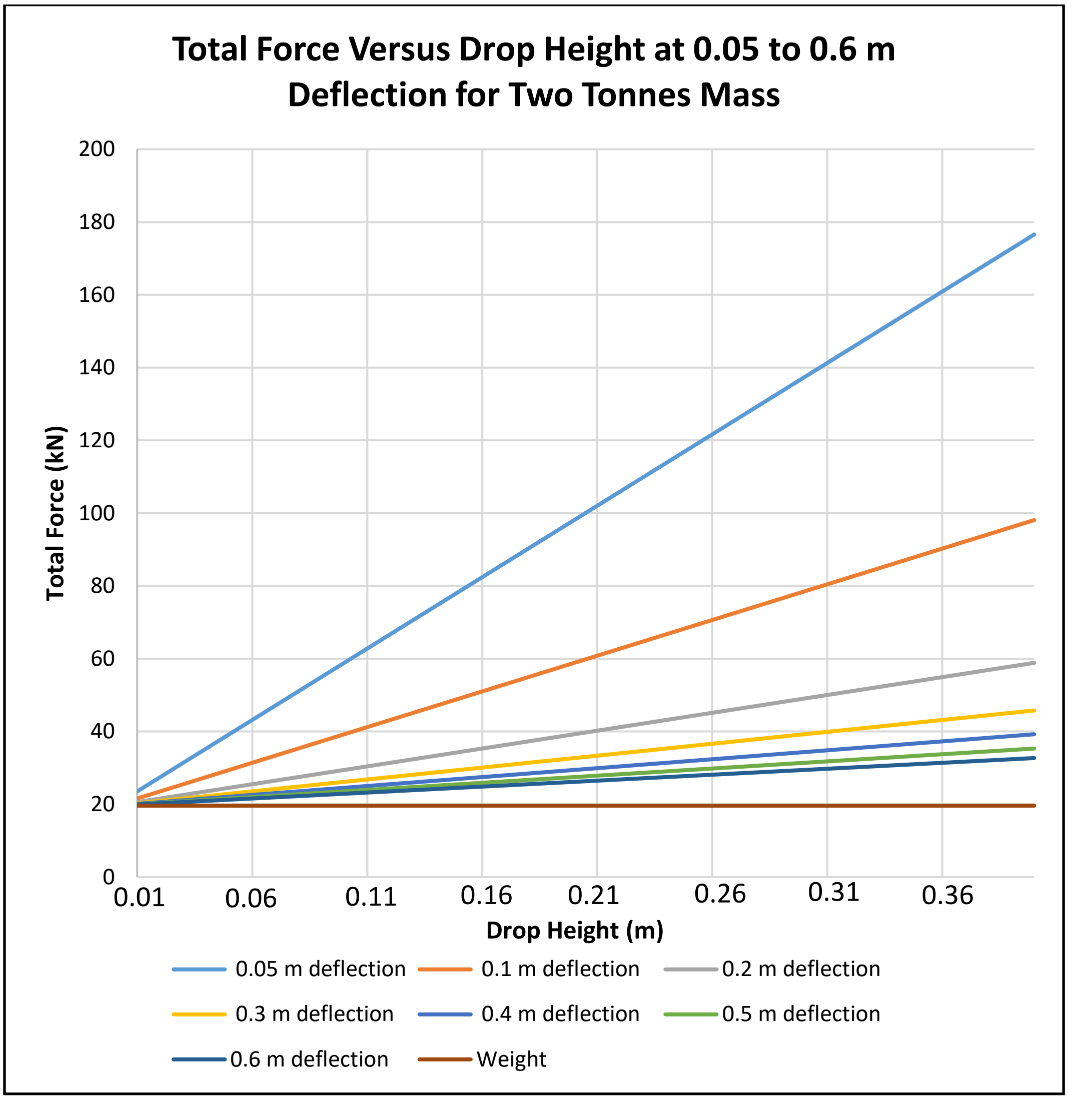



*Figure 4-10: Theoretical relationship between total force and drop height at various deflections*

The total force is observed to increase as the drop height increases for all deflections. However, materials with a lower deflection experience higher levels of impact force. It is important to note that the weight of the two tonnes mass, equivalent to 19.62 kN (represented by the maroon line in Figure 4-9), remains constant regardless of the drop height. The primary factor contributing to the increase in total force is the impact force. The lowest deflection of 0.05 m resulted in the highest total force. This relationship was utilized to plot the total vertical forces acting on the surface (mesh or net) against different drop heights for various deflections.

## 4.8 Drop Tests Set-ups for Thembelani Support Standard

### 4.8.1 Safety nets

Eight drop tests were conducted on the Rock-stop safety nets, with a capacity of two tonnes using the installation standard of Thembelani Mine. During the testing at NCM Frame 1, each of the safety nets with dimensions of 1.4 m x 3.1 m and apertures of 130 $mm^2$ were subjected to a two tonnes mass that was dropped at the centre of the nets.

*Table 4-4: Drop tests on Rock-stop safety nets*

| Sample Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Initial sag (m) | 0.010 | 0.010 | 0.050 | 0.010 | 0.010 | 0.010 | 0.010 | 0.020 |
| Drop height above hooks (m) | 0.000 | 0.100 | 0.100 | 0.290 | 0.290 | 0.290 | 0.300 | 0.300 |
| Total height above net (m) | 0.010 | 0.110 | 0.150 | 0.300 | 0.300 | 0.300 | 0.310 | 0.320 |
| Drop mass (t) | 2.004 | 2.004 | 2.004 | 2.004 | 2.004 | 2.004 | 2.004 | 2.004 |
| Attachment spacing (m) | 1.500 | 1.500 | 1.500 | 1.500 | 1.500 | 1.500 | 1.500 | 1.500 |
| Deflection (m) | 0.020 | 0.080 | 0.080 | 0.100 | 0.120 | 0.120 | 0.130 | 0.100 |

The drop height varied from 0.01 m to 0.32 m, considering the initial sag of the net before the test as shown in Table 4-4. The drop height for typical underground installations ranged from 0.00 m to 0.11 m. Drop heights of 0.15 m to 0.32 m aimed to simulate worst case scenarios. The safety net was secured to the test frame using 16 mm NCM-supplied flexible S-hooks spaced 1.5 m apart. Deflections ranged from 0.02 m to 0.13 m.

### 4.8.2 Face plates and hooks

A mass of two tonnes was dropped onto the two tonnes Rock-stop safety nets which were attached to the test frames with hooks inserted in the face plates holes at spacings and drop heights as detailed in Table 4-5.

*Table 4-5: Drop tests on face plates and hooks*

| Test Facility | Hook diameter (mm) | Hook spacing (m) | Number of hooks | Face plate thickness (mm) | Drop mass (t) | Total height (m) | Total deflection (m) |
|---|---|---|---|---|---|---|---|
| NCM | 12.000 | 1.500 | 6 | NCM frame-fitted face plate | 2.004 | 0.300 | 0.200 |
| NCM | 14.000 | 1.500 | 6 | NCM frame-fitted face plate | 2.004 | 0.300 | 0.130 |
| Videx | 14.500 | 1.500 | 6 | 4.500 | 2.000 | 0.300 | 0.800 |
| Videx | 14.500 | 1.500 | 6 | 6.000 | 2.000 | 0.300 | 0.150 |

Two drop tests were carried out at NCM test Frame 1 to compare the 12 mm G-hooks used at Thembelani Mine in 2019 with the 14 mm S-hooks that came with the two tonnes safety nets. Additionally, two more tests were conducted at the Videx drop test facility to assess the improved 14.5 mm hooks that were supplied with Resin bolts. The Videx drop tests also included 4.5 mm and 6 mm thick face plates used at Thembelani Mine. Deflection ranged from 0.13 m to 0.8 m.

### 4.8.3 Long headboard Mechanical props

A two tonnes mass was dropped onto the two tonnes Rock-stop safety net secured onto the mechanical props by 16 mm flexible G-hooks which come attached to the headboard of each prop at NCM test Frame 2 as detailed in Table 4-6.

*Table 4-6: Drop tests on long headboard mechanical props (Grease box props)*

| Test Number | Mechanical prop type | Number of props | Prop spacing (m) | Net type | Total drop height (m) | Deflection (m) |
|---|---|---|---|---|---|---|
| **1** | Grease box | 6 | 1.500 | Two tonnes Rock-stop webbing net | 0.100 | 0.400 |
| **2** | Grease box | 6 | 1.500 | Two tonnes Rock-stop webbing net | 0.100 | 0.090 |
| **3** | Grease box | 6 | 1.500 | Two tonnes Rock-stop webbing net | 0.100 | 0.100 |
| **4** | Grease box | 6 | 1.500 | Two tonnes Rock-stop webbing net | 0.100 | 0.050 |
| **5** | Grease box | 6 | 1.500 | Two tonnes Rock-stop webbing net | 0.100 | 0.070 |

A mass of two tonnes was dropped from a height of 0.1 m above the net attached to six Grease box props fixed to NCM Frame 2. The drop height of 0.1 m simulated initial sags of 0.05 m and 0.1 m for stoping and flat excavation safety nets suspended by mechanical props at Thembelani Mine. During drop tests 1 and 2, a two tonnes mass was dropped at the centre of the Rock-stop safety net. Subsequently, on drop tests 3 to 5, the same two tonnes mass was dropped at the edge of the safety net at distances of 0.15 m and 0.25 m from the central and corner attachments, respectively, to simulate eccentric loading on the attachments. During test 1, one of the props was struck and pulled out by a swinging mass, which resulted in a higher deflection of 0.4 m. However, the deflection on test 2 dropped to 0.09 m when the struck prop was replaced and a new safety net was used. Tests 3 to 5 yielded deflections ranging from 0.05 m to 0.1 m, while using the same props and simply replacing the Rock-stop safety net with a new one for each test.

### 4.8.4 Blast-on mesh with face plates and spike plates

The drop tests involved the use of MINAX 80/3 BOM fastened to the test frame by roof bolts, with face plates and spike plates at the Videx drop test facility are shown in Appendix A-1. A weight of two tonnes was dropped onto the centre of the BOM to determine the deflection and strength of the BOM using installation scenarios as detailed in Table 4-7.

*Table 4-7: Drop tests on MINAX 80/3 BOM with face plates and spike plates*

| Test Number | Number of attachments | Attachment spacing along the frame (m) | Attachment spacing across the frame (m) | Plate type | Initial sag (m) | Total drop height (m) | Deflection (m) |
|---|---|---|---|---|---|---|---|
| 1 | 6 | 1.500 | 1.200 | Face plate | 0.000 | 0.000 | 1.080 |
| 2 | 6 | 1.500 | 1.200 | Face Plate | 0.000 | 0.100 | 0.520 |
| 3 | 6 | 1.500 | 1.200 | Spike plate | 0.010 | 0.010 | 0.480 |
| 4 | 6 | 1.500 | 1.200 | Spike Plate | 0.000 | 0.100 | 0.450 |

The first two tests in Table 4-7 were carried out in May 2022 on MINAX 80/3 BOM samples that were delivered to Thembelani Mine for trials before being used underground. For the first two tests, face plates supplied with roof bolts at Thembelani Mine were used. The third and fourth tests were conducted in April 2023 to evaluate the performance of BOM with spike plates. It should be noted that during the third test, two mesh sheets were connected with clips along the middle spike plates to simulate underground connections. All the BOM samples that were tested were equipped with 8 mm diameter blast-on cable on one of the longer sides. Deflections of 1.08 m and 1.52 m were recorded on test 1 and test 2 were spike plates were used. Deflections reduced to 0.48 m and 0.45 m where spike plates were used.

### 4.8.5 Blast-on mesh with mechanical props and spike plates

Two tests were conducted on MINAX 80/3 BOM with mechanical props and spike plates at the Videx drop test facility in April 2023. A two tonnes mass was dropped onto the mesh at drop heights of 0 m to 0.11 m simulating worst case initial sag in an underground environment as detailed in Table 4-8.

*Table 4-8: Drop tests on MINAX 80/3 BOM with mechanical props and spike plates*

| Test Number | Number of attachments | Attachment spacing along the frame (m) | Attachment spacing across the frame (m) | Plate type | Initial sag (m) | Total drop height (m) | Deflection (m) |
|---|---|---|---|---|---|---|---|
| 1 | 6 (3 props and 3 spike plates) | 1.500 | 1.200 | Spike Plate | 0.000 | 0.100 | 0.500 |
| 2 | 6 (3 props and 3 spike plates) | 1.500 | 1.200 | Spike plate | 0.080 | 0.110 | 0.480 |
| 3 | 6 (3 props and 3 spike plates) | 1.500 | 1.200 | Spike Plate | 0.000 | 0.000 | 0.440 |
| 4 | 6 (3 props and 3 spike plates) | 1.500 | 1.200 | Spike plate | 0.000 | 0.100 | 0.450 |

One side of the 3 m x 1.2 m MINAX 80/3 BOM was attached to the test frame by bolts and spike plates spaced 1.5 m apart as shown in Appendix A-2. The side with blast-on cable was pressed to the frame by long headboard (370 mm x 100 mm) Videx mechanical props spaced 1.5 m apart at tests 1 and 2 and with Grease box mechanical props on tests 3 and 4.

### 4.8.6 Blast-on mesh with mechanical props

Due to limited availability of mechanical props, a single test involving a 1.2 m x 3 m MINAX 80/3 mesh, which was pressed onto a test frame by six long headboard Videx mechanical props as shown in Appendix A-3, was conducted. The attachment spacing and drop height for this test are detailed in Table 4-9.

*Table 4-9: Drop tests on MINAX 80/3 BOM with mechanical props*

| Test Number | Number of attachments | Attachment spacing along the frame (m) | Attachment spacing across the frame (m) | Initial sag(m) | Total drop height (m) | Deflection (m) |
|---|---|---|---|---|---|---|
| 1 | 6 props | 1.500 | 1.200 | 0.000 | 0.100 | 0.46 |

The props were spaced 1.5 m apart along the frame's length and 1.2 m apart across its width at the Videx drop test facility. One long side of the mesh had an 8 mm diameter blast-on cable. A two tonnes mass was dropped from a height of 0.1 m onto the centre of the mesh, simulating the worst-case initial sag on the mesh underground. This test was conducted in April 2023 to simulate the first installation of mesh underground before it is attached to the hangingwall with roof bolts and plates (face plates or spike plates).

## 4.9 Chapter Summary

The temporary support elements used at Thembelani Mine, such as Rock-stop safety nets, MINAX 80/3 BOM, face plates, hooks and mechanical props underwent testing at NCM and Videx testing facilities. The tests were conducted in a way that simulated the complete underground systems used at Thembelani Mine. The objective of the tests was to determine whether the tested systems could support two tonnes at acceptable deflection levels. A graph that showed the total force versus drop heights at various deflections was created to validate the results obtained from the drop test facilities, based on the physics of falling objects.

# 5 FINDINGS AND ANALYSIS

The results were thoroughly analysed to identify any failures or successes observed in the tested systems. Additionally, the improved systems were subsequently analysed, tested and subsequently presented.

## 5.1 Findings and Analyses for Two Tonnes Safety Nets

### 5.1.1 Total force and deflection on the two tonnes safety nets

An accelerometer was used to measure the deflection and total force on the safety net while holding the mass. The 16 mm S-hooks used in this regard were also assessed and found to not have stretched or deformed. Figure 5-1 illustrates the relationship between force and deflection at different drop heights.

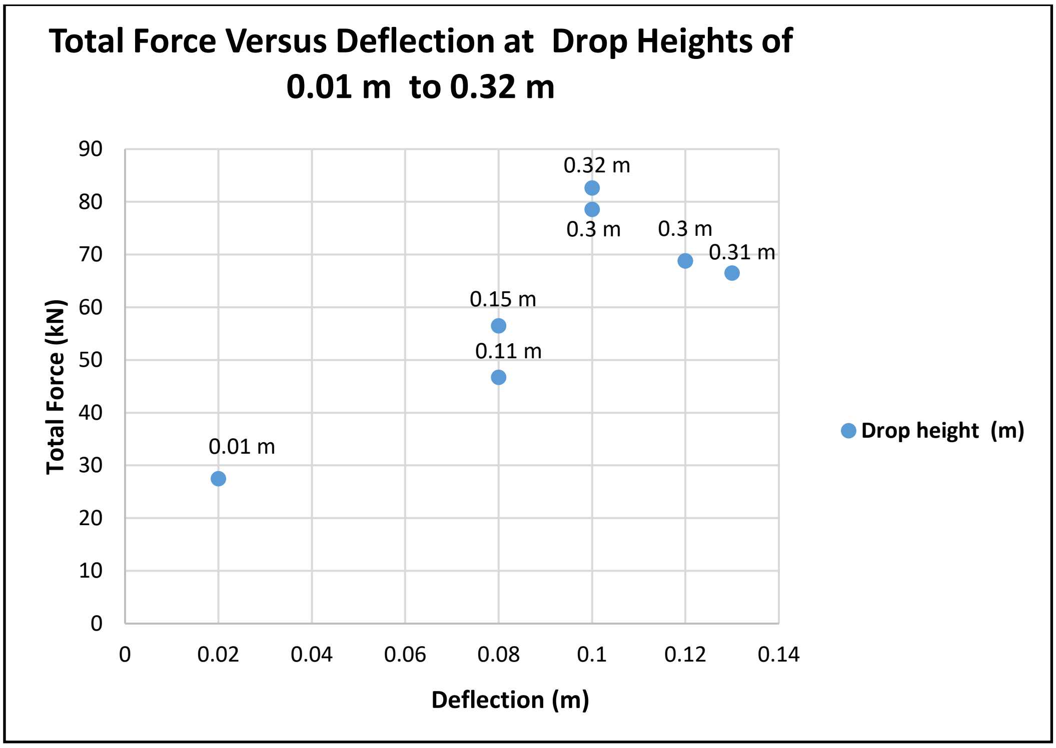



*Figure 5-1: Results for drop tests on Rock-stop safety nets with 16mm S-hooks*

As expected, the total force increased as the drop height increased, as seen in Figure 5-1. This trend was evident in the drop heights of 0.11 m, 0.15 m, 0.3 m and 0.32 m. It can also be seen that as the deflection started increasing the impact force decreased, leading to a decline in the total force. This has been demonstrated in samples with drop heights ranging from 0.3 m to 0.32 m, where deflection increased from 0.12 m to 0.13 m. It should be noted that two tests gave similar results for a drop height of 0.3 m with a deflection of 0.12 m. Moreover, the net could withstand a total force of 82.6 kN, which is higher than the tensile strength of its inner webbings, outer webbings, and perimeter webbings, which are 7.5 kN, 39.5 kN, and 58.6 kN, respectively. Figure 5-2 displays the result of an accelerometer measurement that recorded the change in force over the distance travelled by the falling mass until it was stopped by the safety net.

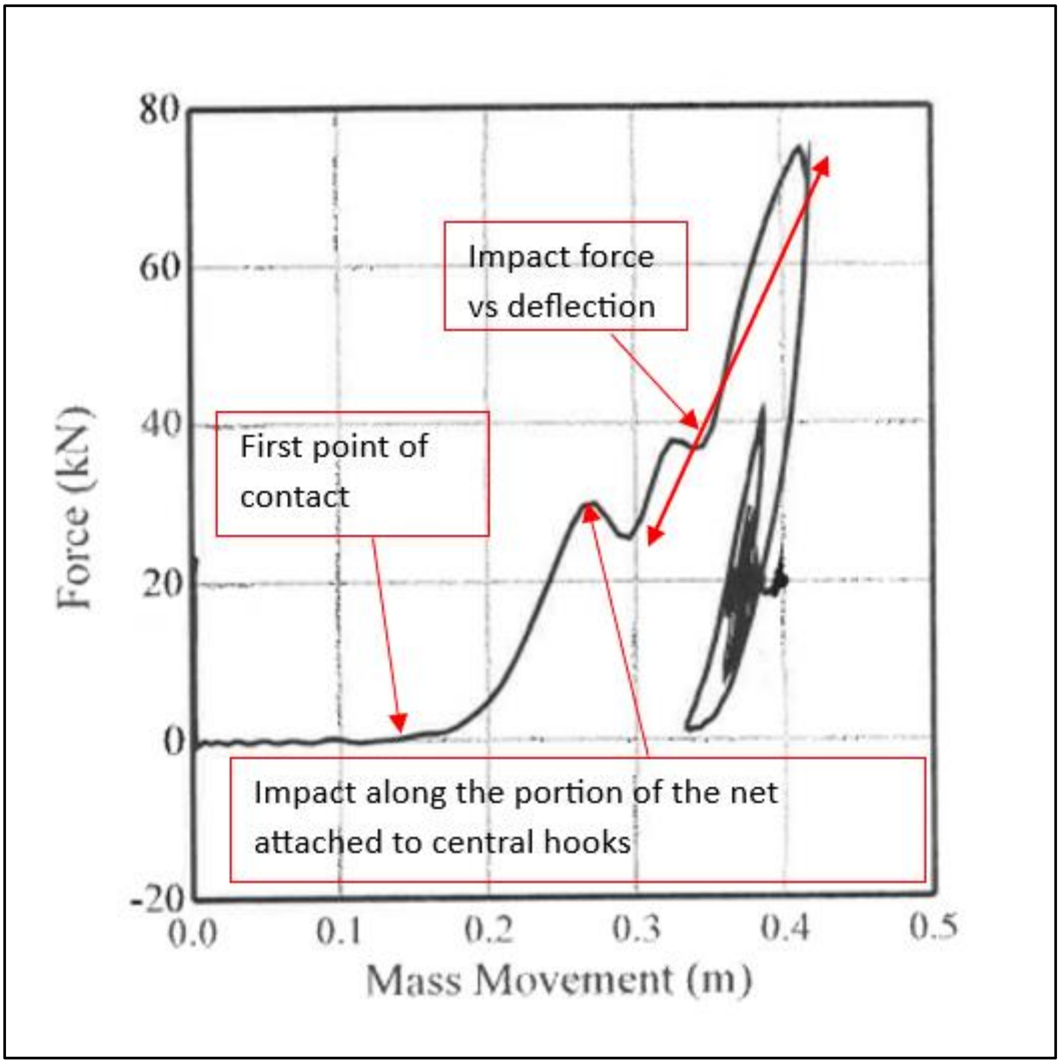



*Figure 5-2: Total force versus mass movement over 0.42 m*

The data presented in Figure 5-2 shows that the mass touched the net for the first time at a drop height of 0.15 m. This equates to a stretched portion of the net near the corner hooks 0.15 m above the net. It encountered resistance at a height of 0.26 m, which suggests that the central hook portion of the net was slightly above the rest of the net. During the period between first contact and resistance, the force increased from 0 kN to 28 kN. After that, the force dropped to around 24 kN before rising rapidly to 79 kN due to the impact force over a deflection of 0.12 m. The peak force of 28 kN and the slump after it suggest that the mass was subjected to a point- or line-loading effect. This coincides with the drop test video recording, which indicates that the elastic deformation occurred near the highest point closer to the edge hooks on either side of the mass. The mass impact took place along the portion of the net along central attachments, which was sitting 0.26 m below the mass. The net repositioned itself to rest fully on the surface of the net (positioned 0.3 m below the mass) after deformation in the form of outwards shifting of the perimeter straps on either side of each central hook took place. The results presented in Figures 5-1 and 5-2 conform to the laws of physics governing falling objects, which demonstrate a relationship between the total force and the drop height for different deflections.

### 5.1.2 Failure mechanisms on the two tonnes safety nets

During the test, all eight samples of the Rock-stop safety nets successfully held the two tonnes mass without failing. However, there was deflection due to the detachment of the inside webbing from the outside webbing along the rivet pins, and the stitches of the outside webbing broke off from the perimeter webbing. Although the loop of the outside webbing did not fail, it shifted along the perimeter webbing due to the broken stitches.


*Figure 5-3: Failure mechanism along the two tonnes Rock-stop safety net and 16 mm S-hooks*

During the safety net testing, it was observed that all six 16 mm S-hooks remained undamaged even after holding two tonnes for all samples. Deflections were also physically measured and were to correspond to accelerometer readings. The centre of the mass tended to experience higher loading as the failure of the webbing occurred mostly in this region. The stitches on the outside webbing broke and moved outwards on both sides of the central hook along the longer extents. This movement pulled the inside webbing along the path of the moving outside webbing, causing it to detach from the rivet pins.

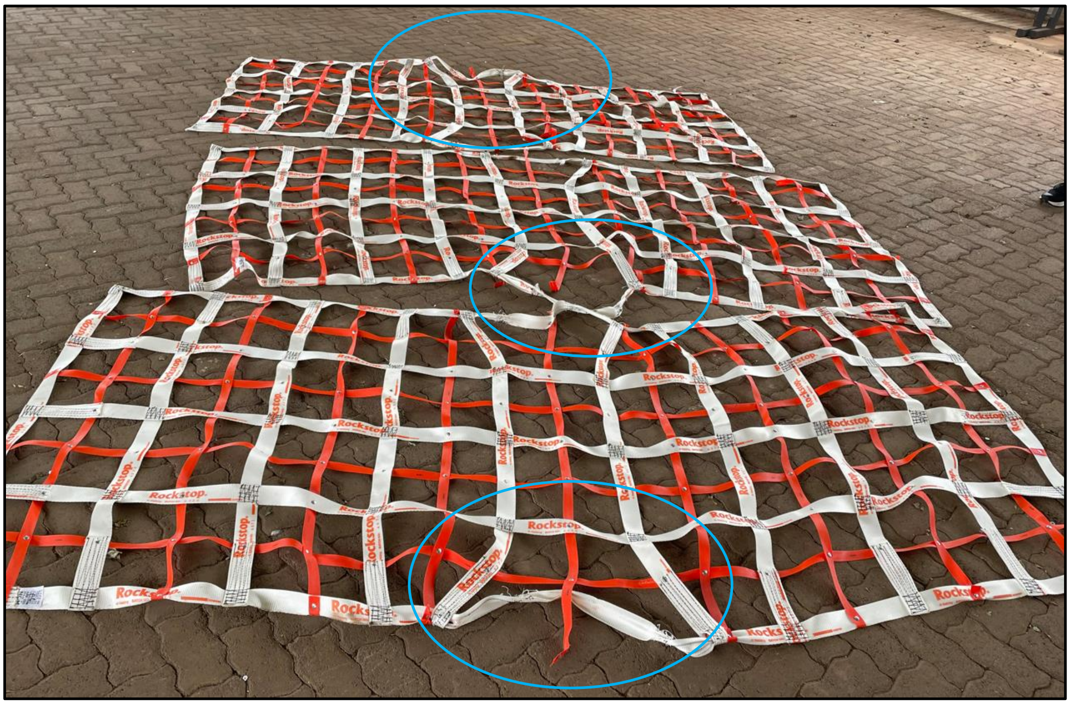


*Figure 5-4: Central failure of webbing along the two tonnes Rock-stop safety nets*

Two outside webbing straps shifted outwards from the perimeter webbing on either side of the central attachment point. The central failure was driven by the fact the centre of the steel mass hit the centre of the net first before settling on the rest net thereby resulting in higher central loading on the central attachment points. This was due to net sag between the central attachment points and corner attachment points, resulting in the positions of attachments being higher than the rest of the net from the floor.

### 5.1.3 Validation of the results obtained with an accelerometer

Figure 5-5 displays a graph illustrating the physics of falling objects, along with data points for drop heights and deflections obtained from measurements. The graph serves the purpose of determining whether there is any correlation between the physics of falling objects and the measured results.

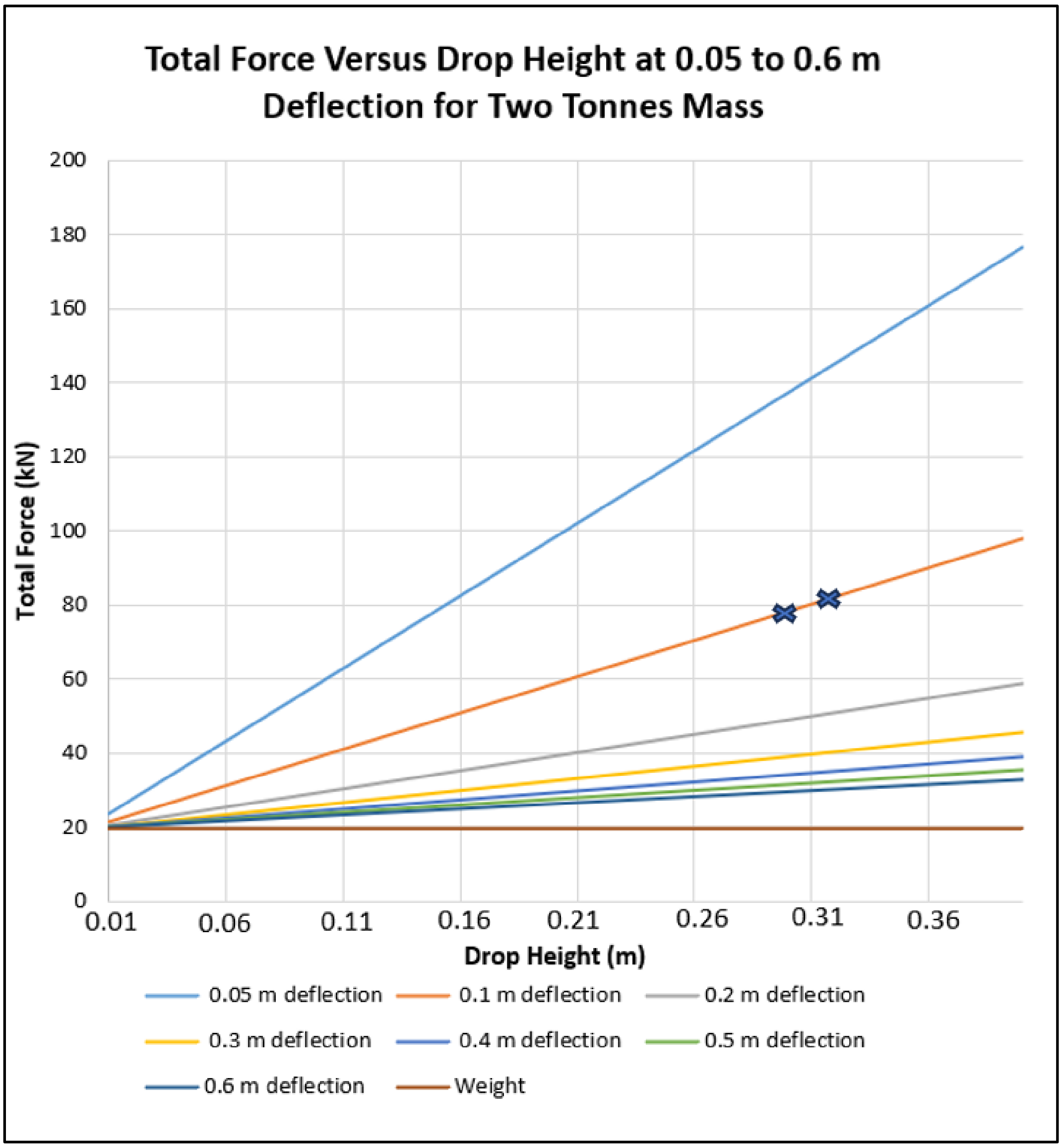



*Figure 5-5: Comparison of accelerometer results with the physics of falling objects*

In Figure 5-5, there are two data points marked with crosses that demonstrate results equivalent to those obtained with the accelerometer in Figure 5-1. These points correspond to drop heights of 0.3 m and 0.32 m, where a similar deflection of 0.1 m resulted in total forces of 78.5 kN and 82.6 kN, respectively. This is in line with the expectation as per the physics of falling objects.

## 5.2 Findings and Analysis for Hooks and Face Plates

### 5.2.1 Deflection with hooks and face plates

Four tests were performed using a two tonnes Rock-stop safety net and the results are presented in Figure 5-6. The tests involved varying the hook diameter and face plate thickness. The tests that passed are indicated in green, while the ones that failed are highlighted in red.

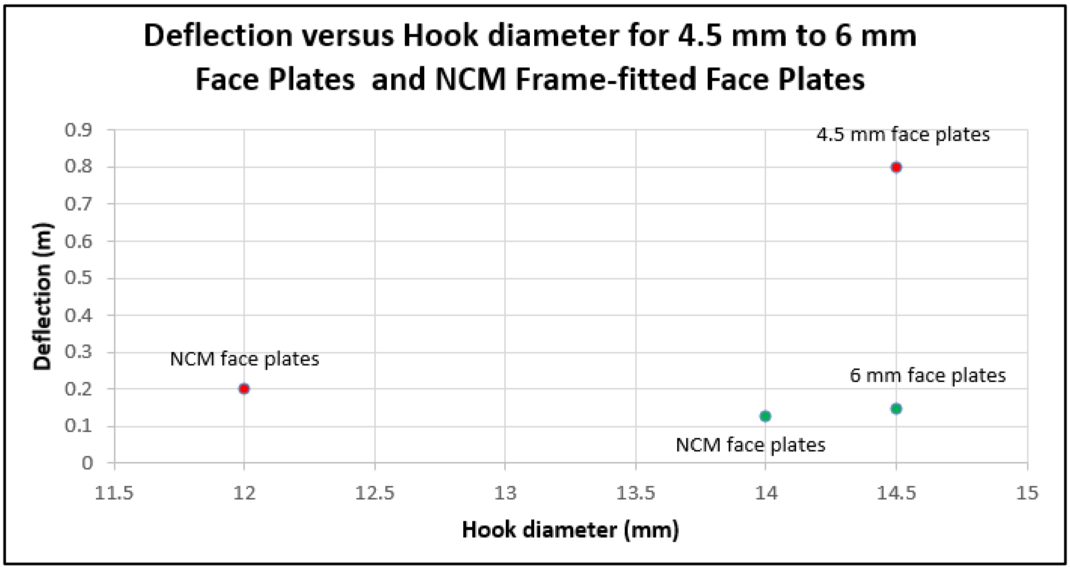



*Figure 5-6: Drop test results for hooks and face plates*

During the first two tests, where the NCM frame-fitted face plates were used, there were no failures observed on the face plates. However, the 12 mm G-hooks stretched by 0.05 m to 0.07 m, which resulted in an overall deflection of 0.2 m on the safety net and hooks. On the other hand, the 14 mm NCM S-hooks were able to hold two tonnes with an overall deflection of 0.13 m. These hooks underwent stretching of 0.003 to 0.005 m, which did not have an effect on hook performance as it was within the elastic deformation of the hook material. Meanwhile, when 14.5 mm G-hooks were tested with 4.5 mm face plates, two of the face plates failed, resulting in an overall deflection of 0.8 m which is greater that the allowed amount for stoping operations. However, the use of 6 mm face plates together with the 14.5 mm hooks resulted in an overall deflection of 0.15 m. In this case, both hooks and face plates did not deform permanently.

### 5.2.2 Failure mechanisms on hooks and face plates

The deformation of the hooks and face plates is shown in Figures 5-7, 5-8, and 5-9.

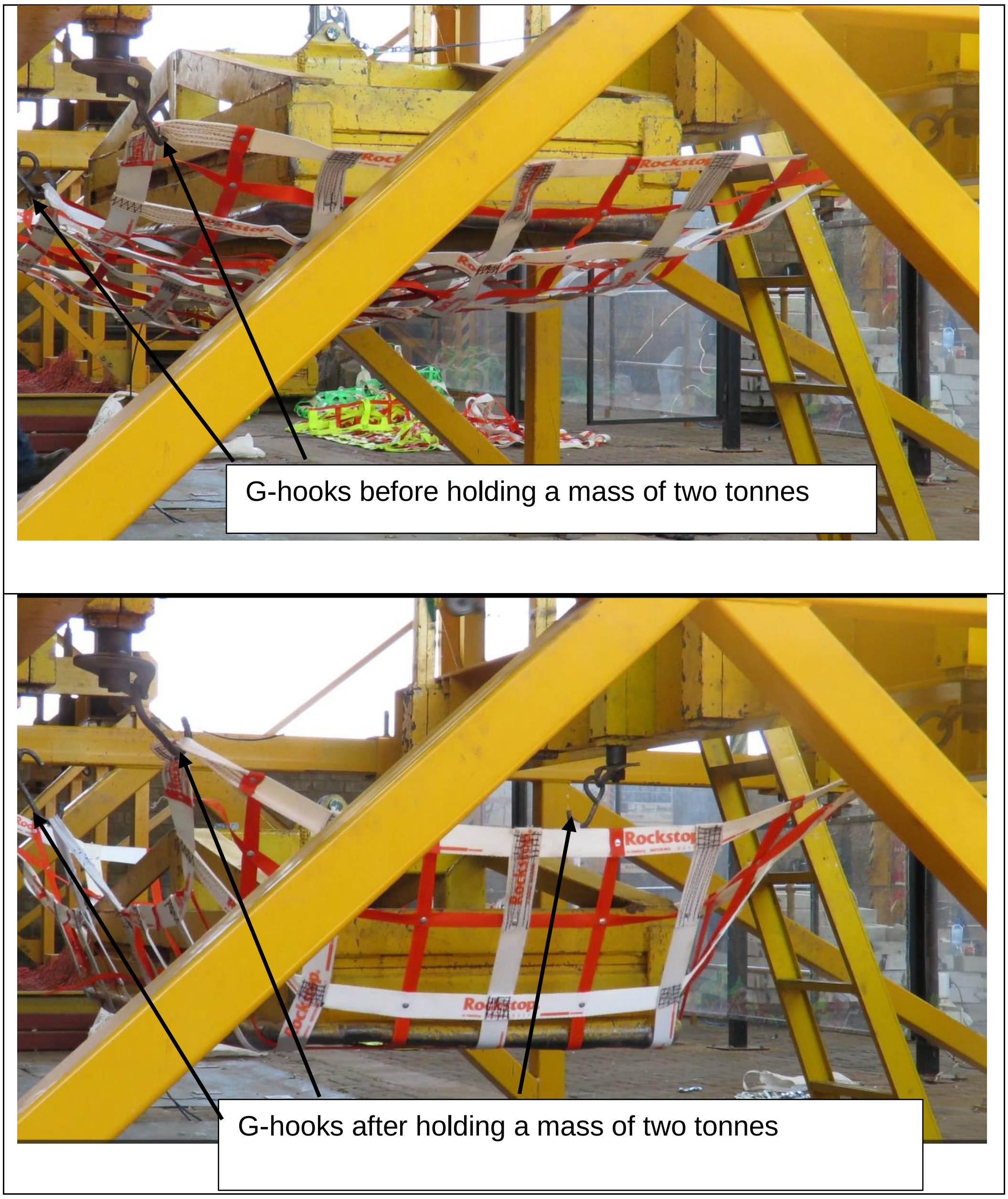



*Figure 5-7: Drop test on G-hooks with diameter of 12 mm*

In Figure 5-7, the opening of the hooks has changed from G to C shape. The safety net performance was not affected by the opening of the 12 mm G-hooks, as the failure on the net was similar to that observed when using 16 mm hooks. The deformation on the net was recorded on both sides of the central perimeter hooks along the longer extents, just like with the 16 mm hooks. However, the deformation of the hooks led to a total deflection of 0.2 m, compared to 0.12 m with 16 mm S-hooks, at a drop height of 0.3 m.

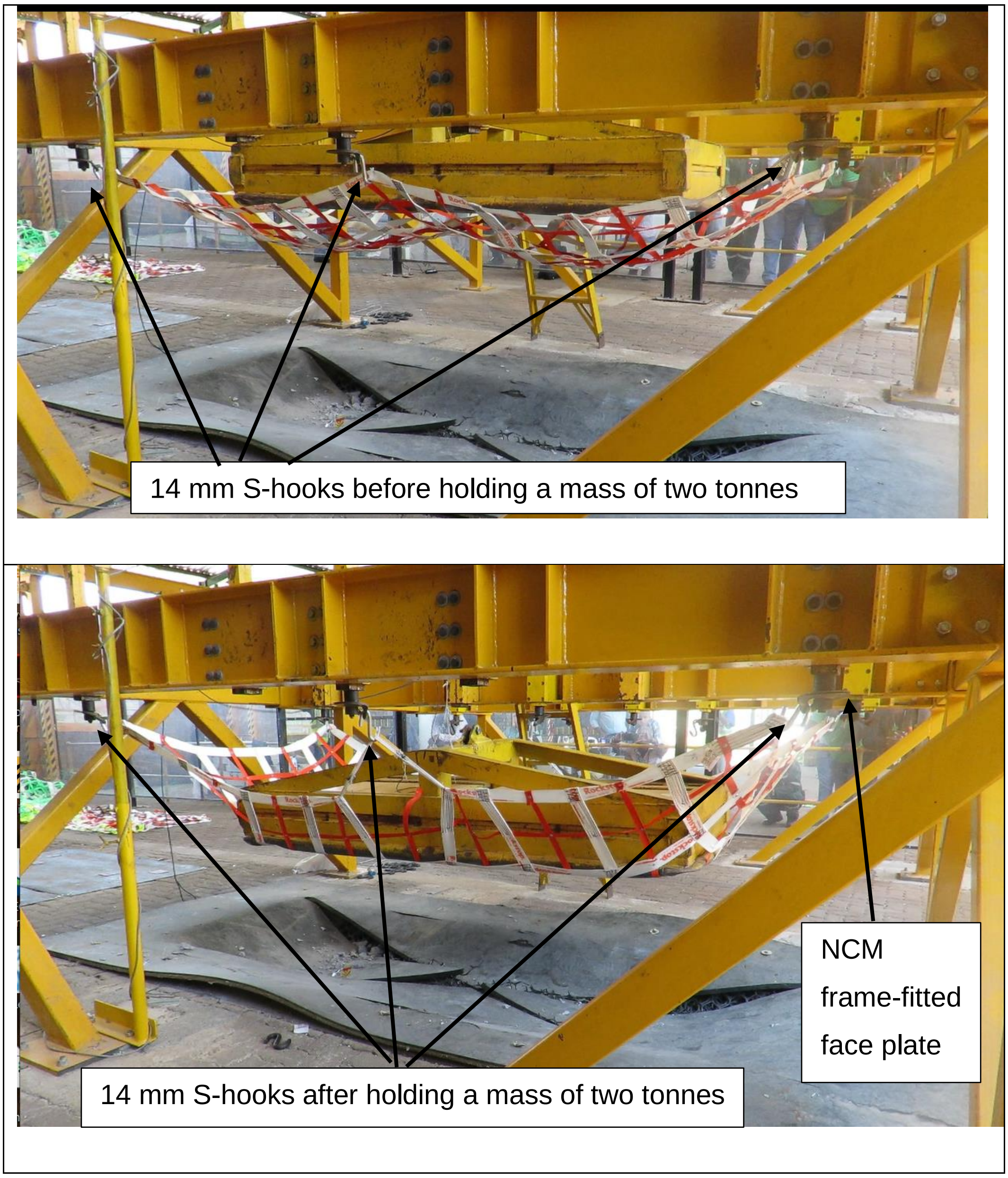



*Figure 5-8: Drop test on S-hooks with a diameter of 14 mm*

During the test, it was observed that the 14 mm S-hooks did not undergo any significant deformation as their shape remained consistent before and after the test. However, when a weight of two tonnes was held along the U sections of the hooks that were attached to the net, the hooks stretched between 0.003 m and 0.005 m which was within the elastic deformation of the hook material. Despite the minor stretch, all the hooks effectively held the perimeter webbing of the net in place after holding the weight.

*Figure 5-9: Typical failure of the 4.5 mm thick face plates*

During the test, two of the 4.5 mm face plates located at the corner and middle of the frame failed as indicated in Figure 5-9. The hooks broke the hook-hole which caused the net to deflect downwards with the two tonnes mass. The total deflection recorded was 0.8 m on the side where the face plates failed. The increased deflection was due to the shifting of the outside webbing on either side of each of the remaining four hooks. Moreover, the inside webbing detached from the rivets on either side of each of the remaining hooks. A stretch of 0.02 to 0.05 m was recorded on the remaining four hooks with a diameter of 14.5 mm.

## 5.3 Findings and Analyses for Mechanical props

### 5.3.1 Deflection with Grease-box mechanical props and two tonne Rock-stop safety nets

The deflections on the Rock-stop safety nets attached to the Grease-box mechanical props with 16 mm flexible G-hooks are shown in Figure 5-10.

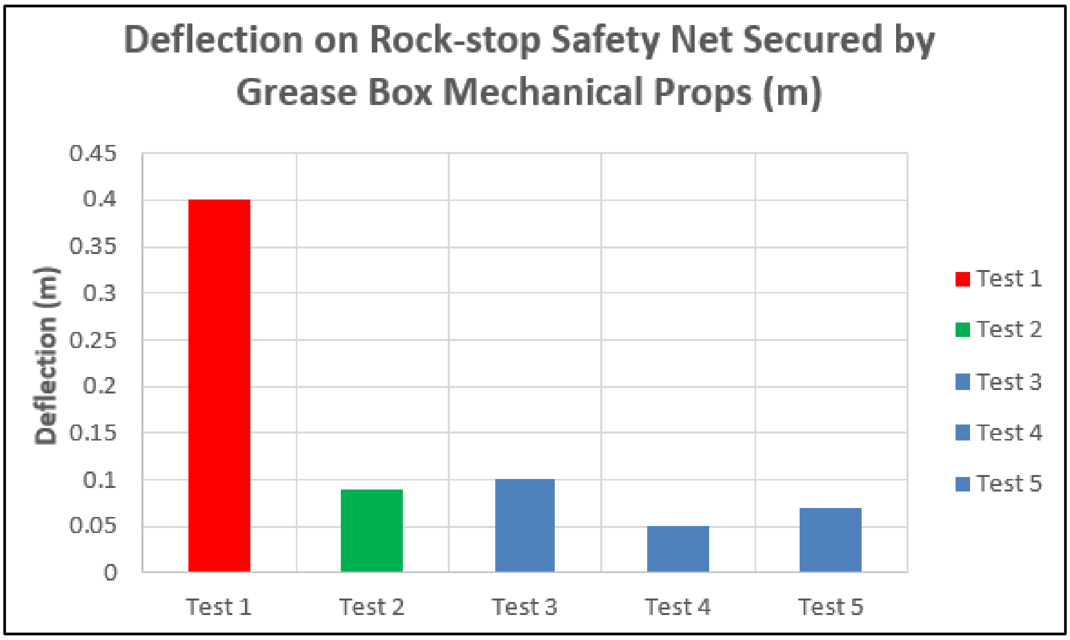



*Figure 5-10: Results for Grease box props with Rock-stop safety nets*

On test 1, a single mechanical prop positioned at the corner of the frame was struck by the two tonnes mass due to swing during the fall and resulted in the prop pulling out. Maximum deflection was measured on the corner where the prop came out and found to be 0.4 m. On test 2 the Rock-stop safety net and one prop which came out were replaced. The replaced prop did not come out and results indicated an overall deflection of 0.09 m on the two tonnes Rock-stop safety net. Tests 3 to 5 simulated eccentric loading, with a two tonnes mass dropped closer to the attachments at 0.15 m and 0.25 m from the central and corner attachments respectively. Tests 3 to 5 used a new set of props that were repeated throughout the tests. However, the safety net was replaced with each test conducted. Tests 3, 4 and 5 produced deflections of 0.1 m, 0.05 m and 0.07 m. During tests 3 to 5, none of the props slipped out, and there was no stretch on any of the hooks from tests 1 to 5.

### 5.3.2 Failure mechanisms on Grease-box mechanical props and Rock-stop safety nets

The failure mechanisms along the temporary system comprising of the Grease-box mechanical props and the two tonnes Rock-stop safety nets are shown in Figure 5-11.

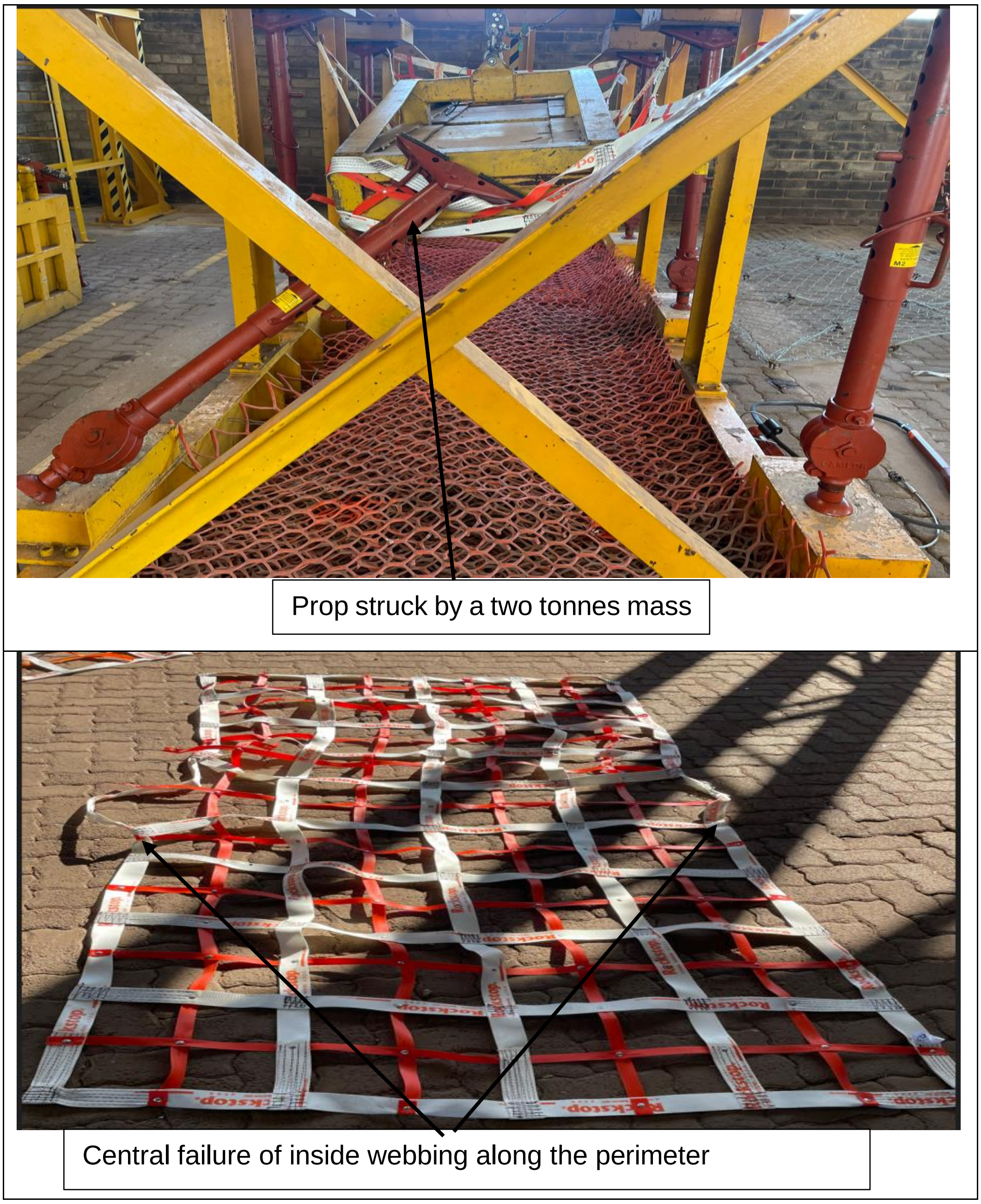



*Figure 5-11: Excessive deflection due to pulled out mechanical prop*

On test 1, the corner prop was struck by the two tonnes mass before it settled on the net resulting in the prop pulling out. However, the remaining five props held the mass yet with a higher deflection of 0.4 m. The load from the fallen prop was transferred mostly to the central prop adjacent to it. This is indicated by excessive shifting out of the outside webbing on the central prop adjacent to the fallen one which in turn resulted in a relatively increased deflection on the net. The 16 mm hooks on the props remained intact after the test. Furthermore, during tests 3 to 5, the mass was dropped closer to the attachments, and the props did not slip out.

## 5.4 Findings and Analyses for Blast-on Mesh with Face Plates and Spike plates

### 5.4.1 Deflection on Blast-on mesh with face plates and spike plates

During testing, a two tonnes mass was dropped from heights ranging from 0.0 m to 0.1 m onto a MINAX 80/3 BOM bolted to a test frame with face plates and spike plates. The BOM underwent deflections, as shown in Figure 5-12.

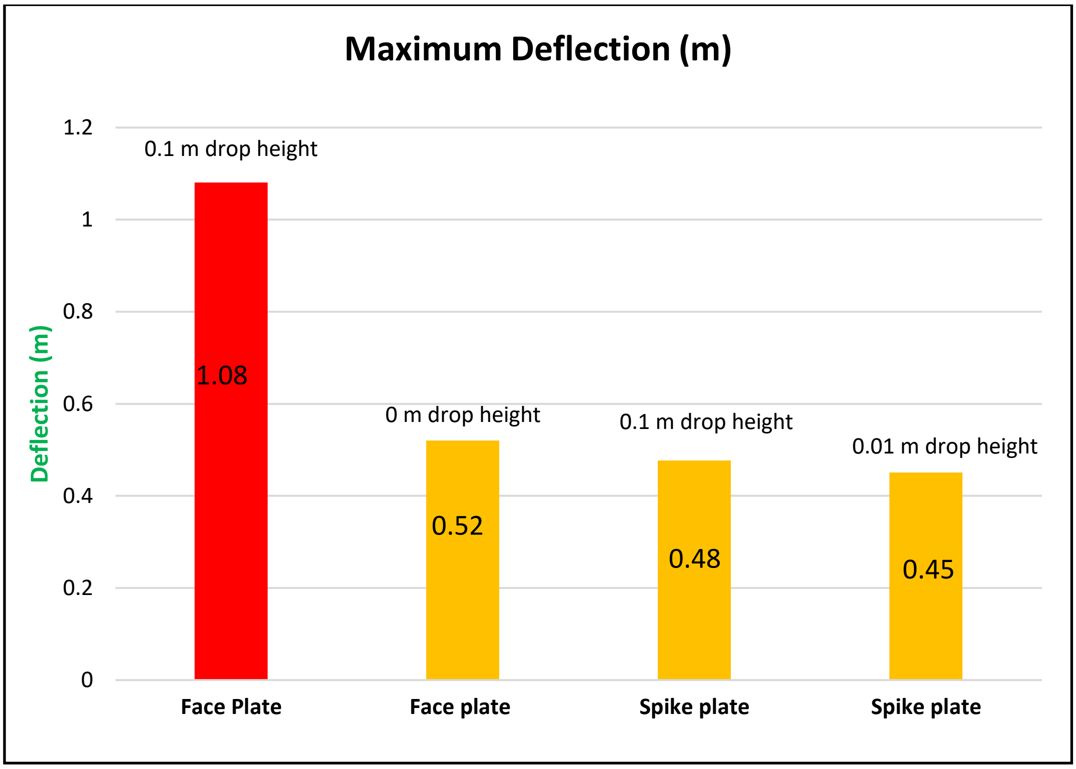



*Figure 5-12: Results for MINAX 80/3 BOM with face plates and spike plates*

The first BOM test with face plates (red bar) exceeded the acceptable limit of deflection, which is 0.35 m and 0.55 m for 1.2m and 1.4m stoping widths, respectively. On the other hand, the second, third and fourth tests (orange bars) only showed deflections beyond the acceptable limit for the 1.2 m stoping width but were within the acceptable limits for the 1.4m stoping width. It should be noted that the maximum deflection for all tests was less than the acceptable deflection for flat excavations, which is 1.3 m. Furthermore, the tests revealed that lower deflections were achieved when reducing the drop height for both faceplates and spike plates. Spike plates demonstrated lower deflections compared to faceplates.

### 5.4.2 Failure mechanisms for Blast-on mesh with face plates and spike plates

**Failure mechanism for Blast-on mesh with face plates for 0.1 m drop height**

Figures 5-13 shows the deformation and failure mechanisms of BOM with face plates and spike plates at 0.1 m drop height.

*Figure 5-13: Deformation and failure mechanism of MINAX 80/3 BOM with face plates for 0.1 m drop height*

The wires on the side without the blast-on broke off and caused the mesh to deflect 1.08 m with the two tonnes mass. The wire failures began at the corner attachment and extended towards the central attachment. No deformation was recorded on the face plates.

**Deformation of Blast-on mesh with face plates at 0 m drop height**

Figures 5-14 shows the deformation of BOM with face plates and spike plates at 0 m drop height.


*Figure 5-14: Deformation of MINAX 80/3 BOM with face plates at 0 m drop height*

During the test, no wire failures were observed. Instead, the wires tended to stretch into a straight shape along the attachments, causing a change in the diamond aperture shape and resulting in a deflection of 0.52 m. No deformation was observed on any of the face plates.

**Deformation of Blast-on mesh with spike plates at 0.1 m drop height**

Figures 5-15 shows the deformation of BOM with face plates and spike plates at 0.1 m drop height.

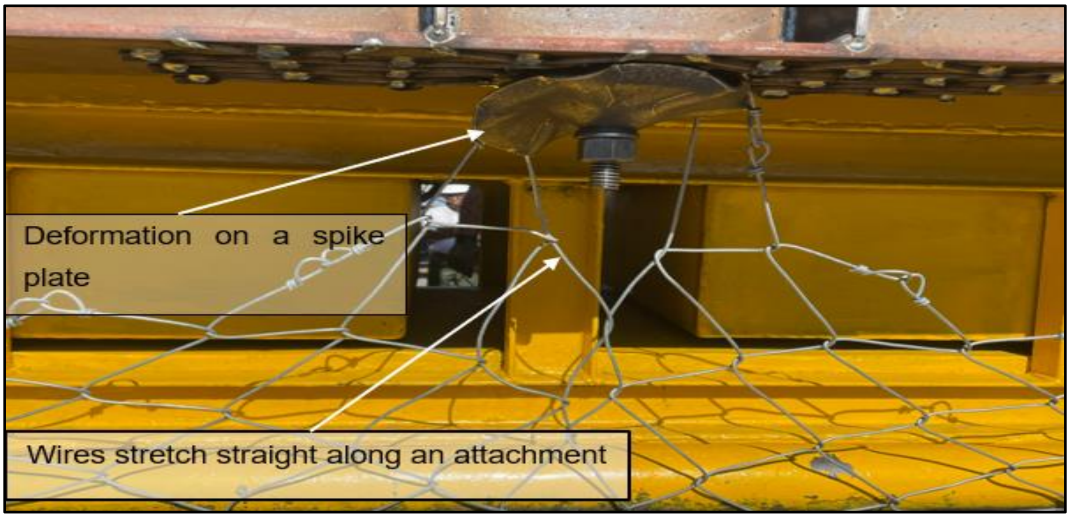



*Figure 5-15: Deformation on MINAX 80/3 BOM with Spike plates at 0.1 m drop height*

During the test, no wire failures were observed. Instead, the wires stretched into a straight shape along their attachments, causing a change in the diamond aperture shape and resulting in a deflection of 0.48 m. Although there was a slight deformation (bending downward by 0.02 to 0.03 m) on all spike plates on the sides facing the load, the spike plates were still firmly holding the loaded BOM to the test frame.

**Deformation of Blast-on mesh with spike plates at 0 m drop height**

Figures 5-16 shows the deformation of BOM with face plates and spike plates at 0 m drop height.


*Figure 5-16: Deformation of MINAX 80/3 BOM with spike plates for 0 m drop height*

During the test, there were no wire failures observed on either the wires or mesh connection clips that are used to link the mesh pieces together underground, creating a continuous sheet. However, the wires tended to stretch into a straight shape along the attachments, which resulted in a change in the diamond aperture shape, causing a deflection of 0.45 m. The spike plates did not show any deformation during the test.

## 5.5 Finding and Analyses for Blast-on mesh with Mechanical Props and Spike Plates

### 5.5.1 Deflection on Blast-on mesh with mechanical props and spike plates

The results for MINXA 80/3 BOM which was pressed by frame by three long headboard (370 mm x 100 mm) T-shaped Videx props (test 1 and test 2) or three Grease box mechanical props (test 3 and test 4) on the side with blast-on cable and bolted to the frame on the other side with three spike plates are shown in Figure 5-17.

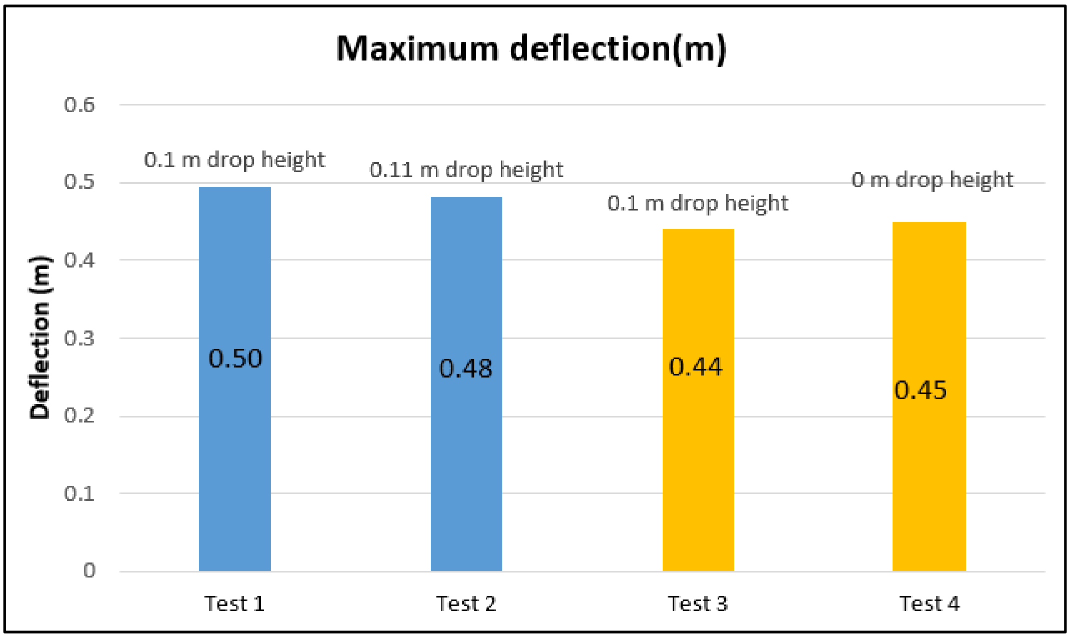



*Figure 5-17: Deflection for MINAX 80/3 BOM with mechanical props and spike plates*

Deflections of 0.50 m and 0.48 m were recorded for drop heights of 0.1 m and 0.11 m respectively when Videx props were used. In the case where Grease box props were used deflections were recorded to be 0.44 m and 0.45 m for drop height of 0.1 m and 0 m respectively. Mechanical props did not pull out and mesh did not slip out from the props in all tests conducted.

### 5.5.2 Deformation for Blast-on mesh with mechanical props and spike plates

The deformation for BOM with T-shaped long headboard (370 mm x 100 mm) mechanical props and spike plates are indicated in Figure 5-18.

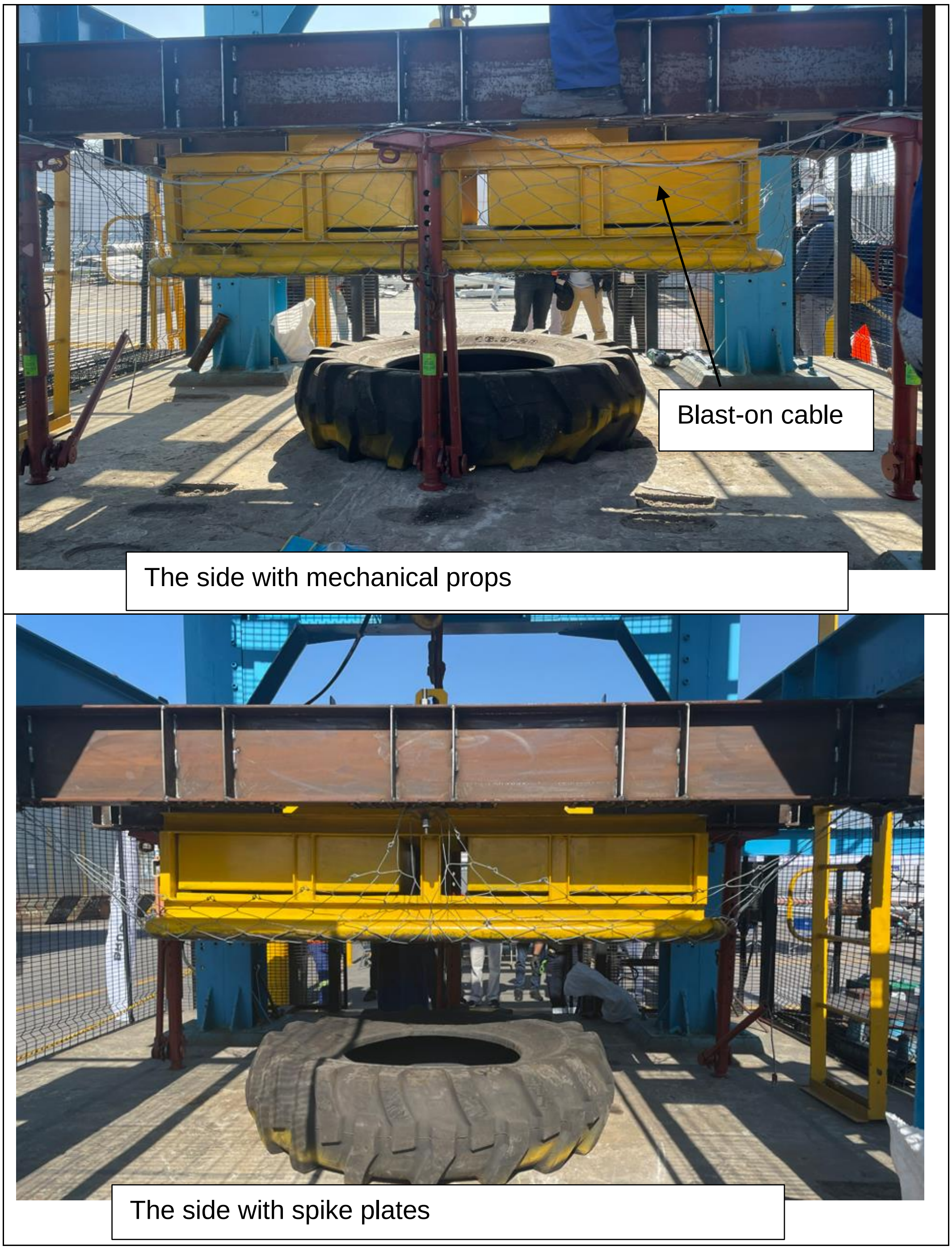



*Figure 5-18: Deformation of MINAX 80/3 BOM with mechanical props and spike plates*

During the tests, it was observed that the wires around the spike plates and mechanical props' headboards stretched into a straight shape while holding the weight. However, there was no breaking of wires, and the blast-on cables remained intact. The spike plates were slightly deformed by bending downwards between 0.02 to 0.03 m on the side facing the load. it was also noticed that there was less wire stretching on the side with props due to the reinforcement with blast-on, as opposed to the side with spike plates.

## 5.6 Findings and Analyses for Blast-on Mesh with Mechanical Props

### 5.6.1 Deflection on Blast-on mesh with mechanical props

A single test was conducted for MINAX 80/3 BOM using six T-shaped long headboard (370 mm x 100 mm) Videx mechanical props with similar headboard dimensions to Grease-box props. A drop height of 0.1 m resulted in a deflection of 0.46 m on the MINAX 80/3 BOM.

### 5.6.2 Deformation for Blast-on mesh with mechanical props

Mechanical props did not fail and the BOM did not slip from the props. The BOM deformed around prop headboards, causing deflection as shown in Figure 5-19.

*Figure 5-19: Deformation of MINAX 80/3 BOM with mechanical props*

The wires around the headboards tended to stretch into a straight shape when holding the mass. There were no broken wires on the mesh, and the blast-on also appeared intact after holding the mass. Less deformation (stretching of wires) was observed on the side with the blast-on compared to the side without the blast-on.

## 5.7 Chapter Summary

### 5.7.1 Two tonnes Rock-stop safety nets

Based on drop tests, it has been determined that Rock-stop webbing safety nets with a capacity of two tonnes can withstand the impact of a two tonnes mass dropped from heights ranging from 0 to 0.32 m. The 16 mm S-hooks used in this testing have also been evaluated and found to maintain their shape and size without stretching or deforming. During testing, the safety net recorded a maximum deflection of 0.13 m at a drop height of 0.31 m. This deflection was caused by the stitches on the outer webbing breaking and moving outward on both sides of the central hook along the longer length while supporting the two tonnes mass. Additionally, accelerometer measurements were in line with the expected results for falling objects, validating the accuracy of the testing.

### 5.7.2 Hooks and face plates

During the testing, it was found that the attachments that held two tonnes of mass without failing had 6 mm face plates with either 14 mm Carbon steel S-hooks or 14.5 mm Spring steel G-hooks at a drop height of 0.3 m. However, the 4.5 mm face plates failed to hold two tonnes as they allowed the hooks to pull open the hook hole and caused the net to sag to 1.08 m. The 14.5 mm G-hooks held two tonnes of mass without permanent deformation while the 14 mm S-hooks stretched by 0.002 m to 0.005 m while securely holding two tonnes. On the other hand, the 12 mm G-hooks opened from G-shape to C-shape by 0.05 m to 0.07 m, resulting in an overall deflection of 0.2 m at a drop height of 0.3m. Also, the perimeter of the safety net shifted towards the edges of the hooks while holding two tonnes with the 12 mm hooks. Hence, it was concluded that the 12 mm G-hooks did not securely hold the Rock-stop safety net loaded with two tonnes.

### 5.7.3 Grease-box mechanical props

The grease-box mechanical props, equipped with 16 mm G-hooks and a two tonnes Rock-stop safety net, successfully held two tonnes at deflections of 0.4 m and 0.09 m when dropped from a height of 0.1 m. Although, one prop was struck out by the two tonnes mass on test 1 resulting in excessive deflection of 0.4 m, the remaining mechanical props were able to hold the mass. An additional three tests conducted with the two tonnes mass dropped closer to attachments indicated that the props do not slip out while holding the mass if they are installed correctly. The 16 mm flexible G-hooks on the props did not deform in all the tests conducted.

### 5.7.4 Blast-on mesh

During the tests conducted on the MINAX 80/3 BOM with plate attachments, it was observed that the face plates failed to hold a mass of two tonnes when dropped from a height of 0.1 m. This resulted in a BOM deflection of 1.08 m, which is worse than the acceptable limits for all stopes and flat excavations at Thembelani Mine. However, when the drop height was reduced to 0 m, BOM along with the face plates, held two tonnes, with a deflection of 0.52 m. The deflection was further reduced to 0.48 m and 0.45 m at drop heights of 0.1 m and 0.01 m respectively, above the mesh when spike plates were used.

When mechanical props and spike plates were used to secure the BOM, a mass of two tonnes was held with a BOM deflection of 0.44 m to 0.50 m at drop heights of 0 m, 0.1 m and 0.11 m. Furthermore, mechanical props together with BOM held two tonnes with a deflection of 0.46 m.

It was concluded that the MINAX 80/3 BOM does not meet the requirements for two tonnes systems, for a maximum deflection of 0.35 m in a normal stoping width of 1.2 m. However, the BOM can be used in 1.4 m stoping width and flat excavations with deflection limits of 0.55 m and 1.3 m respectively.

# 6 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the study's key findings, observations, research limitations and recommendations for future work based on the initial and complementary studies.

## 6.1 Introduction

Based on the drop tests conducted at NCM and Videx, it has been concluded that the strength of the safety net or BOM alone should not be the sole determinant of whether the system can support two tonnes of FOGs. All other components of the temporary support system, including face plates, hooks, mechanical props hooks and mechanical prop headboard, must be taken into consideration in every installation scenario. If any of these components fail, it may fail the entire system. This confirms the failure of the two-tonne system in 2020 when a 1.65 t FOG occurred due to other constituents of the temporary support system rather than the two tonnes Rock-stop safety net.

## 6.2 Summary of Chapters

This report has presented six chapters that cover the following:

- Introduction and problem statements for a holistic approach to the design of the two tonnes temporary support systems on chapter 1;
- Chapter 2 reviewed the literature on temporary support systems and BOM for the face area. It also covered drop test facilities for testing safety nets and BOM;
- Chapter 3 established the criteria that temporary support units and BOM must meet to fulfil the two tonnes' requirement;
- Chapter 4 included details of temporary support characteristics, design requirements and testing procedures. It outlined the manufacturer specifications for temporary support system units and BOM used at Thembelani Mine, as well as the installation standards.
- Chapter 5 discussed the findings and analyses based on the criteria that each constituent of the temporary support system must fulfil. It listed the drop test results and;

- Chapter 6 present the conclusion and recommendation. It summarises the chapters, research observations, research contributions, research limitations and recommendations for future research work.

In summary, it is crucial to consider all constituents of the two tonnes temporary support system during installation scenarios. The report recommends a holistic approach to the design of the system, including the safety net, face plates, hooks, mechanical props and BOM based on drop tests. The findings emphasize the importance of considering all elements of the system to prevent failures like the one that occurred in 2020.

## 6.3 Initial and Complementary Studies

### 6.3.1 Initial studies

Two previous studies were carried out to evaluate the performance of safety nets at drop test facilities. One study was conducted in Europe and the other in RSA at the SAVUKA facility. The European study examined the construction of a drop test facility that tests safety nets with attachments at various spacings. The study performed dynamic drop tests by dropping a specific mass onto the net to evaluate the force of the loading mass and deflection on the net. The study concluded that safety nets designed to hold free-falling objects should be tested in a dynamic drop test facility.

On the other hand, the SAVUKA study assessed the strands, mesh size, and interaction between the safety net strands, net ropes and net attachments to determine their impact on the safety net while holding the mass. A system of mechanical props pressing the safety net against the hangingwall was also evaluated at SAVUKA.

At WASM, dynamic drop tests were conducted on 4mm BOM, used in mining applications. The rupture force and rupture displacement were measured during the tests. The drop test facilities used in Europe and at WASM both had load cells to measure the force and displacement accurately. However, the Savuka drop test facility did not mention load cells.

It is important to note that all the previous tests did not account for the temporary support system installation scenarios as practised at Thembelani Mine. These scenarios are safety nets with hooks and face plates, safety nets with mechanical prop hooks, 3 mm BOM with face plates or spike plates, 3 mm BOM with spike plates and mechanical props and 3mm BOM with mechanical props only.

### 6.3.2 Complementary study

Thembelani Mine is a shallow mining environment less than 1000m deep, where FOGs are gravity-induced. The history of FOGs at Thembelani Mine from 2017 to 2022 supports the idea that gravity-induced FOGs are prevalent in the mine. Therefore, dynamic drop tests, where a specific mass is dropped vertically from a certain distance above the net, are a better representation of the FOGs at Thembelani Mine. For this study, two dynamic drop test facilities such as the NCM and Videx were used to test Thembelani Mine temporary support installation scenarios to ensure they fulfil the two tonnes temporary support systems requirements.

## 6.4 Key Findings and Observations

### 6.4.1 The initial two tonnes temporary support systems used at Thembelani Mine

The two tonnes safety nets were rolled out without consideration for the strength and deflection properties of other components of the temporary support systems. These components include 12 mm diameter flexible G-hooks, roof bolt face plates with a thickness of 4.5 mm, and square headboard mechanical props with welded 12 mm U-hooks and dimensions of 130 mm x 130 mm.

An analysis of FOGs that occurred between 2019 and 2020 revealed that the safety net was not the only cause of failure for the temporary support systems. Failures could be caused by any item within the temporary support systems, such as flexible hooks attached to the face plates of roof bolts stretching, welded hooks on mechanical props stretching, safety net strands breaking, safety nets deflecting to the footwall, and safety nets held to the hangingwall by square headboard mechanical props slipping out and falling with the rock.

In 2020, a 1.65 tonnes FOG occurred, which collapsed with the two tonnes safety net and resulted in a death of an employee. The safety net was held to the hangingwall by 130 mm x 130 mm square headboard mechanical props, which slipped out from the hangingwall and allowed the safety net to collapse with the FOG. As a result, the square headboard props were immediately replaced by the T-shaped Grease box mechanical props with longer headboards (370 mm x 100 mm) and 16 mm flexible G-hooks.

Therefore, it was decided to test the temporary support systems holistically using installation scenarios as practiced at Thembelani Mine as opposed to testing each the constituents of the systems individually. The aim of the test was to assess if all components fulfil the requirements of the two temporary support systems from system test point of view.

### 6.4.2 Two tonnes Rock-stop safety nets

Results from drop tests have shown that Rock-stop safety nets with a capacity of two tonnes can handle a two tonnes mass dropped from heights of 0 m to 0.32 m without any failure. These tests were conducted with attachment spacing of 1.5 m x 1.5 m as per Thembelani Mine standard for support spacing. The 16 mm S-hooks used during testing have also been evaluated, and they were found to maintain their shape and size without any inelastic deformation. During the testing, the safety net experienced a maximum deflection of 0.13 m at a drop height of 0.31 m. This deflection was due to the outer webbing stitches breaking and moving outward on both sides of the central hook along the longer length while supporting the two tonnes mass. Additionally, accelerometer measurements matched the expected results for falling objects, validating the accuracy of the testing.

### 6.4.3 Hooks and face plates

All tests were conducted following the Thembelani Mine support standard. The two tonnes Rock-stop safety net was attached to face plates on the test frame using hooks spaced at 1.5 m x 1.5 m. The testing revealed that a 6 mm face plate, along with either a 14 mm Carbon steel S-hook or a 14.5 mm Spring steel G-hook, could hold two tonnes of mass without failing at a drop height of 0.3 m. However, 4.5 mm face plates proved insufficient as the hooks pulled open the hook hole and caused the net to sag to 1.08 m.

The 14.5 mm G-hooks held two tonnes of mass without deforming, while the 14 mm S-hooks stretched by 0.002 to 0.005 m. However, the stretching did not affect the safety net deflection. It was determined that the Rock-stop safety net could securely hold two tonnes of mass when paired with either the 14 mm S-hooks or 14.5 mm G-hooks.

On the other hand, the 12 mm G-hooks opened from G-shape to C-shape by 0.05 m to 0.07 m, resulting in an overall deflection of 0.2 m at a drop height of 0.3m. Additionally, the perimeter of the safety net shifted towards the edges of the hooks when holding two tonnes with the 12 mm hooks. As a result, it was concluded that the 12 mm G-hooks were not capable of securely holding the Rock-stop safety net loaded with two tonnes of mass.

### 6.4.4 Grease-box mechanical props

During the tests, the two tonnes Rock-stop safety net was attached to the headboard of the Grease-box mechanical props using 16 mm flexible G-hooks. The spacing between the props was 1.5 m x 1.5 m, as per the Thembelani Mine support standard. The setup could hold two tonnes at safety net deflections of 0.4 m and 0.09 m from a drop height of 0.1 m when the mass falls to centre of the net. Although, one prop was struck out by the two tonnes mass on test 1 resulting in excessive deflection of 0.4 m, the remaining mechanical props were able to hold the mass. An additional three tests conducted with the two tonnes mass dropped closer to attachments indicated that the props do not slip out while holding the mass if they are installed correctly. The 16 mm flexible G-hooks on the props did not deform in all the tests conducted. This indicates that increasing the headboard dimensions from 130 mm x 130 mm to 370 mm x 100 mm helped stabilize the props and prevent them from slipping while holding the mass.

### 6.4.5 Deflections on Rock-stop safety nets

The deflections for two tonnes Rock-stop safety nets with attachments or props were all below the maximum allowable limit. The highest recorded deflection was 0.13 m, which is less than the allowable limits of 0.35 m, 0.55 m and 1.3 m for normal stoping width, higher stoping, and flat development end, respectively.

Therefore, two tonnes Rock-stop safety nets, together with 6 mm face plates and 14mm S-hooks or 14.5 mm G-hooks spaced 1.5m x 1.5m, meet the requirements for the two tonnes temporary support systems. Additionally, Grease box props fitted with 16 mm hooks holding two tonnes Rock-stop safety nets at 1.5 m x 1.5m spacing meet the requirements for the two tonnes temporary support systems.

### 6.4.6 Blast-on mesh

According to Thembelani Mine support standards, the MINAX 80/3 BOM with 8 mm blast-on was tested to hold two tonnes with face plates spaced at 1.5 m x 1.2 m. The BOM deflection was 0.52 m and successfully held two tonnes when dropped from a height of 0 m. However, at a free fall height of 0.1 m, the face plates failed to hold the mass, resulting in a BOM deflection of 1.08 m. The deflection reduced to 0.48 m and 0.45 m at drop heights of 0.1 m and 0.01 m respectively, above the BOM when spike plates were used.

The BOM held two tonnes with a deflection of 0.44 an d 0.48 m at drop heights of 0.1 m and 0.11 m, respectively, when installed with long headboard (370 mm x 100 mm) mechanical props and spike plates. BOM held two tonnes with a deflection of 0.44 m and 0.45 m at drop heights of 0.1 m and 0 m respectively when installed with Grease box mechanical prop and spike plates. Furthermore, mechanical props together with BOM held two tonnes with a deflection of 0.46 m.

Overall, it was concluded that the MINAX 80/3 BOM does not meet the requirements for two tonnes systems with a maximum deflection of 0.35 m in a normal stoping width of 1.2m. However, it can still be utilized in higher stoping widths of 1.4 m and flat excavations with deflection limits of 0.55 m and 1.3 m respectively.

### 6.4.7 Underground trials

Underground trials conducted at Thembelani Mine after the drop tests indicated that the two tonnes systems indicated that it was more work to install two lines of mechanical props with only two Timbers (timber elongate and mechanical prop installation employees) in crew stoping crew with 11 members. The solution to this problem is to get all crew members participating in the installation mechanical props instead of two Timbers during Entry Examination and Making Safe (EEMS) before the start of the shift. The crews also reported that the releasing spanner of mechanical props were sometimes unable to release the prop at the end of the shift. Investigations indicated that the Grease-box props which bent are the ones which proved difficult to remove with the releasing spanner. Coaching was conducted to safely store the mechanical props so that they are not damaged or bent by blasting and scraping activities. Moreover, bend and damaged props should be discarded. After resolving issues identified with the trials, the two tonnes temporary support systems could be effectively rolled out.

## 6.5 Research Limitations

### 6.5.1 Recording instrumentation and drop mass

During the study conducted at Videx and NCM drop test facilities, it was found that these facilities did not have load cells on attachments, unlike European drop test facilities that are used for testing nets. Test Frame 1 at the NCM facility, however, had one load cell attached to the centre of the drop mass which could only measure the central displacement and total force. Thus, this set-up was unable to record displacement and total force on each attachment point. Physical measurements of displacement were taken at the Videx drop test facility and test Frame 2 at NCM (for mechanical props). The drop mass for both NCM and Videx facilities comprised steel blocks with smooth edges, and hence, did not account for the sharp edges of the FOGs underground. The amount of deformation of face plates and hooks was measured immediately after the tests as there was no automated instrument available to record this information.

### 6.5.2 Sample sizes

During the testing of safety nets for the Thembelani Mine, sample sizes of 3.1 m x 1.4 m Rock-stop nets and 3 m x 1.2 m BOM were used. However, the drop test facilities were not designed to accommodate larger samples of 3 m x 4 m for flat excavation safety nets and BOM. Results from European standards for testing safety nets revealed that the increase in attachment spacing led to increased loading on attachment and displacement. Hence, if attachment spacing of 1.5 m x 4 m is used, reflecting the flat excavations standard, a higher deflection than the maximum deflection of 0.13 m and 0.52 m obtained with lesser attachment spacings for Rock stop nets and BOM respectively is expected.

### 6.6 Recommendations for Future Research Work

Trial the NCM Blast-on steel cable nets which also hold two tonnes with a relatively low deflection of 0.07 m at a drop height of 0.1 m as indicated in Appendix B. The trial would establish if Blast-on cable mesh can withstand the blast and not be damaged by cleaning equipment such as a winch scraper. In this regard, it should be proven that this mesh could act dually as re-usable areal coverage and as permanent areal coverage along the face. If successful, it could be compared with BOM and safety nets. After that, continuous improvements may be applied regarding suitable nets from safety, ergonomics and cost point of view.

Drop test facilities should be set up to accommodate larger samples of 3 m x 4 m for flat-end safety nets and BOM to trial installation scenarios for cleaning shifts in a flat development end. For future tests when drop test facilities are adjusted for larger nets and mesh samples, the deflection limit of 1.3 m should be used as a criterion for acceptance for flat excavation nets. To simulate underground set-up for flat excavations the test frames should also be equipped with slots to screw in pigtail eye bolts representing hooking of the nets on the face side. The frame should also be adjusted to hold the net and mesh onto the bottom of the test frame with four 3.2 m long mechanical props spaced at 2 m x 2 m. In the meantime, entry examination and barring must be conducted thoroughly to identify and remove loose rocks from the hangingwalls and sidewalls before they fall uncontrollably and injure employees.

Due to logistical constraints whereby the author had to supply the test samples from Thembelani Mine to the drop test facilities, a limited number of drop tests were conducted in this study. Continuous testing is thus required to ensure that the temporary support elements supplied to the mine conform to the two tonnes' requirement. The quality control and quality assurance procedure of Sibanye-Stillwater SA PGM should be updated to include testing of face plates, hooks, safety nets, mechanical props and BOM from the drop test facilities. The suppliers should continue to provide test certificates for safety nets, mechanical props, face plates, hooks and BOM to the mine. The certificates should account for the drop test results for every batch of products delivered to the mine. Additionally, an independent company should select random samples of the temporary support delivered to the mine and test them as per the quality control and quality assurance procedure of Sibanye-Stillwater SA PGM. If the results of the tests from either the supplier or independent contractor indicate that some items do not fulfil two tonnes, the information should be shared with the mine management urgently. Such batches should be prevented from being used at the mine. The supplier should conduct further investigation as to why the products do not fulfil the requirements and provide a solution to the mine to prevent the recurrence of such mishaps.

The results of the drop tests have shown that the two tonnes temporary support system is effective when two lines of Grease box mechanical props spaced at 1.5 m x 1.5 m hold the Rock-stop safety net to hangingwall. The Rock-stop safety nets were also found to be effective in holding two tonnes when attached to 6 mm thick face plates with 14 mm NCM S-hooks or 14.5 mm G-hooks from Videx. Additionally, it was found that MINAX 80/3 BOM could hold two tonnes when pinned to the hangingwall by two rows of mechanical props spaced at 1.5 m x 1.2 m. The BOM could also be held to the hangingwall by spike plates at a spacing of 1.2 m x 1.5 m. However, due to exceeding deflection limits, BOM is recommended to be used in stope width of 1.4 and flat excavations with a height 3.2 m. The findings from drop tests should therefore be incorporated into the temporary support installation procedure, Early Entry Examination and Making Safe (EEMS) procedure, BOM installation procedure, and Trigger Action Response (TARP) procedure. Management should conduct an awareness campaign of the updated procedures together with the OEM, employee representatives, training department, full-time health and safety representatives, and the Rock Engineering department. Furthermore, the OEM, in conjunction with the training department, should provide on the job training and continuous coaching on the aforementioned procedures to the crews working underground. Planned task observations and visible felt leadership (coaching) should be conducted by supervisors, management and members of the Rock Engineering department to assess the level of competency of employees, identify any shortcomings, and provide continuous improvement from an implementation point of view.

# REFERENCE LIST

Botha G., (2010) Introduction to Strata Control. *Unpublished in-house course notes for candidate strata control officers*, Anglo American Platinum, Rustenburg Section, South Africa.

Brändle R., Rorem E., Luis R., and Fisher G., (2017) Full-scale dynamic tests of a ground support system using high-tensile strength chain-link mesh in El Teniente mine, Chile. *Proceedings of the First International Conference on Underground Mining Technology,* Australian Centre for Geomechanics, Perth, pp. 25-43.

Daehnke A., Acheampong E., Reddy N., Le Bron K.B., and Haile A.T., (2000) Support Technologies to cater for Rockburst and fall of ground in the immediate face area*. Safety in Mines Research Advisory Committee, Project Summary*, GAP 606.

DMRE (2018) Mine Health and Safety Act 29 of 1996 and Regulations. *Mine Health and Safety Council.*

Durapraj S., (2023) Discussion on temporary support systems. *Personal communication between the Manager of the Rock Engineering department at Sibanye-Stillwater SA PGM section and the author on 19 June 2023*.

Flanagan B., (2020) Rock-stop blast-on safety net areal support. *Unpublished material specification sheet prepared by the Business Development Manager,* New Concept Mining powered by Epiroc, Rustenburg Section, South Africa.

Flanagan B., (2023) Discussion on the two tonnes Rock-stop safety nets. *Personal communication between the author and the Business Development Manager of New Concept Mining powered by Epiroc at the New Concept Mining drop test facility on 23 May 2023*.

Gardner L.J., and Fernandes N.D., (2008) The ongoing evolution of stope Panel support at Impala Platinum Limited. *The 6th international symposium on ground support in mining and civil engineering construction*, SAIMM, SANIRE and ISRM, PP 651-664.

Haile A.T., (1999) A mechanistic evaluation and design of tunnel support systems for deep level South African mines. *Ph.D. Thesis,* Department of Mechanical Engineering, University of Natal, South Africa.

Heera V., (2024) Mine Design Review Presentation for Thembelani Mine. *Unpublished internal presentation on a business plan for the year 2025 compiled and presented by the Mineral Resources Manager of Thembelani Mine to Sibanye-Stillwater SA PGM executives*.

Hoek E., and Wood (1987) Support in Underground Hard Rock Mines. *A paper published in Underground Support Systems*, Volume 35, PP 1-6.

Humans J.L., and Fernandes N., (2004) Testing of temporary face support systems under rockfall conditions. *International Platinum Conference 'Platinum Adding Value'*, The South African Institute of Mining and Metallurgy. PP 71-76.

Jager A.J., and Ryder J.A., (1999) A handbook of Rock Engineering practice for tabular hard rock mines. *Safety in Mines Research Advisory Committee,* Johannesburg, South Africa.

Kotze J.E., Rymon-Lipinski W.K., Noble K.R., Klokow J.W., and More O'Ferrall (2002) Guideline for the compilation of a mandatory code of practice to combat rock fall and rock burst accidents in tabular metalliferous mines. *Department of Mineral Resources and Energy, South Africa.*

Le Roux L., (2020) Hooks and roof bolt face plates at Videx drop test facility. *Personal communication between the Managing Director of Videx Mining and the author on 23 June 2020*.

McCann P., (2011) Evaluation of safety nets by experiment. *Health and Safety Laboratory report 835, Executive Health and Safety.* Harpur Hill Buxton-Derbyshire.

Mathews D., (2023) Ultra High Tensile Strength Steel Mesh. *Personal communication between the Sales Director of M and J Mining and the author on 15 August 2023.*

Meriam J.L., and Kraige L.G., (2012) *Engineering mechanics dynamics Volume 2*. 7th edition, Virginia Polytechnic Institute and State University, United States of America. John Wiley and Sons Inc.

Morton E.C., Thompson A.G., Villaescusa E., and Roth A., (2007) *Testing and analysing of steel wire mesh for mining application of rock surface support.* 11th ISRM Conference.

Mulenga P.A., Joughin W.C., Murphy S.K., Walls J., and Zermatten C., (2016) Guide booklet to assist rock engineering and mining practitioners in the selection of permanent areal support in varying underground mining environments. *Mine Health and Safety Council SIM* 15 02 02.

Mulenga P.A., (2018) Designing a feasible methodology for selecting permanent areal support for varying environments in underground mines. *MSc. Research Report.* School of Mining Engineering, University of the Witwatersrand, Johannesburg, South Africa.

Mutsvanga C., (2018) Conventional stope support standard and temporary support procedure. *Internal standard operating procedure for stope and flat excavations.* Sibanye-Stillwater, SA PGM, Rustenburg section.

Mutsvanga C., (2019) Sibanye-Stillwater Platinum Mines Rustenburg section temporary support system. *Personal communication between the Unit Manager Rock Engineering and the author on 06 March 2023*.

Player J.R., Morton E.C., Thompson A.G., and Villaescusa E., (2008) Static and dynamic testing of wire mesh for mining applications of rock surface support. *6th International symposium on ground support in mining and civil engineering construction,* Villaescusa (ed) PP. 693-706

Ryder J.A., and Jager A.J., (2001) A textbook on rock mechanics for tabular hard rock mines. *Safety in Mines Research Advisory Committee, in conjunction with CSIR Division of Mining Technology,* Johannesburg, South Africa.

Seoka L., and Van Niekerk H., (2020) Salt spray testing for New Concept Mining – Cables with hog-rings. *Unpublished corrosion test results on NCM cable nets*, New Concept Mining, South Africa.

Skarbøvig N.M., Lamos A.W., and Lamos R.A., (2011), Mine Safety Net Development and Applications. *Journal of the Southern African Institute of Mining and Metallurgy,* Volume 111, 2011, PP. 19-28

Stacey T.R., (2001) Best practice rock engineering handbook for “other” mines, final report. *Safety in Mines Research Advisory Committee,* Johannesburg, South Africa.

Stacey T.R., (2006) Design-a strategic issue. *Journal of the Southern African Institute of Mining and Metallurgy*, Volume 109, 2009, PP. 157-162

Stacey T.R., (2023) Defining the design-Mechanical properties of rocks and rock masses. *Lecture Notes*, Schoof of Mining Engineering, University of the Witwatersrand, Johannesburg, South Africa.

Steyn T., De Bruin P., Judeel G., Nortje T., and Flanagan B. (2018) Risk Assessment for Rock-stop webbing safety net. *Unpublished material specifications on Rock-stop webbing safety nets*, New Concept Mining, South Africa.

Strong (2016) Prestressing tests grease-box mechanical props and exposed cams square headboard props. *Unpublished test certificates on prestressing of mechanical props*, M props, South Africa.

Strong (2023) *Specifications* of grease-box mechanical props. *Personal communication between the Technical Specialist of M Props and the author on 18 August 2023.*

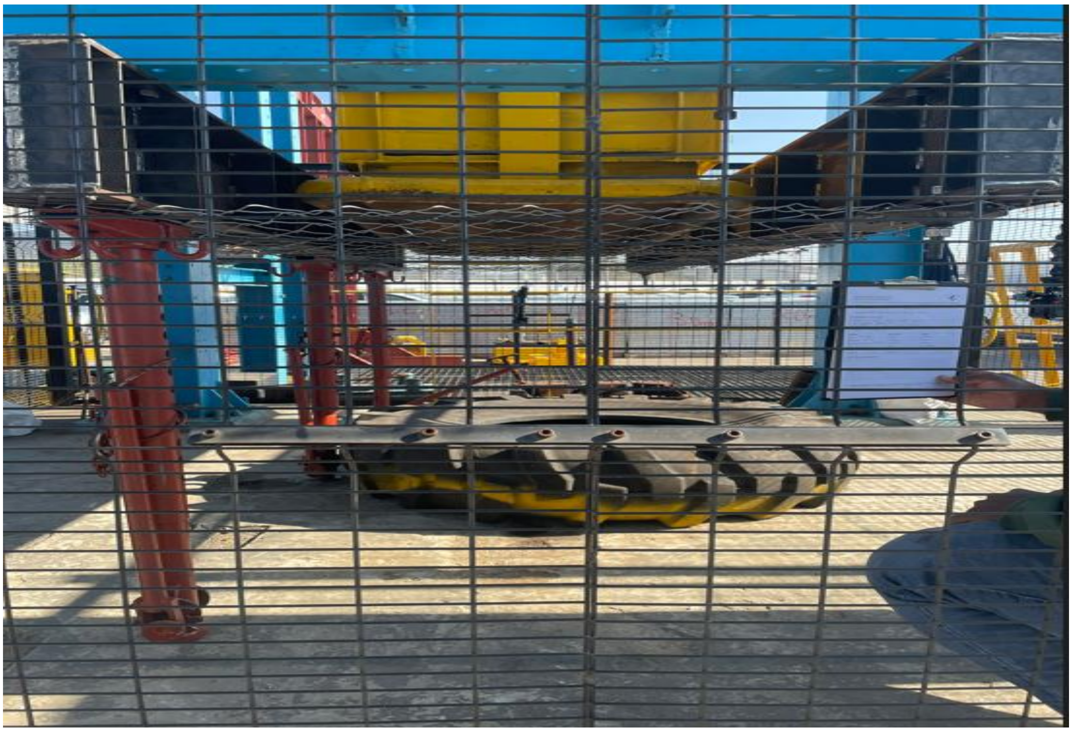
Van der Merwe J.N, Wojno L., and Toper A.Z., (2001) Implementation of state-of-art mining knowledge and technologies in design and operation of a safe and efficient deep gold mine stope for 21st Century. *Safety in Mines Research Advisory Committee, Final Project GAP 712.*

Zaayman P., (2020) Drop test on Polypropylene safety nets. *Unpublished drop test results on Polypropylene safety nets*, Cat-Mining Supplies, South Africa.

Zaayman P., (2023) The use of Polypropylene safety nets A Sibanye-Stillwater Hlanganani Mine. *Unpublished material specifications on Polypropylene safety nets*, Cat-Mining Supplies, South Africa.

# APPENDIX A. DROP TEST SET-UP AT VIDEX FACILITY

*Appendix A-1: Drop test set-up for MINAX 80/3 BOM with spike plates only*



*Appendix A-2: Drop test set-up for MINAX 80/3 BOM with mechanical props and spike plates*

*Appendix A-3: Drop test set for MINAX 80/3 BOM with long headboard Videx mechanical props*

# APPENDIX B: NCM BLAST-ON STEEL NETS

## Gravity Induced FOG Test

New Concept Mining

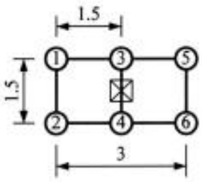
**Customer Details**

| | |
|---|---|
| Name: | SIBANYE |
| Sector: | THEMBELANI |
| Representative: | MOSES |

| | |
|---|---|
| Date: | 2023-05-23 |
| Test No. | 2305017 |
| Result | Passed |

**Product Info**

| | |
|---|---|
| Net Stock Code: | WBS-1.5X3.0X130 |
| S-Hook Stock Code: | WB-S-HOOK16 |
| Face PlateS tock Code: | HYFO435 |
| Hydra Bolt Stock Code: | Nil |




**Test Conditions**

| | |
|---|---|
| Support Spacing: | 3 x 1.5m |
| Stope Height: | 1.2 m |
| FOG Mass: | 2004 kg |
| FOG Height: | 0.10 m |
| Number of Attachments: | 6 |
| Number of Load Cells: | 0 |

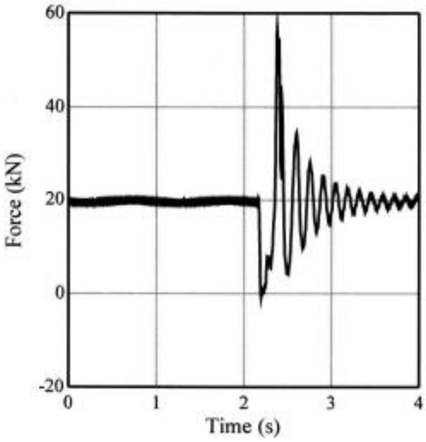
**Results**

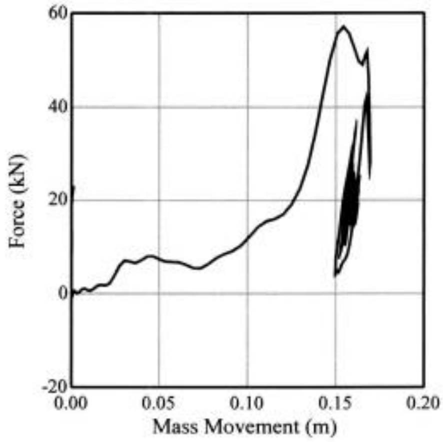
| | |
|---|---|
| Impact Velocity: | 1.2 m/s |
| Kinetic Energy: | 1.5 kJ |
| Total Energy: | 3.3 kJ |
| Final Deformation: | 0.06 m |
| Maximum Deflection: | 0.07 m |
| Maximum Force: | 57.1 kN |
| Survival Height | 1.13 m |

**Maximum Forces**

**Comments:**

Steel Net - Customer Test 2




**Methodology:** A mass of known weight is positioned over the net at a specific height above the net. The Weight is then dropped onto the net to evaluate the total energy that is absorbed and the total displacement of the net without failure.

*Appendix B-1: Drop test results for NCM Blast-on steel nets at 0.1 m drop height*

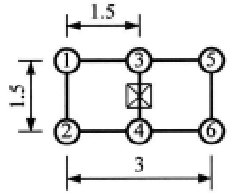
# Gravity Induced FOG Test

**Customer Details**
Name: SIBANYE
Sector: THEMBELANI
Representative: MOSES

New Concept Mining

Date: 2023-05-23
Test No. 2305016
Result Passed

**Product Info**
Net Stock Code: WBS-1.5X3.0X130
S-Hook Stock Code: WB-S-HOOK16
Face PlateS tock Code: HYFO435
Hydra Bolt Stock Code: Nil

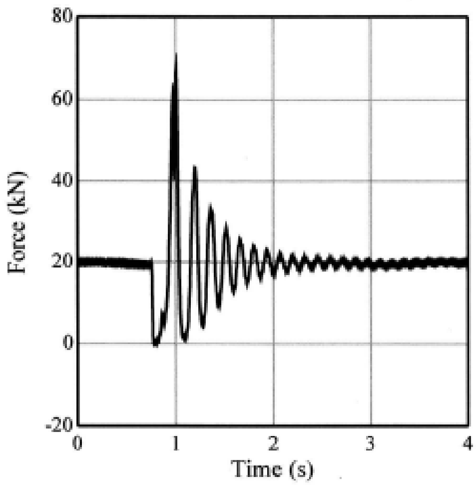


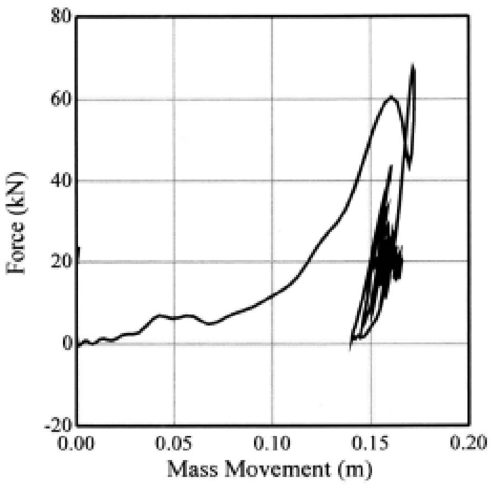

**Test Conditions**
Support Spacing: 3 x 1.5m
Stope Height: 1.2 m
FOG Mass: 2004 kg
FOG Height: 0.00 m
Number of Attachments: 6
Number of Load Cells: 0

**Results**
Impact Velocity: 0.0 m/s
Kinetic Energy: 0.0 kJ
Total Energy: 3.4 kJ
Final Deformation: 0.15 m
Maximum Deflection: 0.17 m
Maximum Force: 67.5 kN
Survival Height 1.03 m

**Maximum Forces**

**Comments:**
Steel Net - Customer Test 1




Methodology: A mass of known weight is positioned over the net at a specific height above the net. The Weight is then dropped onto the net to evaluate the total energy that is absorbed and the total displacement of the net without failure.

*Appendix B-2: Drop test results for NCM Blast-on steel nets at 0.1 m drop height*