CHAPTER 5

ROCKMASS MODEL

5.1 BACKGROUND TO THE STUDY – ROCKMASS STIFFNESS CONCEPT

The conventional classification of established mining methods is based on the type and degree of support provided in the mine structure created by ore extraction. Thomas (1973) recognised two fundamentally different types of mine structures:

(a) naturally and artificially supported mine structures (generated by such methods as open stoping), and
(b) caving structures (generated by block caving or sub level caving).

The mine stability objective is to ensure that unstable release of stored energy cannot occur. The distinction between various mining methods can be made on the basis of the displacements induced in the country rock and the energy redistribution that accompanies mining.

Whatever mining method(s) is applied in ore extraction, four general rock engineering objectives are to be satisfied in the design of the mine structure, these are to:

(a) ensure the stability of the mining structure or opening as orebody extraction proceeds;
(b) preserve unmined ore in a minable condition;
(c) protect major service openings until they are no longer required; and
(d) provide secure access to safe working places.

The stability of the mine opening ought to be considered as the prime design requirement. In a properly designed engineering structure, small changes in operating conditions and geometry should result in only small changes in the stability of the structure. According to Brady and Brown (1981) an unstable structure is one where small external disturbances produce large, sudden, and frequently catastrophic changes in the structure geometry. Avoiding such conditions in a mine opening should be a fundamental design requirement.

5.2 BACKGROUND TO THE FIRST APPROACHES

5.2.1 Instrumentation

Convergence is defined as the elastic rebound of the rockmass into the excavation due to the removal of stresses from the surface of the excavation, while closure is defined as convergence plus the inelastic rockmass movement due to bed separation. The closure component of deformation is utilised in the research as part of the process to determine the rockmass stiffness. The stope closure at a specific point quantifies the x-value of the load-deformation presentation of rockmass stiffness.

Stope panels were instrumented and stope closure at specific stations measured at regular time intervals for the purpose of determining the closure at a specific point at a given time. Measuring stations were initially installed approximately 6 m from the stope face and measured throughout the working life of the stope panel.

The measuring stations consist of survey pegs installed into the hanging- and footwall of the stope. The pegs were installed in such a way that closure was measured normal to the hanging- and footwall. Measurements were taken at monthly intervals except for panels where the stope closure rate was higher than the average of 2 mm/day. The reason for this was that any abnormality in the rate of closure could be identified in time and pro-active steps implemented prior to a potential stope collapse. This formed part of the mine's pro-active strategy to combat large falls of ground.

5.2.2 M-factor approach

It is vital that the magnitude of the force component be established to determine the rockmass stiffness, and this is perhaps the most complex value to determine for the purpose of this exercise. A number of different approaches were taken in an attempt to determine this value.

A methodology was developed that can be implemented without digitising and numerically model the area of interest at first. The objective was to enable the rock engineer to determine the force component for rockmass stiffness at a measuring station for any given mining geometry at the time. The aim is thus to relate the force component of the rockmass stiffness to the mining geometry. A number of different approaches were adopted and experimented with initially to determine the force component for the rockmass stiffness. The very first one was to establish the force "required restoring the hangingwall" to its original or pre-mining position. The force determined this way was assumed at zero deformation, i.e. the deformation of the hangingwall prior to the mining operation. This value was used in fixing the one point on the force axis of the rockmass stiffness representation. The other fixed point, deformation, is taken as the measured deformation underground where the magnitude of the force exerted onto the hangingwall is assumed to be zero. The mathematical function connecting these points defines the rockmass stiffness.

It is not possible in reality to generate a load with sufficient magnitude that will restore the hangingwall to its original pre-mining position. An analytical method was employed for this in order to determine the magnitude of such a fictitious force. This was achieved through numerical modelling where the results of the analysis were related to the mine plan in a way that is to be described.

Deformation at any point in a mined out area relates to the mining span. Deformation at that point will increase as the mining span increases. When considering the rockmass stiffness concept, will the force component also increase as deformation increases. The force component is thus related to the mining span.

The fictitious force exerted onto the hangingwall that will result in zero deformation at that point for the given mining geometry was determined by numerical modelling. Minsim W was utilised for this purpose. This was accomplished by modelling a fictitious solid pillar at the position of the measuring station for the given mining geometry. Theoretically the deformation at that point is zero with the fictitious pillar in position. The stress on the pillar was converted into a force, taking into consideration the dimensions of the pillar.

The modelling was repeated for all the mining intervals at which measurements were taken underground. The objective of this part of the analysis was to establish the correlation between the mined area and the force that was calculated. Through this it was believed that the methodology would take into consideration the existing mining geometry and regional support.

The mined out area was determined by means of a planimeter and was repeated for all the mining steps. This was performed as a first attempt to determine the relationship between the force and the cumulative square meters mined up to the date that underground closure measurements were taken. The calculated force was then compared to the cumulative square meters mined for that particular mining stage.

The objective with this approach was that it must be possible for the design engineer to determine the force exerted onto the hangingwall at any stage of mining from the cumulative area mined (m^2). It was foreseen that the force be calculated in practice through this potential relationship that might exist between the force and the cumulative area mined. A good correlation was found to exist between the calculated force and the cumulative square meters mined for any specific mining interval. This relationship was referred to as the so-called Mining factor or M-factor.

The M-factor was determined for the first analysis of the 15A47 Stope and yielded an average value of 0.2. The positions of the measuring stations and the consecutive mining steps are shown in Figure 7.2 of Chapter 7. The following table gives a summary of typical results for the different measuring stations that were obtained through the application of this methodology.

Table 5.1: M-factor for the 15A47 Stope

Date (Mining Stage)	**m^2 mined**	**Cumulative m^2**	**Force @ Station 1(MN)**	**Force @ Station 1A (MN)**	**Force @ Station 1B (MN)**	**Force @ Station 2 (MN)**	**Force @ Station 2A (MN)**	**Force @ Station 3 (MN)**	**Force @ Station 3A (MN)**
5 July (A_0)	22300	22300	-	-	-	-	-	-	-
16 August (A_1)	3990	26290	5262	5605	-	5406	-	3184	3184
6 September (A_2)	2340	28630	5671	5940	4777	6025	4739	4353	4353
6 October (A_3)	3120	31750	6017	6225	5429	6452	5437	4853	4853
9 November (A_4)	2310	34060	6838	6920	6273	6941	6146	5406	5406
27 December (A_5)	4650	38710	7366	7385	6846	-	-	6270	6270
Date (Mining Stage)	**M-factor Station 1**	**M-factor Station 1A**	**M-factor Station 1B**	**M-factor Station 2**	**M-factor Station 2A**	**M-factor Station 3**	**M-factor Station 3A**	**M-factor Station 5**	**Estimate**
16 August (A_1)	0.20	0.21	-	0.21	-	0.12	0.12	0.22	0.18
6 September (A_2)	0.20	0.21	0.17	0.21	0.17	0.15	0.15	0.22	0.19
6 October (A_3)	0.19	0.20	0.17	0.20	0.17	0.15	0.15	0.21	0.18
9 November (A_4)	0.20	0.20	0.18	0.20	0.18	0.16	0.16	0.21	0.19
27 December (A_5)	0.19	0.19	0.18	-	-	0.16	0.16	0.20	0.18
Averages	**0.20**	**0.20**	**0.18**	**0.21**	**0.17**	**0.15**	**0.15**	**0.21**	**0.18**

Table 5.1 shows the M-factor calculated for the different mining stages at the measuring or observation stations as shown. Column 1 shows the date and stage of mining denoted as A_n, where n indicates the mining stage. Installation of the station is where n=0. The area mined during that stage is shown in the second column. The third column gives a summary of the cumulative square meters mined including that particular stage of mining. The rest of the columns show the forces that were determined for any given station in Mega-Newton (MN) as calculated numerically for the different mining stages.

The bottom row of Table 5.1 shows the M-factors that were calculated at the measuring stations for the different stages of mining. The analysis produced an average value of 0.18 for the M-factor.

The aim in using this approach was to apply the M-factor in the analysis of an area where the cumulative square meters mined is determined from the mine plan and the force calculated from it. It is possible that the force exerted onto the hangingwall at a measuring station be calculated without the use of any numerical analysis this way. The force is calculated as the product of the M-factor and the cumulative m^2 mined.

This methodology was repeated for other working places for a number of mining stages. It also yielded a constant but different magnitude for the M-factor.

(a) Shortcomings of the M-factor approach

It is important that the M-factor should be constant, correct and reliable since it has a major impact on the magnitude of the force that is calculated from it.

This methodology was discontinued even though different underground sites yielded a constant value for the M-factor. Every analysis that was performed yielded a different value for the M-factor. The reason for this is that the initial cumulative area mined (A_0) is not fixed and cannot be established for a stope layout in order to yield the same and constant value for the M-factor.

5.2.3 Elliptical approach

The objective remains that the methodology that is developed should be simple to use by the design engineer.

The mining areas of interest were modelled using Minsim W numerical analysis to calculate the force required to restore the hangingwall to its pre-mining position at the particular measuring station as for the M-factor approach. This exercise was repeated at all the stations where underground measurements were taken for the different mining stages.

The deflection of a simple single beam clamped on both ends is a function of the span, beam thickness and material properties of the beam. The total deflection of combined orthogonal beams is also a function of the orthogonal spans, material properties and beam thickness of the two independent beams.

The second approach in the analysis was to evaluate the combined deflection of two orthogonal beams with the centre at the measuring station in the stope. This was achieved by fitting two orthogonal beams at the point of interest to the closest solid abutments or to regional pillars as illustrated in Figure 5.1.

This principle was put to use in determining the relationship that existed between the force calculated as mentioned and some parameter that can be related to the two orthogonal beams of an ellipse fitted with its the centre at the point of interest.

The forces calculated using numerical modelling at these points were compared to different variables of the ellipse described by the short and long axes of the two orthogonal beams. This approach gave a very good correlation between the force calculated numerically and what is defined as the effective side of the ellipse.

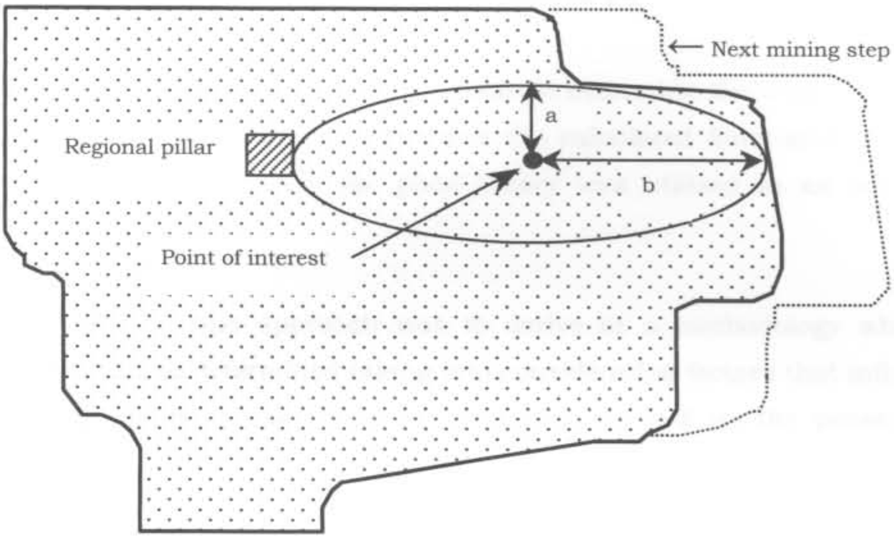

Figure 5.1: Illustration of the elliptical fit at a point of interest to a specific mining geometry.

The effective side (E_s) is defined as the square root of the area of the ellipse:

$$E_s = (\pi ab)^{1/2} \tag{5.1}$$

where:

Es = Effective side of the ellipse (m);

a = Short axis of the ellipse (m); and

b = Long axis of the ellipse (m).

The limitation of this approach is that mining can take place outside the influence area covered by the ellipse but still close enough in proximity to the measuring station to have an influence on the force. This analysis is not able to record this and calculations done under such circumstances may be inaccurate.

5.3 APPLYING THE YIELD LINE THEORY AND CONCEPTS

The previous analysis suggested that the solution to determine the magnitude of the force lies in the correlation that exists between the calculated force and the mining geometry. For the next approach the plate theory was utilised in an attempt to represent rockmass behaviour.

The aim of reverting to this approach was to derive at a methodology where the rockmass stiffness can be determined taking into consideration factors that influence it such as mining geometry, proximity to an abutment, as well as the presence and position of regional support.

At failure, plastic deformations occur along yield lines where the reinforcement has yielded, while the parts into which the slab is divided by the yield lines are only deformed elastically. Since the elastic deformations can be ignored in comparison with the plastic ones, can the individual parts of the slab be regarded as a plane, and their intersections, that is the yield lines, as straight lines with a good degree of approximation. It is thus assumed that deformation occurs only in the yield lines, consisting of relative rotation of the two adjoining parts of the slab about axes whose location depends upon the supports. Each part may be regarded as plane, and will be treated as that. With the aid of this yield lines were constructed for the same underground geometry shown in Figure 5.1 and is as illustrated in Figure 5.2.

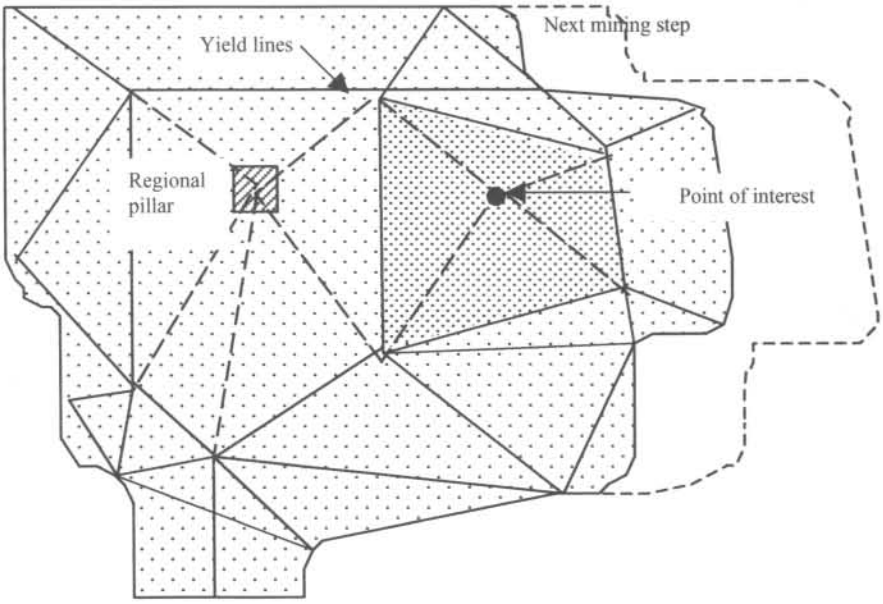

Figure 5.2: Yield Lines for the same underground geometry as shown in Figure 5.1

The area surrounding the measuring station where the stress convention of the skin of the hangingwall is compressive is delineated as the shaded area shown in Figure 5.2. This shaded area was compared to the numerical value of the force determined at that point for the given mining geometry. This yielded a constant Force (MN) to Yield Line Area (m^2) ratio between 2.4 to 2.8.

The force can therefore be calculated with reasonable accuracy when compared to the numerical analysis, once the yield line area is determined. An average value of 2.6 is applied as a constant.

The force is calculated as:

Force (MN) = Yield line area (m^2) x Constant of 2.6.

A good correlation was repeatedly found to exist between the calculated force using the yield line area and the magnitude of the force calculated numerically as described earlier.

The major advantages of this methodology as identified at the time were that this methodology other than the other approaches is able to compensate for a changing mining geometry and the presence of regional support. Mining in close enough proximity to the measuring station can be taken into consideration as the position and orientation of yield lines are determined by the mining geometry. Cognisance is also taken of the presence and position of regional support.

5.4 DEVELOPMENT OF THE ATTRIBUTED AREA ANALYSIS

5.4.1 Introduction

The stiffness representation of rockmass behaviour is the focus of this stope support assessment methodology.

The Yield Line Methodology showed much potential but was a time consuming process and open to interpretation errors when constructing the yield lines and keeping in mind the rules that have to be applied. With the objective that the methodology must be simple and user friendly for the rock engineering practitioner to use, slight modifications were made to the methodology in order to simplify it.

Another phenomenon that was identified during the previous processes were the orders of magnitude difference between the force that was calculated in "restoring" the hangingwall to its original position (as determined by numerical analysis) and the force generated by support units currently being used in the mining industry. In order for the rockmass stiffness concept to be applicable and of use, must the force component of rockmass stiffness and that of the support units be of the same order of magnitude.

5.4.2 Attributed area

A so-called attributed area was created for every measuring station in a similar way than the Yield Line Areas. The previous process was simplified in the way that an area gets attributed to a measuring station, taking into consideration the mining geometry and the presence and position of regional pillars.

The following basic rules are applied during this process:

1. Abutments are assumed to be support points; and
2. A single point at the centre of the pillar represents the regional pillar. This is illustrated in Figure 5.3(a).

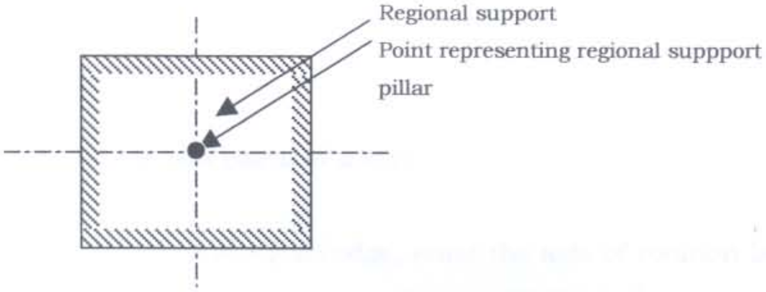

Figure 5.3(a): Regional support represented by a single point

3. Lines demarcating the attributed area are constructed in a similar fashion than the yield lines while the following applies:
   - Lines demarcating the attributed area are drawn midway between the point of interest and the solid abutment in a direction perpendicular to the shortest line connecting the two. This is illustrated in Figure 5.3 (b).

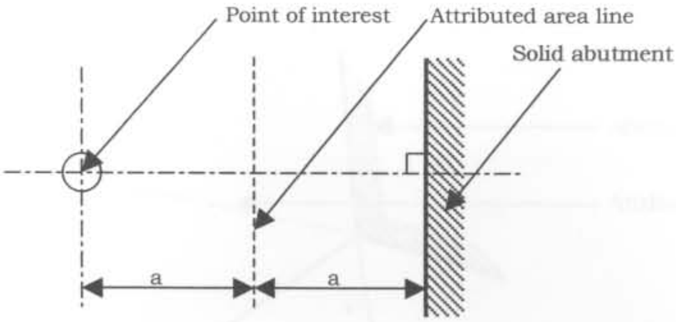

Figure 5.3(b): Line demarcating the attributed area between point of interest and solid abutment

- Attributed area lines between two parts of a slab must pass through the point of intersection of their axes of rotation.

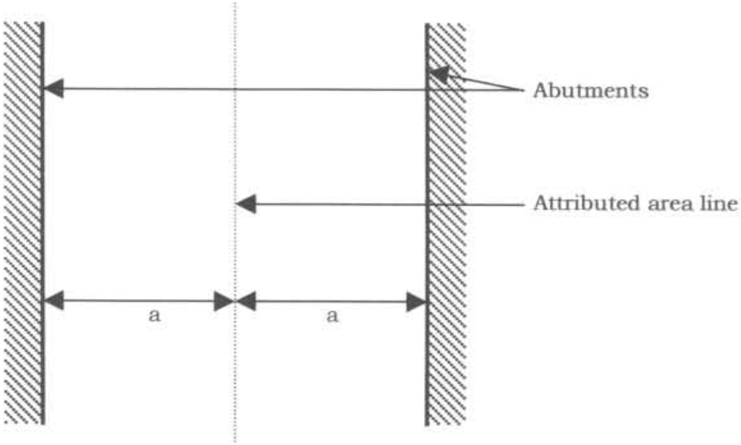

Figure 5.3(c): Attributed line for two parts of a slab

- For a part of a slab supported along its edge, must the axis of rotation lie along the edge, and for a part supported on a column will the axis pass over the column. This is of significance and relevant in the case of regional support in the form of pillars.

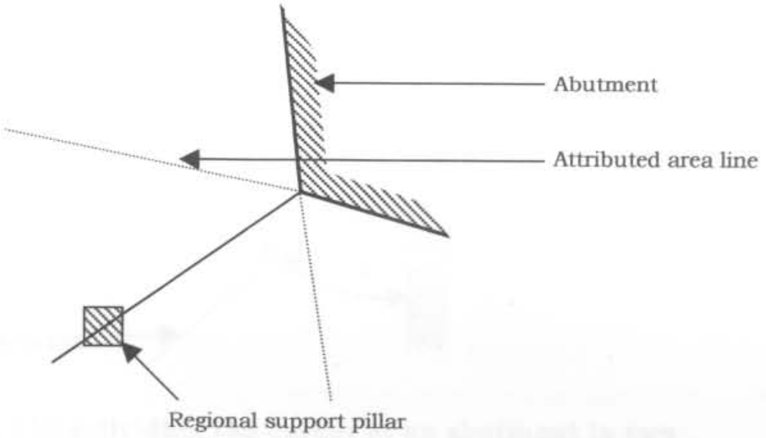

Figure 5.3(d): Attributed area line shown for a slab supported on the edge of an abutment with regional support in the area

- The attributed area line passes midway between two support points and is perpendicular to a line connecting these two points. A point of interest at a measuring station is treated as a support point for purposes of the analysis.

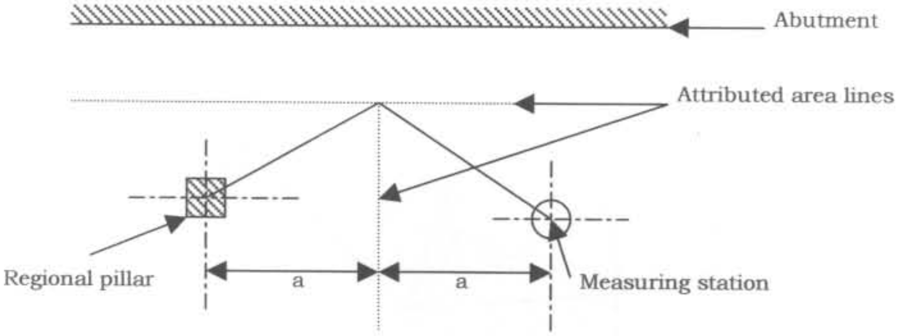

Figure 5.3(e): Attributed lines for a solid abutment, regional pillar and measuring station

- An attributed area line out of a mined corner divides the corner into two equal parts.

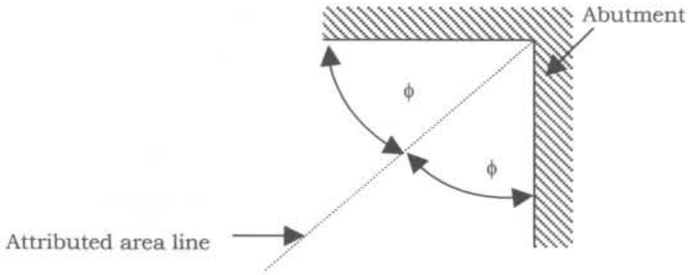

Figure 5.3(f): Attributed line dividing the corner at an abutment in two

With the aid of this, the attributed area was constructed for the same underground geometry as shown in Figure 5.1 and is as illustrated in Figure 5.4. The attributed area is thus a function of the mining geometry and will vary as the mining geometry changes.

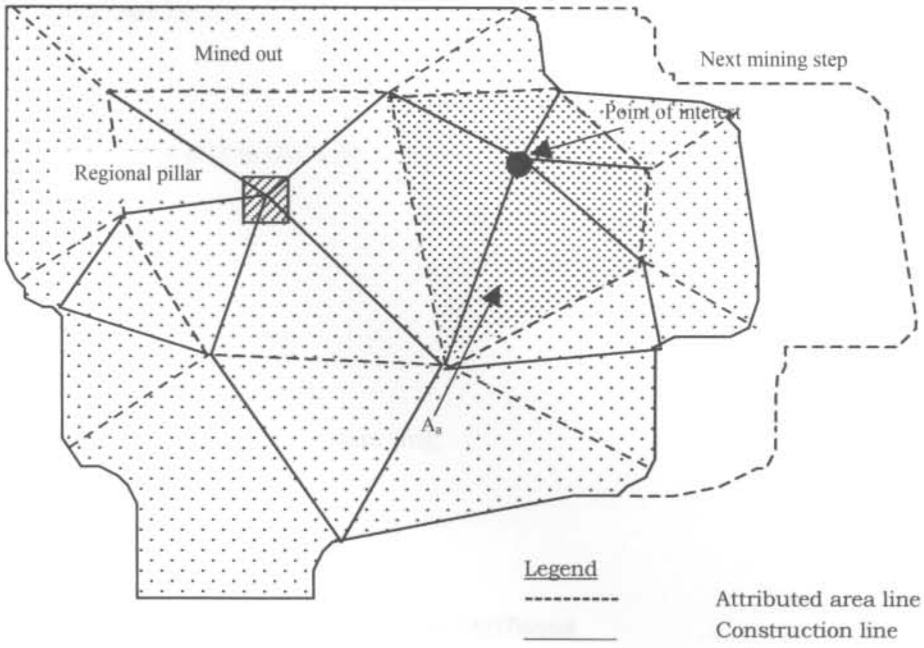

Figure 5.4: Mining geometry showing the Load Attributed Area A_a for the given point of interest

5.4.3 Magnitude of the force component for rockmass stiffness representation

The area represented by the attributed lines around a measuring station is referred to as the Attributed Area (A_a). This area can be determined by using a planimeter or by adding the triangular areas demarcated by the attributed area lines.

The force component (F_o) for rockmass stiffness is determined by assigning a hangingwall plate or beam thickness to the attributed area. The beam thickness is determined using the Voussoir beam for a given span as determined for Beatrix Mine by Kotzé (1991). The beam thickness will therefore change as the mining span increases with consecutive mining steps, and will be specific for a particular reef. The force is calculated by taking the weight of the rockmass plate of the attributed area for a given plate thickness.

The local rockmass stiffness for that particular point in the underground environment is determined using the force component from the attributed area and the closure component as is measured underground. The force component for representation of the rockmass stiffness can be determined for different mining geometries at various stages of mining.

The attributed area force (F_o) is thus given by:

$$F_o = \rho . h_t . A_a . g \quad (N) \qquad (5.2)$$

where:

F_o = Attributed area force (N);
ρ = Rockmass density (kg/m^3);
h_t = Thickness of hangingwall beam (m);
A_a = Attributed area (m^2); and
g = Gravitational accelaration (m/s^2).

5.4.4 Deformation component of rockmass stiffness

To represent rockmass stiffness is it essential that both the force and deformation components be quantified. The force components for the different stages of mining are determined as discussed in 5.4.3

The deformation component for the rockmass stiffness for the different stages of mining at a measuring station is measured underground as discussed in 5.2.1.

5.4.5 Rockmass stiffness representation

The force and deformation for a given mining interval is calculated as discussed in 5.4.3 and 5.2.1 and presented on a force-deformation axis. The slope of the line represents the rockmass stiffness for that particular mining interval.

The yield line representing rockmass stiffness is described by the following equation:

$$g(x) = mx + F_o \tag{5.3}$$

where:

m = tan λ = Rockmass stiffness (N/m);

x = Deformation of the stope at the measuring station (m); and

F_o = Attributed area force (N) where deformation $x = 0$.

Note: It is assumed that the system behaviour is linear. This approach may be criticised but further work is required to determine it accurately.

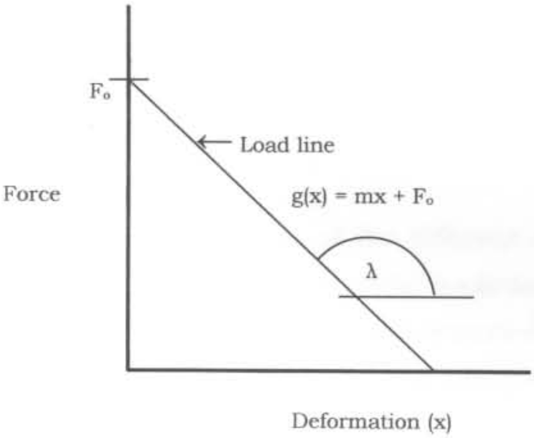

Figure 5.5: Load line representing rockmass behaviour

5.5. FACTORS INFLUENCING THE ROCKMASS STIFFNESS MODEL

The following factors influence the force component of the rockmass stiffness:

1. The mining geometry;
2. The position and dimensions of regional support;
3. The thickness of the hangingwall beam;
4. The density of the rockmass; and
5. The position of the point of interest relative to the mining abutments and regional support.

The deformation component of the rockmass stiffness is represented by stope closure as is measured underground at the point of interest for the given stage of mining.

The following factors influence stope closure at a given point in the stope:

1. The position of the point of interest relative to the mining abutment;
2. The mining geometry;
3. Presence and position of regional support;
4. Rockmass properties;
5. Depth of mining; and
6. Virgin stress condition.

5.6 CONCLUSIONS

This chapter describes the evolution of the different approaches that were developed and tested to represent the behaviour of the rockmass by quantifying the rockmass stiffness. The different approaches that were examined and tested are the so-called M-factor and Elliptical approaches. The shortcomings of each of these are described.

The application of the yield line theory and concepts led to the development of the so-called Attributed Area analysis. The basic rules that are applied in order to derive the attributed area for the point of interest in the stope are described in this chapter. This is done for any given mining geometry. The magnitude of the force component for the representation of rockmass behaviour for the particular mining stage can be calculated applying the attributed area. The deformation component for the rockmass stiffness for the different stages of mining at the point of interest, is as measured at the different time intervals.

The factors that influence the rockmass stiffness are also listed.

This model makes it possible that the rockmass behaviour and stope support performance can be represented and compared on common force-deformation axis.

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