FUZZY APPROACH IN PRELIMINARY DESIGN OF WEAK ROCK SLOPES FOR LIGNITE MINES

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FUZZY APPROACH IN PRELIMINARY DESIGN OF SLOPES IN LIGNITE MINES

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ABSTRACT

FUZZY APPROACH IN PRELIMINARY DESIGN OF WEAK ROCK SLOPES FOR LIGNITE MINES

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Slope mass rating (SMR) system, which is an enhanced version of rock mass rating (RMR), is a useful tool to be utilized for the preliminary stability analysis of rock slopes. Parameter scoring systems of both conventional RMR and SMR systems are based on crisp set theory. Common problems of conventional classification systems are assigning sharp boundaries for ranges, the same values for both upper and lower limits of ranges and presence of uncertainties as a result of complex nature of rock. These problems give rise to misleading final scores for rock or slope masses. In the scope of this study, the above mentioned problems of rock mass and slope mass classification systems will be aimed to be overcame by application of fuzzy set theory to RMR and SMR systems. For the preliminary stability assessment, slope performance chart suggested by Bieniawski was investigated in terms of its suitability to weak rock conditions. Later, the chart of Bieniawski was modified based on the back analysis data taken from real failure cases. Critical slope angles considering rock mass failure were determined from this chart using conventional and fuzzified RMR scores. After that, the SMR was used to investigate the structural failure mechanisms. Finally, SMR system was fuzzified similar to RMR by considering real failure cases. The result obtained from conventional and fuzzy systems were compared. It was observed that the fuzzified SMR and RMR produced more representative results than conventional RMR and SMR.

Keywords: Rock Mass Rating, Slope Mass Rating, Fuzzy Logic, Slope Performance Chart

ÖZ

LİNYİT MADENLERİNDEKİ ZAYIF KAYA ŞEVLERİNDE BULANIK MANTIK YAKLAŞIMIYLA ÖN DURAYLILIK ANALİZİ

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Jeomekanik bir sınıflama sistemi olan kaya kütlesi sınıflama sistemi (KKS) üzerine geliştirilmiş olan şev kütle sınıflama sistemi (ŞKS) kaya şevlerinde ön duraylılık analizi çalışmalarında kullanılan işlevsel bir araçtır. KKS ve ŞKS sistemlerinin parametre derecelendirme mantıkları klasik küme teorisi üzerine kurulmuştur. Geleneksel sınıflama sistemlerinin temel sorunları aralıklar için keskin sınırlar belirlenmesi, aralıkların alt ve üst sınırları için aynı değerlerin atanmış olması ve kayanın karmaşık doğasından kaynaklanan belirsizliklerdir. Bu sorunlar, nihai olarak bulunan kaya kütlesi ve şev kütlesi sınıflarında yanılsamalara sebep olmaktadır. Bu çalışma kapsamında, kaya ve şev sınıflama sistemlerinin yukarıda bahsedilen sorunları bulanık küme teorisi kullanılarak aşılmaya çalışılacak ve şev sınıflarının geliştirilen yeni yaklaşıma göre daha hassas tahmini yapılacaktır. Ön duraylılık çalışmasında Bieniawski'nin geliştirmiş olduğu şev performans grafiğinin zayıf kaya koşullarına uygunluğu araştırılmıştır. Daha sonra bu grafik gerçek yenilme verileri kullanılarak yeniden düzenlenmiştir. Kütle yenilme durumunu göz önüne alarak güvenli şev açıları geleneksel ve bulanık KKS değerleri yardımıyla bu grafikten hesaplanmıştır. Sonrasında ŞKS sistemi diğer yenilme mekanizmalarını tahmin etmek için kullanılmıştır. ŞKS sistemi gerçek yenilme verileri kullanılarak bulanıklaştırılmış ve böylece şev sınıfı, duraylılık durumu, yenilme olasılığı gibi çıktı değerleri daha doğru tahmin edilebilmiştir. Sonuç olarak geleneksel ve bulanık sistemlerden elde edilen veriler karşılaştırılmış ve kurulan yeni sistemlerin performansları incelenmiştir.

Anahtar Kelimeler: Kaya Kütlesi Sınıflama Sistemi, Şev Kütlesi Sınıflama Sistemi, Bulanık Mantık, Şev Performans Çizelgesi

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LIST OF ABBREVIATIONS

Symbol		Description	Units
RMR	**:**	Rock Mass Rating	-
CRMR	**:**	Conventional Rock Mass Rating	-
FRMR	**:**	Fuzzy Rock Mass Rating	-
SMR	**:**	Conventional Slope Mass Rating	-
CSMR	**:**	Slope Mass Rating	-
FSMR	**:**	Fuzzy Slope Mass Rating	-
MRMR	**:**	Mining Rock Mass Rating	-
RMS	**:**	Rock Mass Strength	-
SRMR	**:**	Slope Rock Mass Rating	-
CSMR	**:**	Chinese System For Slope Rock Mass Rating	-
GSI	**:**	Geological Strength Index	-
M-RMR	**:**	Modified Mining Rock Mass Rating	-
BQ	**:**	Index Of Rock Mass Basic Quality	-
RDA	**:**	Rock Slope Deterioration Assessment	-
SSPC	**:**	Slope Stability Probability Classification	-
VRFSR	**:**	Volcanic Rock Face Safety Rating	-
UCS	**:**	Uniaxial Compressive Strength	MPa
RQD	**:**	Rock Quality Designation	-
JS	**:**	Joint Spacing	mm
JC	**:**	Joint Condition	-
GW	**:**	Groundwater	-

CHAPTER 1

INTRODUCTION

1.1 General Remarks

Rock mass classification systems have been extensively used by engineers and researchers as an empirical tool in preliminary design stage of rock structures. Different characteristics of underground and surface structures have forced researchers to modify or establish new classification systems in appropriate ways to be used in geotechnical classification and design. As being a modification of one of the most popular classification systems, which is Rock Mass Rating (RMR) of Bieniawski, Slope Mass Rating (SMR) of Romana is a popular geotechnical slope classification system with the ability of assessing stability conditions of slopes. Although these systems are beneficial design tools, they lack the common drawbacks of classification systems that can be shortly mentioned under the title of uncertainties. These drawbacks may cause rock masses of different properties to be rated with the same scores. Fuzzy set theory is a plausible way to handle the uncertainty problem in order to get more realistic rating scores from classification systems. Prediction of failure mechanisms in the preliminary design stage is also an important item for the safe slope design. Although SMR has the ability to make predictions for failure mechanisms, it is weak in mass failure. This problem can be overcame by the use of slope performance chart, which was generated for the specific purpose of predicting mass failures. Because this chart makes use of RMR, conventional and fuzzy RMR scores will be used and the results will be compared. Also, the SMR scores will be predicted both for conventional and fuzzy ways.

1.2 Problem Statement

Physical properties of rock masses are quantified by the predetermined rating scale of Bieniawski and summed up to find the RMR. Romana adjusted the basic RMR and developed SMR system considering four geometrical factors between the slope and discontinuity sets to predict the stability of rock slopes. The evaluation systems of both RMR and SMR contain some drawbacks like sharp boundaries, assigning same values for both upper and lower limits and presence of uncertainties as a result of complex nature of rock. These drawbacks result in miscalculation of geomechanical class of rock masses and may lead to wrong design. These ambiguities will be overcome by the application of fuzzy set theory both on RMR and SMR, and the results will be validated by two real slope failure cases. While doing these, slope angles will be determined from slope performance by considering rock mass failure. The design chart created by Bieniawski will be taken as the basis and the slope angles determined from performance chart will be compared to real slope failure angles. However, it is a known fact that Bieniawski's chart was prepared with medium to hard rock conditions. Its performance need to be checked for weak rock conditions and if any problem will be observed, the chart needs to be modified. Later, the other failure probabilities like plane, toppling and wedge failures also need to be investigated. For this purpose SMR is known to be a useful tool; however it suffers from the problems of classification methods explained before. For this reason, its performance in fuzzy form needs to be investigated.

1.3 Objectives of the Study

Objectives of the research study include the following items;

1. To reduce uncertainties in CRMR by fuzzy set theory
2. To reduce uncertainties in CSMR of Romana (1985) by fuzzy set theory
3. To examine the suitability of slope performance chart of Bieniawski for weak rock conditions and if any problem exist, to modify the chart.
4. To apply conventional RMR, conventional SMR and fuzzy RMR, fuzzy SMR on real slope cases and determine the possible failure mechanism as being plane, wedge, toppling and circular failures.
5. To validate the failure mechanism that is found from FSMR by deterministic methods on computer models.

1.4 Research Methodology

The methodology of this study includes the following items. The methodology can be better understood from the flowchart presented in Figure 1.1.

1. Selection of study area.
2. Determination of CRMR using the rock mass and material properties.
3. Determination of CSMR on studied slopes using CRMR and discontinuity orientations.
4. Modification of Bieniawski's slope performance chart considering real slope failure cases.
5. Determination of overall slope angle from Bieniawski's slope performance chart.
6. Establishing an FRMR system and application to the slopes of study.
7. Establishing an FSMR system and application to the slopes of study.
8. Validation of the established FRMR, FSMR systems and modified slope performance chart based on real slope failure cases
9. Determination of input parameters by back analysis of two real slope failure cases in the analysis of the above FRMR and FSMR systems.
10. Determination of failure mechanisms of slopes from SMR table according to the values of CSMR and FSMR.

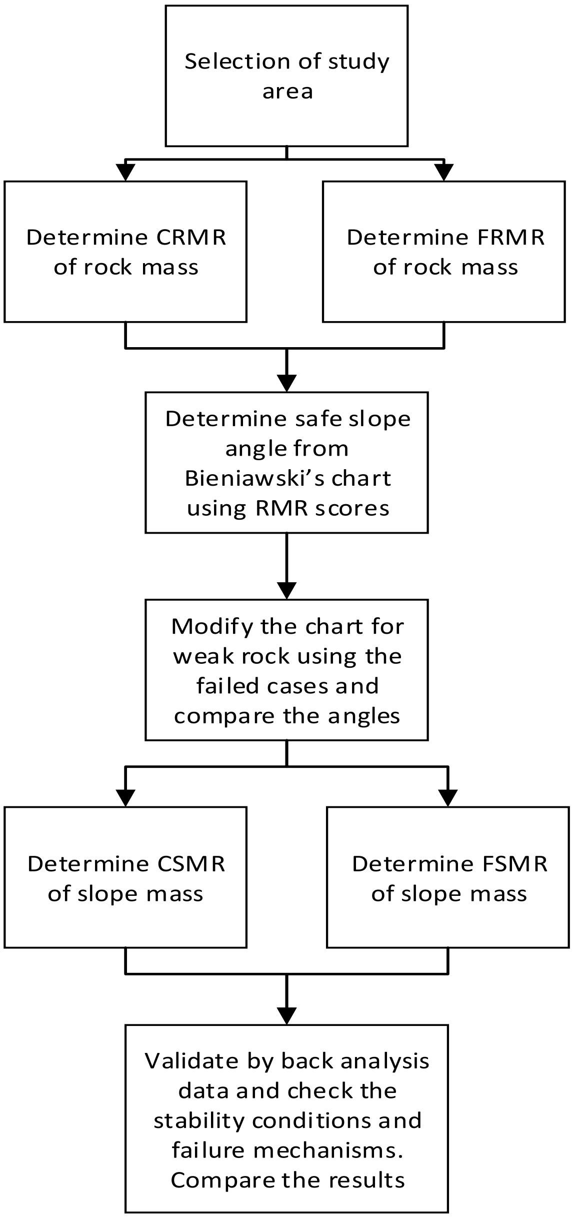


Figure 1.1 Flow chart of the research methodology of this study

1.5 Thesis Outline

In the first chapter of this thesis, brief information about the drawbacks of classification, objectives and research methodology of the study are introduced. The second chapter covers the literature survey about rock classification systems, slope classification systems and fuzzy set theory. The third chapter presents the relevant information for the study area and the rock and slope mass rating determination by conventional and fuzzy evaluation systems are applied on the slopes presented in the preceding chapter. Next chapter covers the comparisons and discussions on the conventional and fuzzy classification systems and the modification of Bieniawski's performance chart. In the sixth chapter, conventional and newly established fuzzy systems of SMR are validated based on actual failure data. The final chapter covers the conclusions and recommendations.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

Engineering design is an activity of application of scientific principles and experience in order to produce economical, safety and useful systems for the benefit of society. In terms of mining, it can be considered to be the process of planning safety and economical underground openings or surface structures such as tunnels or slopes. In engineering design three methods are existing, which are namely analytical, observational, and empirical methods. Analytical methods make use of stresses and deformations around openings to carry out an analysis and they include closed form solutions, numerical methods such as finite element method, analog simulations and physical modelling. Observational methods are based on measuring ground movements while the excavation continues. It is the only way to validate other methods. Finally, empirical methods evaluate stability conditions of mines and tunnels by making use of statistical data. Rock mass classification is one of the empirical methods that relies on case histories and requires periodical update.

Bieniawski is one of the well-known investigators who characterized the rock masses empirically by a classification system. His design process chart in mining (1988) states that the above mentioned methods are not satisfactory by themselves alone but gives better results when they are used in combination. In other words, they are not alternatives but supporters of each other.

Benefits of rock mass classification systems can be summarized in three subjects. First of all, they help to acquire high quality site investigation by requiring less amount of input data as classification parameters. Secondly, they are used to provide a basis for better engineering judgments by quantifying rock mass properties of the site of investigation. Finally, they are helpful in communication of people coming from different disciplines that work on the same project

Rock mass classifications aim to fulfill the requirements that were defined before by Bieniawski (1989)

a. Dominant parameters that determine the behavior of rock mass should be identified.
b. Rock masses of different quality should be divided into classes
c. Generated rock mass classes should provide information about their characteristics.
d. Types of rocks encountered in different sites should be related to each other.
e. Quantitative data representing rock mass properties and guidelines to assess that data should be provided in order for engineering design.

f. An effective way of communication should be established for the members of geotechnical design group coming from different backgrounds.

Bieniawski (1989) stated that classification systems are not replacements of analytical studies, field observations or engineering judgment but they are just useful tools in the preliminary stage of design which is going to be the basis of further advanced analysis techniques leading to the ultimate solution of the design problem.

2.2 General Overview of Rock Mass Classification Systems

Throughout the history many rock mass classification systems were developed and used. Major systems can be seen in Table 2.1 together with their originators and field of applications.

The first attempt to divide rock masses in terms of their geotechnical properties for engineering design purposes was made by Terzaghi in 1946. He defined nine rock classes and recommended support systems by considering dimensions of underground openings.

In 1958, Lauffer introduced a new classification system which highlights the relation of active span and stand up time for support design for the first time. Although it has significant effect on development of recent classification systems, it is not useful due to lack of a rating system. This makes it hard to decide which class the rock mass fall into.

Deere et al. has published a new quantitative index called Rock Quality Designation (RQD) which describes the quality of rock mass in 1964. This system considers the drillhole cores obtained from diamond drilling and takes the proportion of total length of rock pieces that are greater than 100 mm to the total length of drilling. Although it is a fast and easy way to obtain an index showing the rock quality, it does not take other properties of rock mass, such as weathering, into account but it is only interested in fractures.

Today, the most widely used classification systems are Rock Mass Rating (RMR) of Bieniawski and Q –System of Norwegian Geological Institute. Q-system has been specifically developed for and proven itself to be useful in tunneling. RMR has been modified by many researchers to be used in different fields, thus it can be used for both slope and tunneling cases. Modifications of RMR can be seen in Table 2.1.

Table 2.1 Rock mass classification systems (Bieniawski, 1979)

Name of Classification	Originator and Date	Country of Origin	Applications
1. Rock load	Terzaghi, 1946	USA	Tunnels with steel support
2. Stand-up time	Lauffer, 1958	Austria	Tunneling
3.NATM	Pacher et al., 1964	Austria	Tunneling
4.Rock quality designation (RQD)	Deere et al., 1967	USA	Core logging, tunneling
5. RSR concept	Wickham et al., 1972	USA	Tunneling

Table 2.1 (cont'd)

Name of Classification	Originator and Date	Country of Origin	Applications
6. RMR system (Geomechanics Classification)	Bieniawski, 1973 (last modified, 1989)	South Africa	Tunnels, mines, slopes, foundations
RMR system extensions			
	Weaver, 1975	South Africa	Rippability
	Laubscher, 1977	South Africa	Mining
	Olivier, 1979	South Africa	Weatherability
	Ghose and Raju, 1981	India	Coal mining
	Moreno Tallon, 1982	Spain	Tunneling
	Kendorski et al., 1983	USA	Hard rock mining
	Nakao et al., 1983	Japan	Tunneling
	Serafim and Pereira, 1983	Portugal	Foundations
	Gonzalez de Vallejo, 1983	Spain	Tunneling
	Unal, 1983	USA	Roof bolting in coal mines
	Romana, 1985	Spain	Slope stability
	Newman, 1985	USA	Coal mining
	Sandbak, 1985	USA	Boreability
	Smith, 1986	USA	Dredgeability
	Venkateswarlu, 1986	India	Coal mining
	Robertson, 1988	Canada	Slope stability
7. Q-system	Barton et al., 1974	Norway	Tunnels, chambers
Q-system extensions	Kirsten, 1982	South Africa	Excavability
	Kirsten, 1983	South Africa	Tunneling
8.Strength-size	Franklin, 1975	Canada	Tunneling
9.Basic geotechnical description	International Society for Rock Mechanics, 1981	International	General, communication
10.Unified classification	Williamson, 1984	USA	General, communication
11. Weakening Coefficient Systems (WCS)	Singh, 1986	India	Coal Mining
12.Rock Mass Index (RMI)	Palmström, 1996	Sweden	Tunneling

2.3 Rock Mass Rating

In 1973, as a result of his experience in shallow tunnels excavated in sedimentary rocks, Bieniawski published the Geomechanical Classification System that is also called as Rock Mass Rating (RMR) (Kaiser, MacKay, & Gale, 1986). All through the history, RMR system has been revised many times by its author. In 1974, classification parameters were reduced from 8 to 6. In 1975, ratings of parameters were adjusted and support recommendations were reduced. In 1976, class boundaries of parameters were modified. In 1979, ISRM (1978) rock mass descriptions were adopted. The final revision came in 1989. Due to changing class boundaries and ratings throughout the time, same rock mass can take different RMR scores; thus, it is vital to state the RMR version while working on RMR scores.

In time, RMR system has been widely accepted by researchers and engineers. It found many application fields such as tunnels, foundations and slopes. Modifications have been made by researchers to make RMR available to use in a variety of subjects like tunnel stability, slope stability, coal mines, rippability, boreability, etc…

In its basic version, this classification system has five parameters, which are;

i. Uniaxial compressive strength (UCS) of intact rock material
ii. Rock quality designation (RQD)
iii. Spacing of discontinuities
iv. Condition of discontinuities
v. Groundwater conditions

There is also one parameter more to take discontinuity orientations into consideration; however, it is used in the design of underground openings. The RMR score obtained from the above mentioned five parameters is called as RMR basic.

In application, the rock mass should firstly be divided into structural zones and the RMR basic parameters should be obtained for each structural zone according to the RMR table given in Table 2.2. It is a matter of choice to evaluate typical conditions but not the worst conditions. Bieniawski (1989) warns the users about the application of discontinuity spacing parameter. Importance weightings of this parameter is determined for three sets of discontinuities. Thus, in case of two sets, conservative results will be obtained. He also states that D part of Table 2.2 is used in case of lack of RQD or discontinuity data. Also, to determine discontinuity conditions more precisely, E part of Table 2.2 is used.

After determining the importance weightings of RMR basic parameters, they are summed up such as presented in the equation (1).

$$RMR_{basic} = A_1 + A_2 + A_3 + A_4 + A_5 \tag{1}$$

The resultant score can be evaluated using C and D parts of Table 2.2. By this way, the rock quality class and its stand up time for an underground opening can be predicted.

Bieniawski presented importance weighting charts of UCS of intact rock, RQD and discontinuity spacing. They can better predict the rock quality. That is an attempt to avoid assigning same scores to the rock masses of different qualities. In this way, two rock masses of different qualities may take the same score because summation of weightings may be equal although they are different, individually. This is one of the common problems of all classification systems.

Table 2.2 Rock Mass Rating Tables (Bieniawski, 1979)

RMR$_b$= BASIC RMR = Σ RATINGS (BIENIAWSKI, 1979)									
PARAMETER			**RANGE OF VALUES & RATINGS**						
1	Strength of intact rock material	Uniaxial compressive strength (UCS)	> 250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	< 1 MPa
	RATING		**15**	**12**	**7**	**4**	**2**	**1**	**0**
2	Drill core quality RQD		90 - 100%	75 - 90%	50 - 75%	25 - 50%	< 25%		
	RATING		**20**	**17**	**13**	**8**	**3**		
3	Spacing of discontinuities (JD)		> 2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm		
	RATING		**20**	**15**	**10**	**8**	**5**		
4	Condition of disc. roughness, persistence, separation, weathering of walls and gouge (JC)		Very rough surfaces No separation unweathered wall rock not continuous	Slightly rough Separation < 1 mm slightly weath. Walls not continuous	Slightly rough Separation < 1 mm Highly weath. Walls	Slickensided walls Or gouge < 5 mm or Separation1-5 mm	Soft gouge >5 mm or separation >5 mm continuous		
	RATING		**30**	**25**	**20**	**10**	**0**		
5	Ground water in Joints (Pore pressure ratio) (GW)		completely dry (0)	Damp (0-0.1)	Wet (0.1-0.2)	Dripping (0.2-0.5)	Flowing (0.5)		
	RATING		**15**	**10**	**7**	**4**	**0**		
p_w = joint water pressure; σ_1 = major principal stress									

ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS					
Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 20
Class No.	I	II	III	IV	V
Description	**VERY GOOD**	**GOOD**	**FAIR**	**POOR**	**VERY POOR**

2.4 General Overview of Slope Classification Systems

In a wide spectrum from natural slopes to man-made slopes like highway cuts and mining benches, rock slopes are common structures of today's world that even ordinary humans confront very frequently. While this is the case, safety of these structures is highly important. To design safe slopes two factors are important; professional engineers and sufficient budget. Most of the times, these two factors are the limitations of any project. Thus, some practical methodologies that can even be used by unexperienced engineers and results in safe designs are required. According to Song et al. (2008) the first step of slope design is the evaluation of the stability of slopes for the purpose of gathering fundamental information. The second step is carried out by professional experts in the light of those fundamental information and detailed investigation results in a precise design. The mentioned methodology in the first stage is referred to be the preliminary slope design and there are various methods for this purpose. One of the mostly used ones is empirical methods, which are classification systems.

Table 2.3 Rock slope classification systems (Daftaribesheli, Ataei, & Sereshki, 2011)

Name of the system	**Abbreviation**	**Authors**
Rock mass rating	RMR	(Bieniawski, 1989)
Mining rock mass rating	MRMR	(Laubscher, 1977)
Rock mass strength	RMS	(Selby, 1980)
Slope mass rating	SMR	(Romana, 1985)
Slope Rock Mass Rating	SRMR	(Robertson, 1988)
Chinese system for slope rock mass rating	CSMR	(Chen, 1995)
Geological strength index	GSI	(Hoek, Kaiser, & Bawden, 1995)
Modified mining rock mass rating	M-RMR	(Unal, 1996)
Index of rock mass basic quality	BQ	(Lin, 1998)
Rock slope deterioration assessment	RDA	(Nicholson & Hencher, 1997)
Slope stability probability classification	SSPC	(Hack, 2002)
Volcanic rock face safety rating	VRFSR	(Singh & Connoly, VRFSR-An Empirical Method for Determining Volcanic Rock Excavation safety on Construction Sites, 2003)
Falling rock hazard index	FRHI	(Singh A. , 2004)

Existing empirical slope mass classification systems summarized by Daftaribesheli (2011) can be seen in Table 2.3. Slope evaluation for RMR system was developed in 1976. The ratings for adjustments of slopes were: very favorable 0, favorable -5, fair -25, unfavorable -50 and very unfavorable -60. Because of lack of any guideline for determination of these classes, it is not known how these variables were rated. In 1973, MRMR was developed by Laubscher on the basis of RMR. Rock mass strength is another system that depends on a database of natural slopes. From drill-hole cores of weak altered rocks, Slope rock mass rating (SRMR) was developed by Robertson. Modified mining rock mass rating (M-RMR) is a modification of RMR and it was developed by Unal for weak, stratified, anisotropic and clay bearing rock masses. There are also some nouvelle systems such as Slope stability probability classification (SSPC) of Hack that carries out probabilistic assessment of independently different failure mechanics. Singh has two systems; the first one assesses the volcanic rock slopes and the second one rates the degree of danger of slopes to the workers. SMR of Romana is another system that is commonly used and it is modified by Chinese researchers to satisfy the needs of local slope design cases and published in the name of CSMR. Throughout this study SMR of Romana (1985) is used.

2.5 Slope Mass Rating

For the purpose of geomechanical classification of slopes, "Slope Mass Rating" (SMR) has been developed by Romana in 1985 as an enhanced and modified version of RMR of Bieniawski. RMR basic parameters are summed up with the four adjustment factors that are related to the geometrical relations of joint and slope. Equation (2) presents the SMR calculation method.

$$SMR = RMR_{basic} + (F_1.F_2.F_3) + F_4 \quad (2)$$

RMR basic parameters are UCS or point load strength, RQD, spacing of discontinuities, condition of discontinuities, and groundwater conditions. The four adjustment factors are denoted as F_1, F_2, F_3 and F_4. Physical interpretations of F_1, F_2 and F_3 factors can be seen in Figure 2.1. Because F_4 factors denotes the type of excavation, it cannot be seen on the figure.

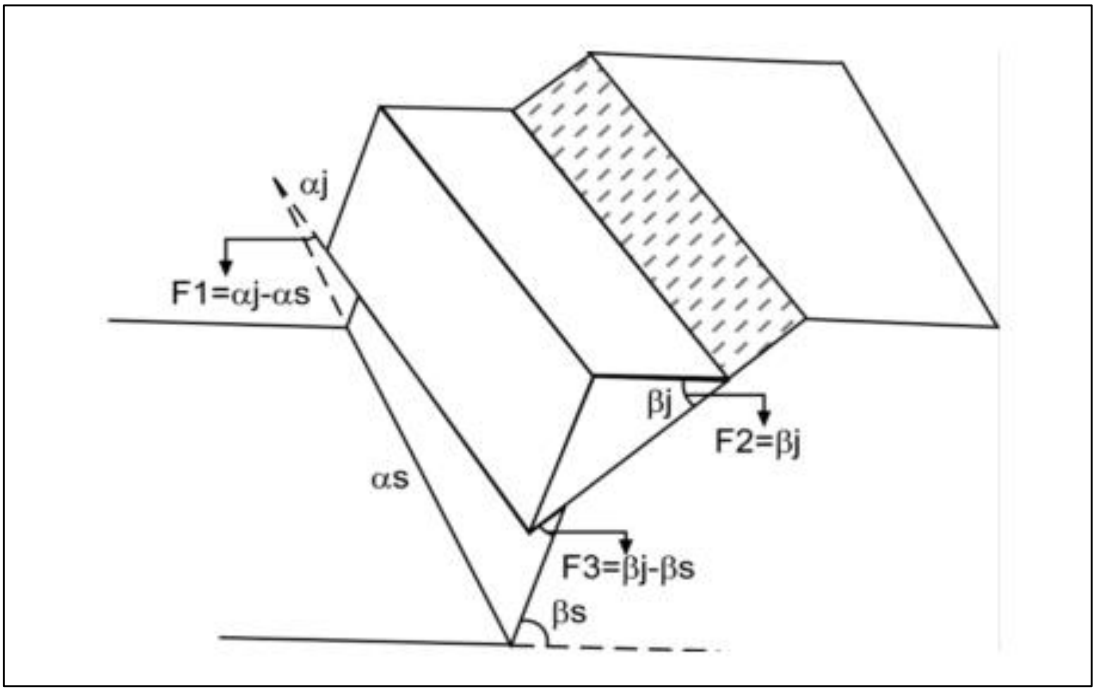


Figure 2.1 Physical interpretations of SMR adjustment factors (Singh & Goel, 1999)

F_1 measures the parallelism of dip directions of discontinuity and slope face. These values range from 0.15 to 1. If the angle between the strike of joint and slope face is denoted by A (α_j-α_s), the following equation gives the mentioned range:

$$F_1 = (1 - \sin A)^2 \quad (3)$$

Romana (1993) states that the range of values were first determined empirically; however, later, they were found to be closely matching with the relationship.

F_2 factor represents discontinuity dip in the planar mode of failure. Romana (1993) mentions that in some manner, this factor is a measure of probability of joint shear strength. Its values range from 0.15 to 1. This range of values is calculated from the following equation:

$$F_2 = tg^2\beta_j \quad (4)$$

where, β_j refers to the dip angle of joint. Just as F_1, values of this factor were also first determined empirically and later, they were found to be closely matching with the equation. For toppling failure mode, value of F_2 is 1.00.

F_3 denotes the relationship between the discontinuity and slope face. The values range between 0 to -60. These ratings are Bieniawski's orientation adjustments that were published in 1976 as being slope modification for RMR.

F_1, F_2, and F_3 factors are calculated using different equations for each failure modes. The scores and equations for F_1, F_2, and F_3 factors depending on the type of failure modes can be seen in Table 2.4.

Table 2.4 SMR adjustment factors for different failure types and discontinuity orientations (Romana, 1985)

Case of slope Failure		**Very Favorable**	**Favorable**	**Fair**	**Unfavorable**	**Very Unfavorable**
P T W	$\lvert \alpha_j - \alpha_s \rvert$ $\lvert \alpha_j - \alpha_s - 180° \rvert$ $\lvert \alpha_i - \alpha_s \rvert$	>30°	30° - 20°	20° - 10°	10° - 5°	<5°
P/W/T	**F_1**	0.15	0.40	0.70	0.85	1.00
P W	$\lvert \beta_j \rvert$ $\lvert \beta_i \rvert$	<20°	20° - 30°	30° - 35°	35° - 45°	>45°
P/W	**F_2**	0.15	0.40	0.70	0.85	1.00
T	**F_2**	1.0	1.0	1.0	1.0	1.0
P W	$\lvert \beta_j - \beta_s \rvert$ $\lvert \beta_i - \beta_s \rvert$	>10°	10° - 0°	0°	0° - (-10°)	<-10°
T	$\lvert \beta_j + \beta_s \rvert$	<110°	110° - 120°	>120°	--	--
P/W/T	**F_3**	0	-6	-25	-50	-60
P T W	**Plane Failure** **Toppling Failure** **Wedge Failure**					

The last adjustment factor, F_4 reflects the method of excavation by empirically determined values of a range between -8 to +15. F_4 is not affected by the failure mode. Scores for each excavation type can be seen in Table 2.5.

Table 2.5 SMR adjustment factors for F_4 factor (Romana, 1985)

Method of Excavation	**F_4 Value**
Natural slope	+15
Pre-splitting	+10
Smooth blasting	+8
Normal blasting or Mechanical excavation	0
Poor blasting	-8

Each slope must be evaluated for each discontinuity in terms of SMR. For instance, if a slope is affected by two discontinuity sets, the primary evaluation should be done for the first set and the secondary analysis should be carried out for the second set. Finally, an evaluation should be done for the intersection of these two discontinuity sets for the case of wedge failure. After completing the evaluation for each joint sets for three possible failure modes, the SMR value of the least one is selected to be the dominant actor in the failure of that slope. The other ones also may result in failure; however, the most probable one is the case with the least SMR score.

Resultant SMR scores can be used to assess the slope mass description, stability state, failure type and probability of failure by looking at Table 2.6.

Table 2.6 SMR stability classes and failure types (Romana, 1985)

Class No	Vb	Va	IVb	IVa	IIIb	IIIa	IIb	IIa	Ib	Ia
SMR Value	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Rock Mass Description	Very bad		Bad		Normal		Good		Very good	
Stability	Completely Unstable		Unstable		Partially stable		Stable		Completely stable	
Failures	Big planar or soil like or circular		Planar or big wedges		Planar along some joint and many wedges		Some block failure		No failure	
Probability of Failure	0.9		0.6		0.4		0.2		0	

It can be remembered from RMR system that support measures for underground openings were suggested by the author. Such a support suggestion system exists for slopes in SMR system. According to the class of slope mass (Table 2.7) less popular supports take place between brackets.

Table 2.7 Support suggestions for various SMR classes (Singh & Goel, 1999)

SMR Classes	SMR Values	Suggested Supports
Ia	91-100	None
Ib	81-90	None, scaling is required
IIa	71-80	(None, toe ditch or fence), spot bolting
IIb	61-70	(Toe ditch or fence), spot bolting
IIIa	51-60	(Toe ditch and/or nets), spot or systematic bolting, spot shotcrete
IIIb	41-50	(Toe ditch and/or nets), systematic bolting/anchors, systematic shotcrete, toe wall and/or dental concrete
Iva	31-40	Anchors, systematic shotcrete, toe wall and/or concrete (or re-excavation), drainage
IVb	21-30	Systematic reinforced shotcrete, toe wall and/or concrete, re-excavation, deep drainage
Va	11-20	Gravity or anchored wall, re-excavation

2.6 Slope Performance Charts

Slope performance charts are practical tools to be used in preliminary design of slopes where rock mass failure is expected to play a major role in the slope instability. They are generated by deriving curves from recorded stability conditions of slopes under various slope heights and angles. Generally, these charts reflect local conditions because they consider site specific variables such as the effects of existing failures, mining time frame and acceptable risks of the operation type (Douglas, 2002).

Globalizing slope charts is not a new idea. First attempts were done by Lane (1961), Fleming et al. (1970) for slopes in shale, Coates et. al. (1963) for incompetent rock slopes, Shuk (1965) for natural slopes, Lutton (1970) and Hoek (1970) for general rock excavations.

The most famous slope chart that was claimed to be generated for global design purposes was created by Hoek& Bray (1981) by collecting data from mines, quarries, dam foundation excavations and highway cuts on stable and unstable hard rock slopes (Figure 2.2). This chart includes extremely high slopes and it can be observed that most of the failures are in flatter slopes. Therefore, this curve can be considered to be a guide for design of high slopes (Douglas, 2002).

In 1976, McMahon discovered correlation between slope length (L) and slope height (H), which allowed him to determine slope angles. Formula of the mentioned correlations can be seen in equations 5 and 6, below. Use of the constants for different rock masses given in Table 2.8, generates a chart to determine slope height and angles (Figure 2.3). From this chart it can be noticed that the curves are poorly fit to data, especially for stronger rock masses.

$$H = aL^b \quad (5)$$

$$L = H/\tan(slope\ angle) \quad (6)$$

Table 2.8 Preliminary slope design parameters of McMahon (1976)

Rock Mass Type	a	b
Massive granite with few joints	139	0.28
Horizontally layered sandstone	85	0.42
Strong but jointed granite and gneiss	45	0.47
Jointed partially altered crystalline rocks	16	0.58
Stable shales	8.5	0.62
Swelling shales	2.4	0.75

In 1991, the attempt to combine slope design charts with rock mass ratings came from Haines & Terbrugge. By benefiting from MRMR system Haines & Terbrugge developed a correlation between slope height and slope angle parameters (Figure 2.4). The graph was divided into three regions. The first region represents the conditions for which classification alone may be adequate. The second region is marginal on classification. Final region warns about the necessity of additional analysis for slope design.

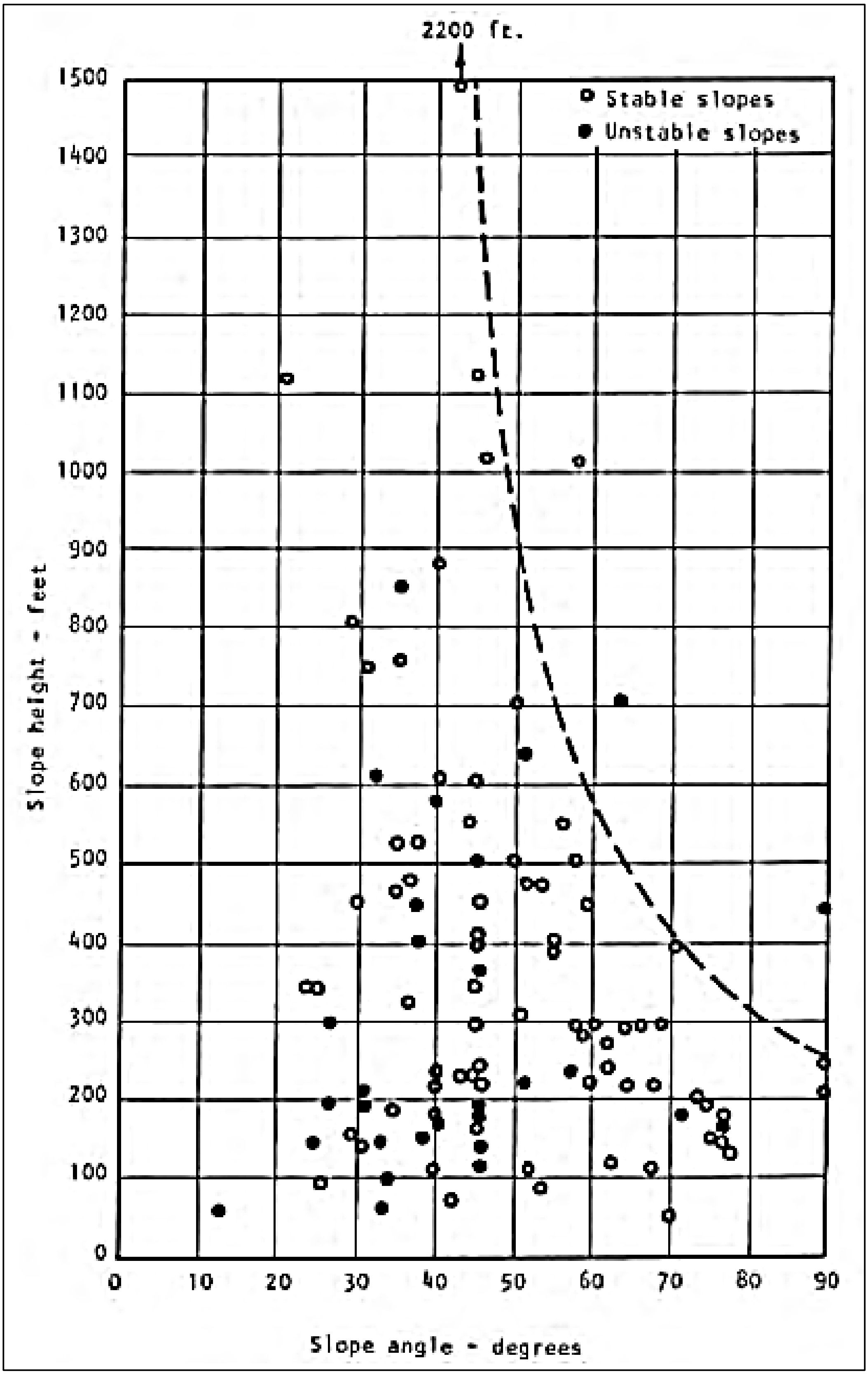


Figure 2.2 Slope height vs. slope angle curve of Hoek & Bray (1981)

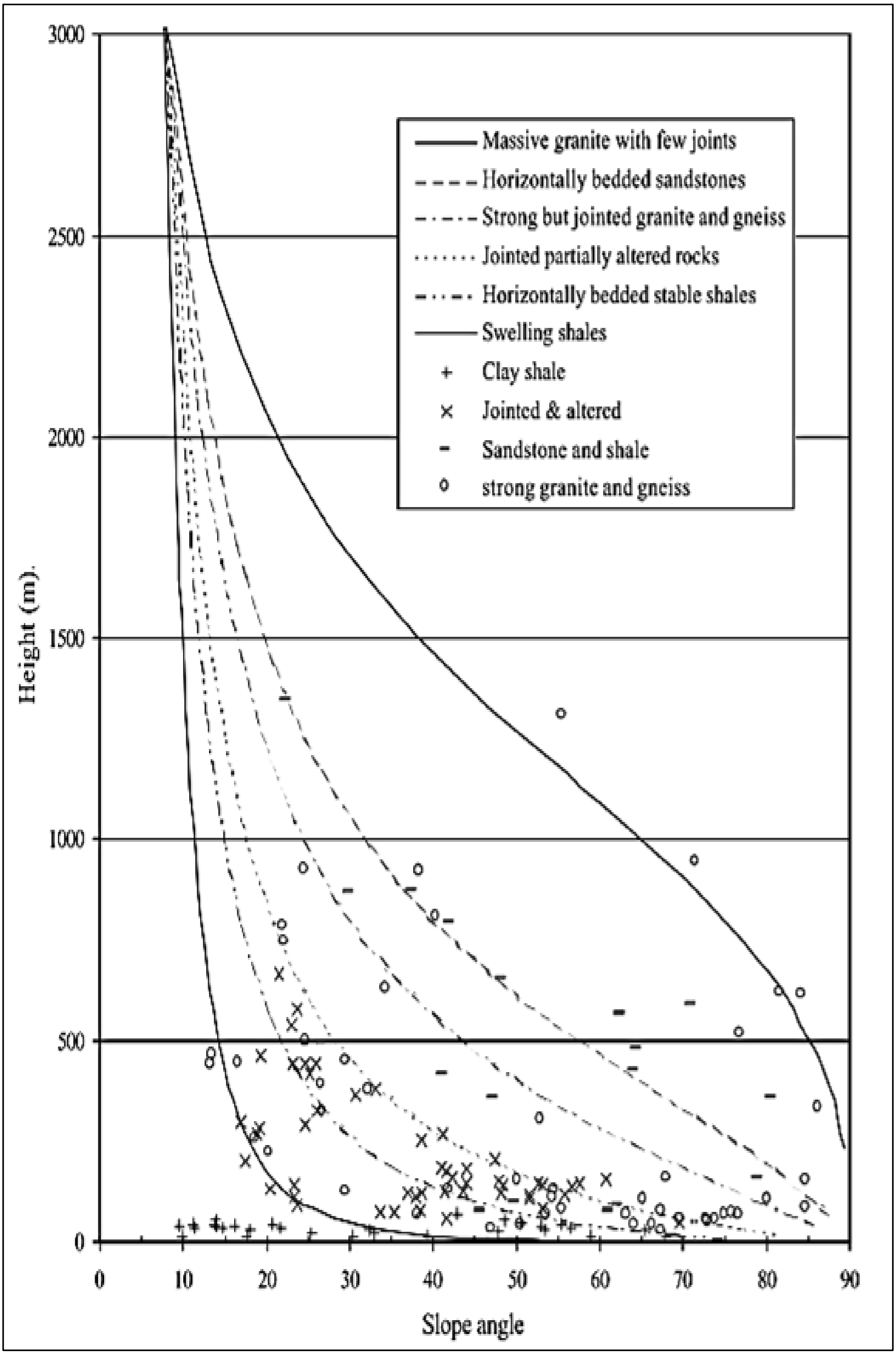


Figure 2.3 Slope height vs. slope angle curve of McMahon (1976)

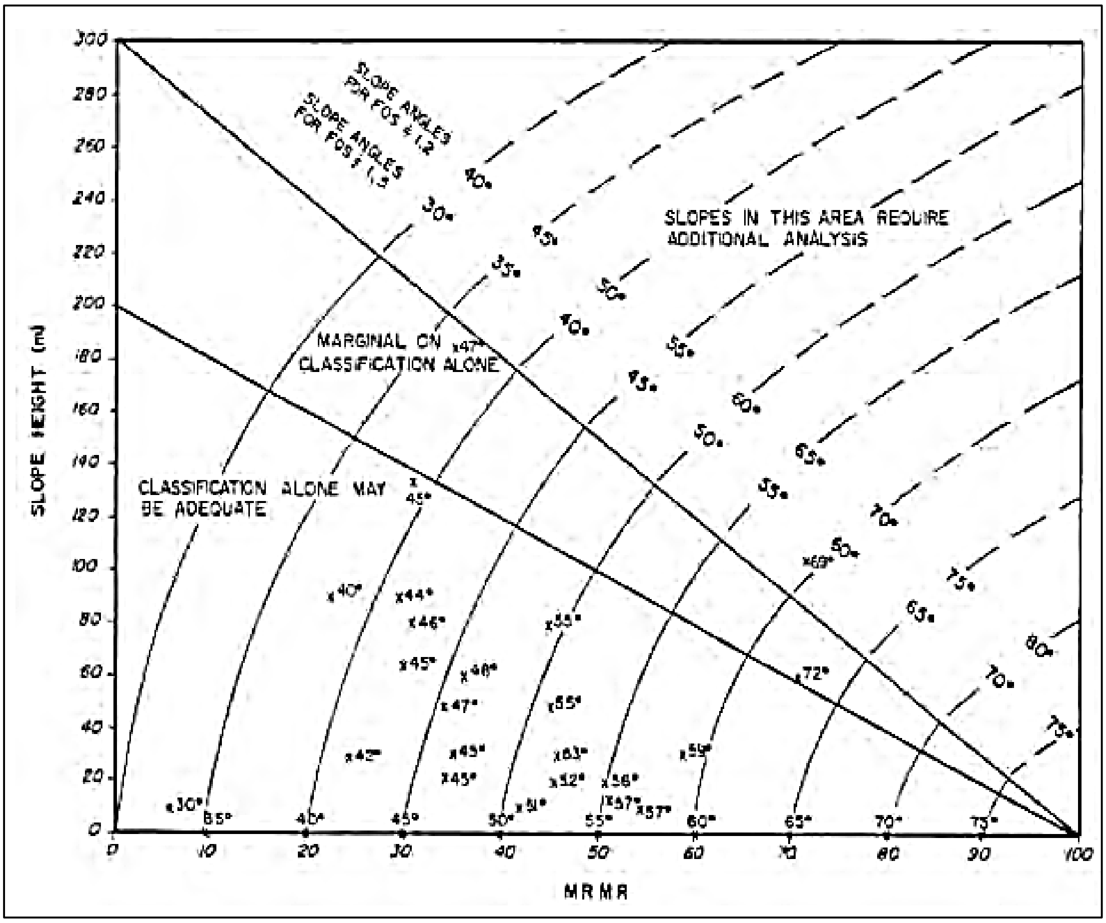


Figure 2.4 Slope height vs. slope angle chart for MRMR (Haines & Terbrugge, 1991)

Slope performance curves were also generated by Robertson (1988) for GSI, Bieniawski (1976) for RMR and Douglas (2002) for GSI in moderate water pressure condition (Figure 2.5). Bieniawski's curves assume to have no adjustment for orientation and based on stability charts of Hoek and Bray (1981) with a factor of safety of one.

The maximum slope height considered in these curves are 200 m and the minimum ones are around 30 m – 50 m. Bieniawski's curves are for stronger rock mass types and based on rock shear strength estimates. Robertson's and Douglas' curves are similar in higher slope heights; however, difference shows itself in lower portions of the graph where slope heights are less than 100 m. Although Robertson's and Douglas' curves reflect weaker rock conditions, it is obvious that a further study should be done to reveal the case for weak rock slopes.

It is well known that most of the slope instabilities are due to structural defects. By authors of these kinds of charts it is a commonly stated idea that slope design charts cannot be used in the existence of structural defects. However, they are useful to predict rock mass failures. It should also be noticed that these charts should only be used in the preliminary design stage and detailed analysis should not be avoided.

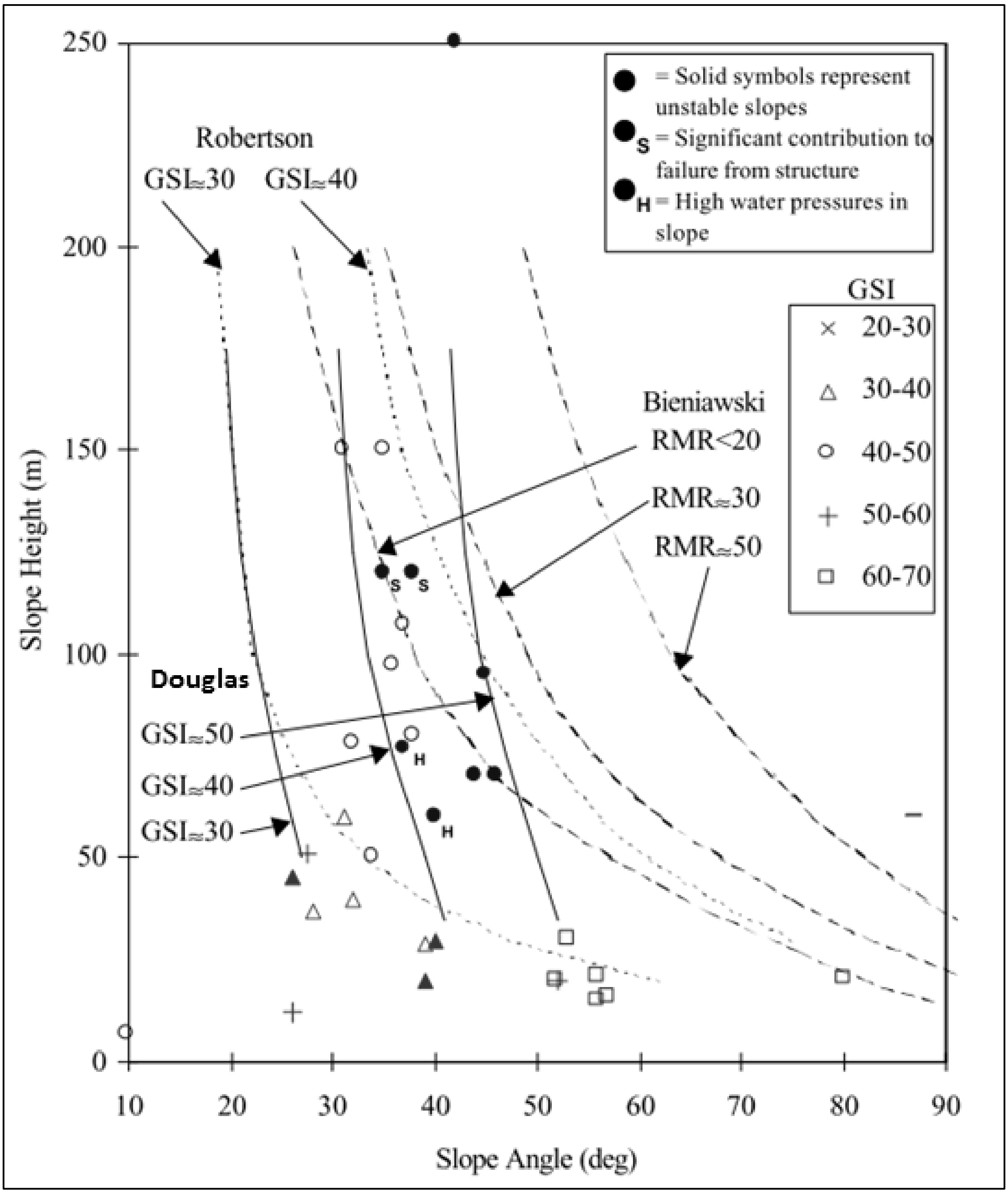


Figure 2.5 Slope height vs. slope angle curves of Robertson, Bieniawski and Douglas for moderate water pressure conditions (Douglas, 2002)

2.7 Failure Modes in Slopes

Failure mechanisms should be considered by slope classification systems. Mostly, slopes fail due to structural defects like joints or faults. Some of the basic failure modes are explained below (Romana, 1985).

i) Plane failures occur along dominant and/or continuous joints dipping towards the slope, with strike near parallel to the slope face. Instability is the result of two conditions. In the first one, critical joints dip less than the slope. The second one is observed when the mobilized shear strength in the joint is not enough to assure stability. Joint continuity is the major factor that gives rise to plane failures. The difference between the dip direction values of the slope and the failed joint is less than 90°

ii) Wedge failures occur along two joints from different families whose intersect dips towards the slope. A 'wedge factor' depending on the geometry, multiplies the joint mobilized shear strength. This mode of failure depends on the joint attitude and conditions, and is more frequent than plane failure, but many apparent wedge failures resolve to plane failures when studied in detail. The size of the failure depends on the joint frequency, and is usually minor compared to plane failures.

iii) Toppling failures occur along a prevalent and/or continuous family of joints which dip against the slope, and with strike near-parallel to the slope face. Joints sup between them, and are frequently weathered. In practice, two kinds of instability can exist: minor toppling occurring near the surface of slope, and deep toppling which can produce big deformations. In both cases the failures develop slowly. Surface toppling can cause rock falls, but deep toppling seldom fails suddenly. The difference between the dip direction values of slope and joint is more than 90°.

iv) Circular failures occur along a surface which only partially develops along joints, but mainly crosses them. These failures can only happen in heavily jointed rock masses with a very small block-type size and/or very weak or heavily weathered rock. In both cases, the RMR value is very low, and the material is borderline with a soil.

Romana (1985) suggests that the following parameters should be considered in any classification systems.

(i) Rock mass global characterization (including joints frequency, state and water inflow).
(ii) Differences in strike between slope face and prevalent joints.
(iii) Differences between joint dip angle and slope dip angle, as they control the 'day lighting' of a joint in the slope face, a necessary condition for plane and/or wedge failure.
(iv) Relationship of joint dip angle with normal values of joint friction (for plane and/or wedge failure).
(v) Relationships of tangential stresses, developed along a joint, with friction (for toppling failure).

2.8 Fuzzy Set Theory

2.8.1 General Overview of Fuzzy Set Theory

Centuries old Aristotelian logic being the most widespread system of thinking dictates bivalent state of situations. According to this structure, any situation can be either true or false, 1-0 binary condition. Anybody experiences that as much as sharp edge situations, life also contains middle states; together with black and white; grey is also an existing color. It cannot be claimed that every situation obeys the classical model which claims their being exactly true or false. Trueness or falseness may have a degree. This concept is the case that is mostly confronted in natural processes. Nature is always in transition from one condition to another, and this process is not accomplished in a sudden moment but takes some time. Let's assume the transition of a system is from A to B condition. Sometime during the process, to describe the system, neither A or B cannot be used because it contains properties of both of them but not exactly one of them. In this case, the system can partially be in A and B conditions that is mentioned with a membership degree. This method of thinking is a nouvelle logical system and named as fuzzy logic.

For the purpose of dealing with data that contain nonstatistical uncertainties, the term fuzzy was first introduced by Prof. Lotfi Zadeh in 1965. According to Alavala (2008) fuzzy logic build a bridge between approximate human reasoning capabilities and knowledge-based systems. He states that, fuzzy logic is helpful in handling uncertainties by making use of strength of mathematics in cooperation with human cognitive processes like thinking and reasoning.

In science and engineering, measurement is an important concept, which helps to create new systems or optimize the existing ones. It is an obvious fact that more precise the measurement, better the process or system is. However, high precision does not every time mean to result in better systems or processes (Figure 2.6). The key of the most optimum system may lie in paying the necessary attention to ambiguities. To sum up, the important thing may not be high precision when a rough or significant answer works better (Alavala, 2008). Fuzzy logic has the capability of representing complex systems by rough models and obtaining better results by simplifying calculation process.

Fuzzy logic makes better predictions in the case of uncertainty by three steps, which are fuzzification, fuzzy inference system and defuzzification. Each of the steps will be explained in detail. The concept can be better understood with an example application. For this purpose, the basic tipping problem from Matlab 2012a help document will be used. In this problem, the purpose is to determine the amount of tip in a restaurant by considering the qualities of service and dinner. Service and food qualities are denoted by linguistic variables such as "good", "bad", etc... Each linguistic term represent a mathematical function for an interval of values between 0 - 10, which are named as membership functions, these functions are used to convert crisp values into fuzzy values. Later, fuzzy inference system evaluates inputs by if-then rules. Finally, defuzzification occurs and the amount of tip is obtained. Scheme of the problem can be seen in Figure 2.7.

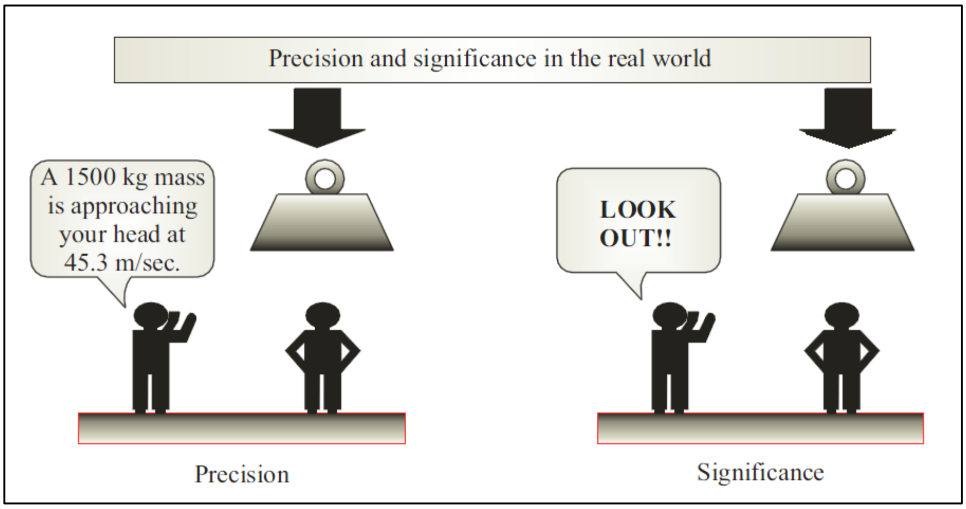


Figure 2.6 Precision and significance (The MathWorks, Inc., 2012)

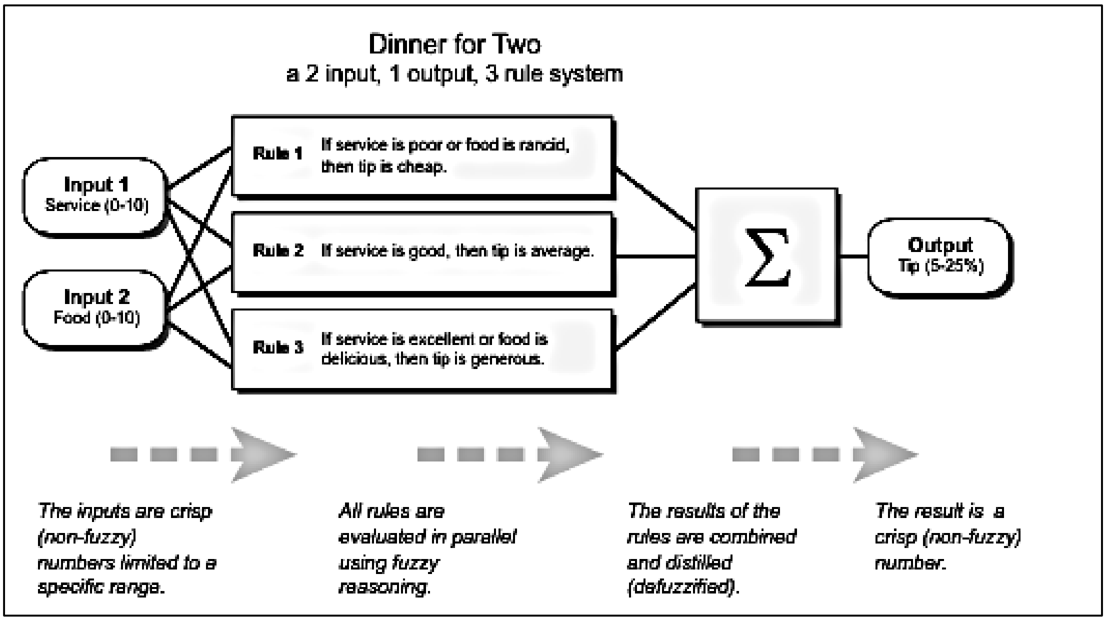


Figure 2.7 Scheme of the basic tipping problem (The MathWorks, Inc., 2012)

For an example application, let's assume the food is delicious and the variable "delicious" represents the interval of 7-10. Food quality rating for delicious variable is 8. Fuzzy value of this crisp rate is evaluated as shown in Figure 2.8. According to this evaluation delicious food that has a rate of 8 is 0.7 delicious and 0.3 not delicious (over 1). The same procedure should be repeated for each combination of food and service quality probabilities. The obtained fuzzy values are ready to be evaluated in fuzzy inference system and obtain the resultant fuzzy value of the appropriate tip.

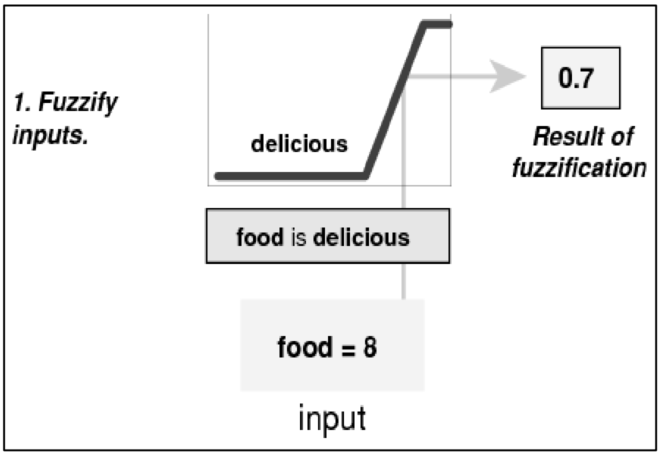


Figure 2.8 An example of fuzzification

In fuzzy inference part, if-then rules helps to get final fuzzy value of the tip. Because in this problem, rules are composed of two items, they must be processed in a logical operation such as “and” or “or”. This problem connects two variables by “or” logical operator and the operation can be seen in Figure 2.9.

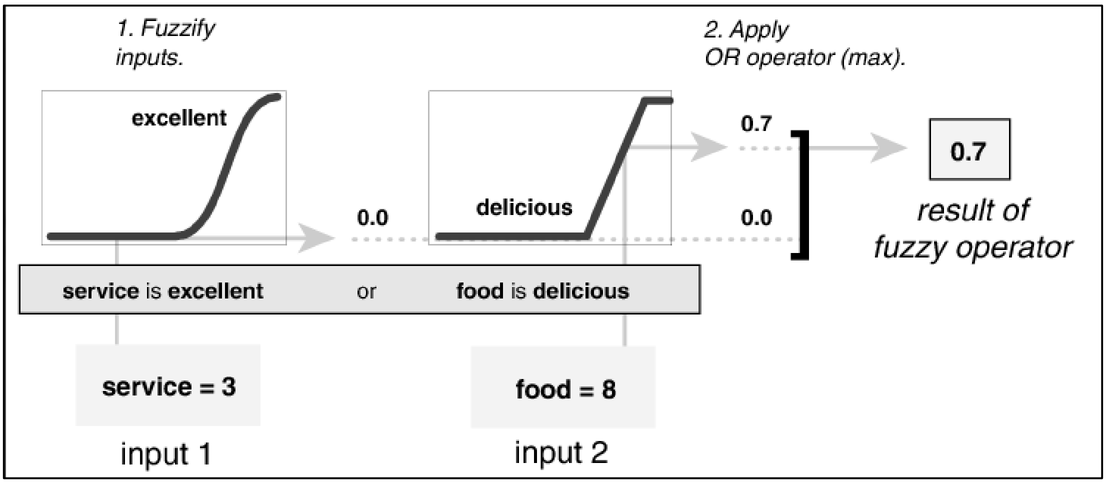


Figure 2.9 Fuzzy logical operation (The MathWorks, Inc., 2012)

Sometimes, it may be desirable to weight rules, according to their importance in the final score. Otherwise, every rule takes the weight of 1. In this problem there are three rules and each of them takes the weighting of 1.

Flow chart of fuzzy implication for a simple process can be seen Figure 2.10. For each rule, resultant membership value is obtained as shown in Figure 2.11. For three rules there are three results. These functions must be aggregated and a final result should be obtained. There are different methods for this job. The most widely used one due to its ease of computation is center of area (COA) method. In this method, resultant functions of each rule are summed up and finally the center of gravity of the aggregated shape gives the resultant crisp value.

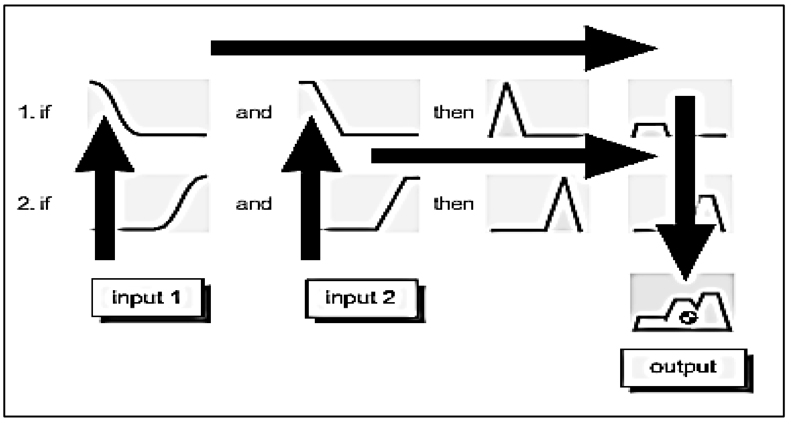


Figure 2.10 Flow chart of fuzzy implication process (The MathWorks, Inc., 2012)

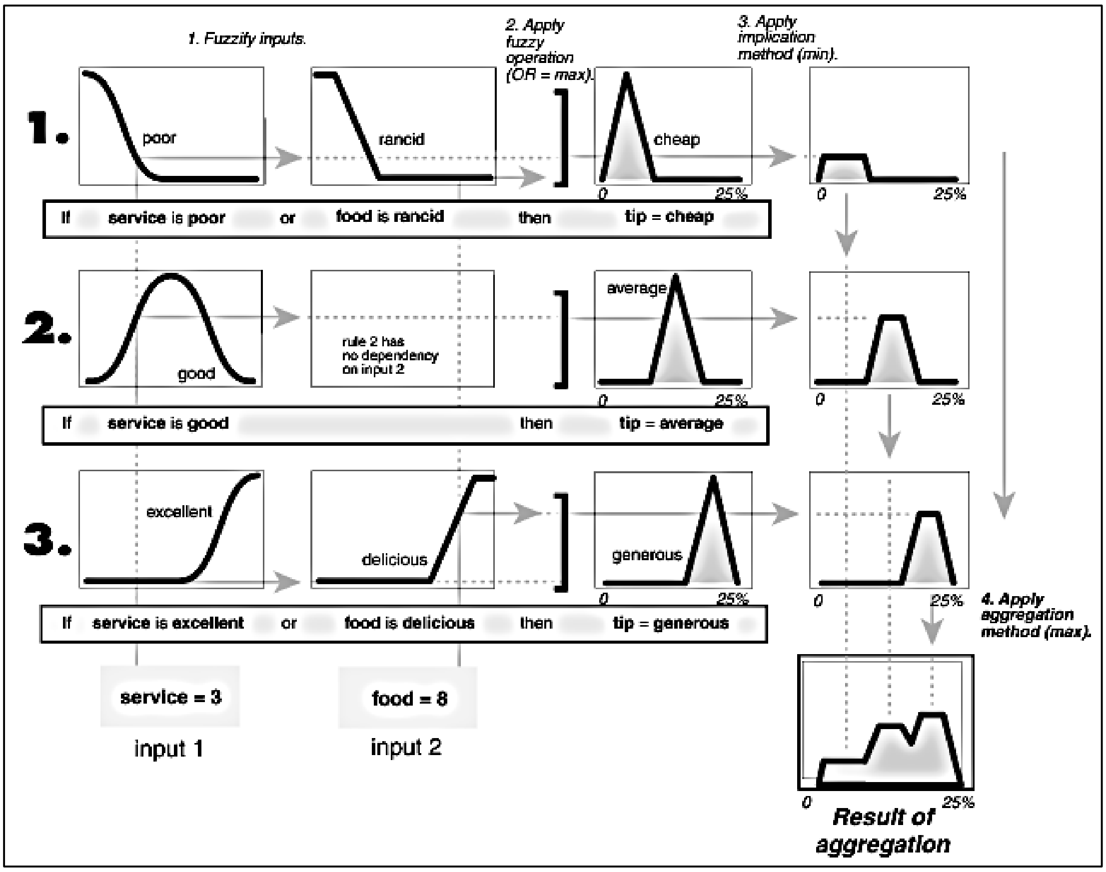


Figure 2.11 Fuzzy inference system (The MathWorks, Inc., 2012)

As can be seen, in this example it is not certain how to decide whether a tip amount is good or bad, or food quality and service quality may change depending on the person. However, fuzzy logic allows to reflect expert view and decisions of the user. This flexibility and usefulness of fuzzy systems are due to their characteristics that are summarized by Alavala (2008) in two titles;

1. Fuzzy systems are highly capable of handling uncertain or approximate reasoning. Systems with complex mathematical models are the best field of application for them.
2. Fuzzy logic provides a strong basis for decision making with incomplete or uncertain information.

2.8.2 Fuzzy Sets and Membership Functions

The main distinguishing factor of fuzzy sets from classical or crisp sets is the concept of membership functions. In a classical set, every object can be in a binary condition: either member of the set or not. In fuzzy sets membership can have a degree between 0 and 1. The higher the degree, the more the member belongs to that set. In other words, boundaries of fuzzy sets are not as sharp as crisp sets but a new type of boundary, that is hazy boundary, is existent. The situation can be seen in Figure 2.12

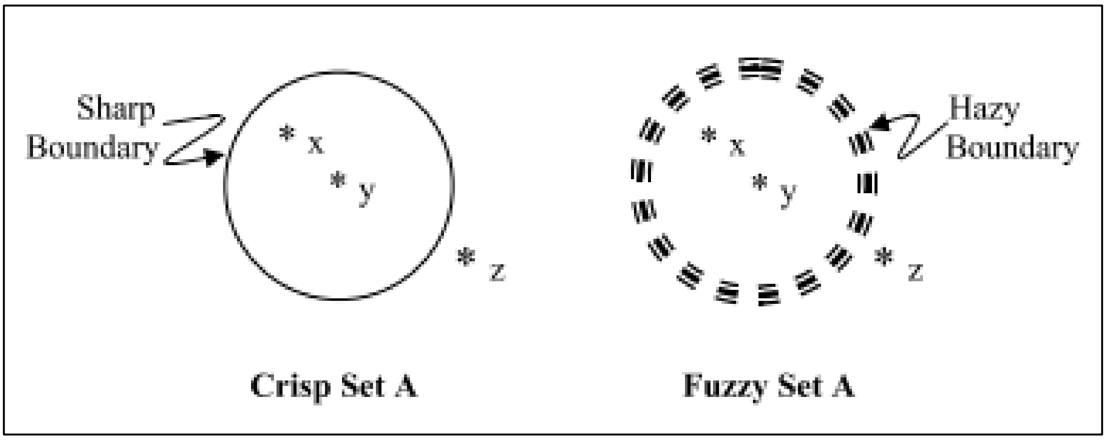


Figure 2.12 Boundaries of crisp and fuzzy sets

In mathematical notation let's assume a nonempty set X. It is the membership function that characterize a fuzzy set A in X.

$$\mu_A : X \rightarrow [0,1]$$

$\mu_A(x)$ denotes the degree of membership of element x in fuzzy set A for each $x \epsilon X$
As can be seen, the fuzzy set A is determined completely by the set of tuples and it is denoted by

$$A = \{(u, \mu_A(u)) \text{I} u \epsilon X\}$$

However, the most frequently denotation is;

$$A = {}^{\mu_1}/_{x_1} + \cdots + {}^{\mu_n}/_{x_n}$$

where μ_i represents the grade of membership of x_i in A and the plus sign represents the union.

A membership function is a curve that defines the connection of each point in the input space to a membership value between 0 and 1. There are various types of membership curve types. The vital point is to select the most appropriate curve type that defines the variable. For this job, there are various methods. The first method is using artificial leaning techniques. By this way, a set of input data is examined and the curve is drawn according to this database. This method is both time taking and requires lots of reliable data. The second and the mostly used method is selecting some simplified shape of curves that define best the variable and make use of expert experience to determine boundaries. This method is helpful in the case of lack of huge amount of data. It is also advantageous because it allows expert view to be taken into consideration. Here, the idiom that was mentioned before should be remembered again "if the same job can be done roughly and does not result in vital differences, why use smooth and more complex method?". The most widely used curve types, due to their simplicity of calculation are triangular and trapezoidal curves. Other curves are gaussian, sigmoidal and polynomial. Some properties and terminology about the membership functions can be seen in Figure 2.13

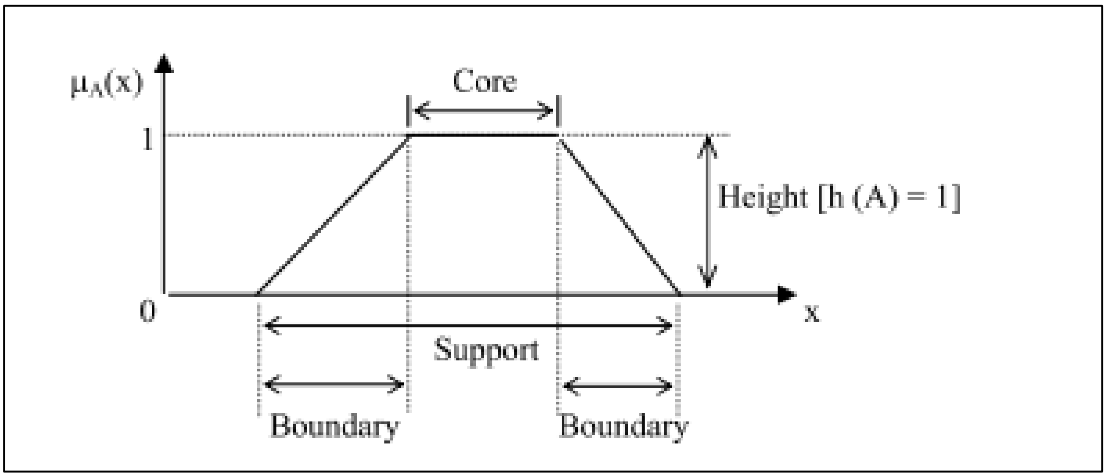


Figure 2.13 Features of membership functions (Bhattacharyya, 2003)

Other important subject about the fuzzy set is logical operations. It must be remembered that fuzzy logic is the super set of the standard Boolean logic (The MathWorks, Inc., 2012). Thus, if the fuzzy values are at their extremes (0 or 1) standard logical operations works (Figure 2.14).

A	B	A and B
0	0	0
0	1	0
1	0	0
1	1	1

AND

A	B	A or B
0	0	0
0	1	1
1	0	1
1	1	1

OR

A	not A
0	1
1	0

NOT

Figure 2.14 Standard logical operation (The MathWorks, Inc., 2012)

It is known that in fuzzy sets everything is a matter of degree between 0 and 1. If these interval values are used, how could it be possible to preserve the tables shown in Figure 2.14. The answer is min(A,B) function for “AND” operator, max(A,B) function for “OR” operator and 1-A for “NOT” operator (Figure 2.15).

A	B	min(A,B)
0	0	0
0	1	0
1	0	0
1	1	1

AND

A	B	max(A,B)
0	0	0
0	1	1
1	0	1
1	1	1

OR

A	1 - A
0	1
1	0

NOT

Figure 2.15Functions to preserve the truth tables for fuzzy sets (The MathWorks, Inc., 2012)

In the Figure 2.16 in graphical format it is shown how the logical operations mentioned above works. In the figure two fuzzy sets are applied to create a new one. The upper part show the operation for two valued logic that is either 1 or 0. The lower part applies the same procedure for multivalued logic that has continuously varying range.

The Mathworks Inc. (2012) defines fuzzy sets and operators as the subjects and verbs of fuzzy logic. These operations are used in if-then rules for the purpose of evaluation. Every rule has at least one variable and may have more. An example rule is

$$If\ x\ is\ A\ then\ y\ is\ B$$

In this rule, “If x is A” part is called as antecedent and the rest is called as consequent. Together with the above mentioned logical operators, final fuzzy values are obtained as shown in Figure 2.17.

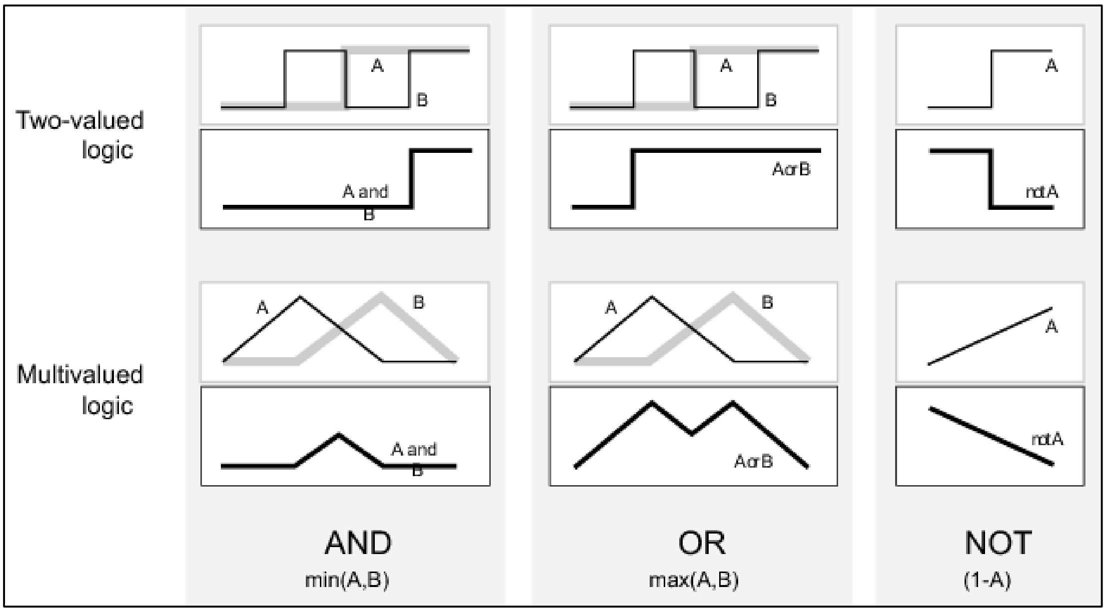


Figure 2.16 Logical operations for two valued and multi valued logic (The MathWorks, Inc., 2012)

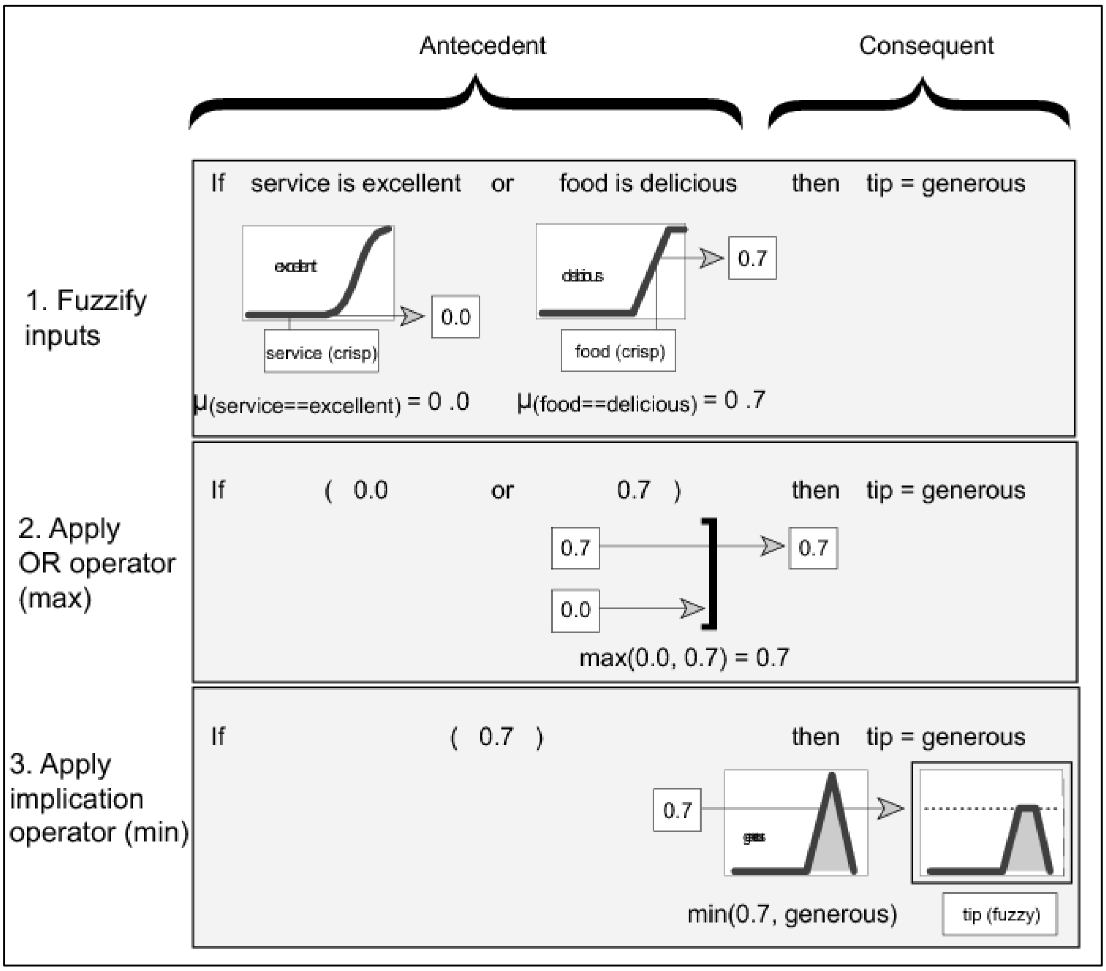


Figure 2.17 An example for the evaluation of If-Then rule (The MathWorks, Inc., 2012)

In addition to logical operations there are also arithmetic operations, which are addition, subtraction, multiplication and division. If A and B are two fuzzy sets, procedure of graphical interpretations of arithmetic operations and the resultant functions can be seen in Figure 2.18 and mathematical notations can be seen below (Bhattacharyya, 2003).

(a) The addition of A and B:

$$\mu_{A(+)B}\ (z) = \vee\ \{\mu_A\ (x) \wedge\ \mu\ _B(y)\}$$
$$where\ z\ =\ x\ +\ y$$

(b) The subtraction of A and B:

$$\mu_{A(-)B}\ (z) = \vee\ \{\mu_A\ (x) \wedge\ \mu\ _B(y)\}$$
$$where\ z\ =\ x - y$$

(c) The multiplication of A and B:

$$\mu_{A(.)B}\ (z) = \vee\ \{\mu_A\ (x) \wedge\ \mu\ _B(y)\}$$
$$where\ z\ =\ x.y$$

(d) The division of A and B:

$$\mu_{A(:)B}\ (z) = \vee\ \{\mu_A\ (x) \wedge\ \mu\ _B(y)\}$$
$$where\ z\ =\ x\ /\ y$$

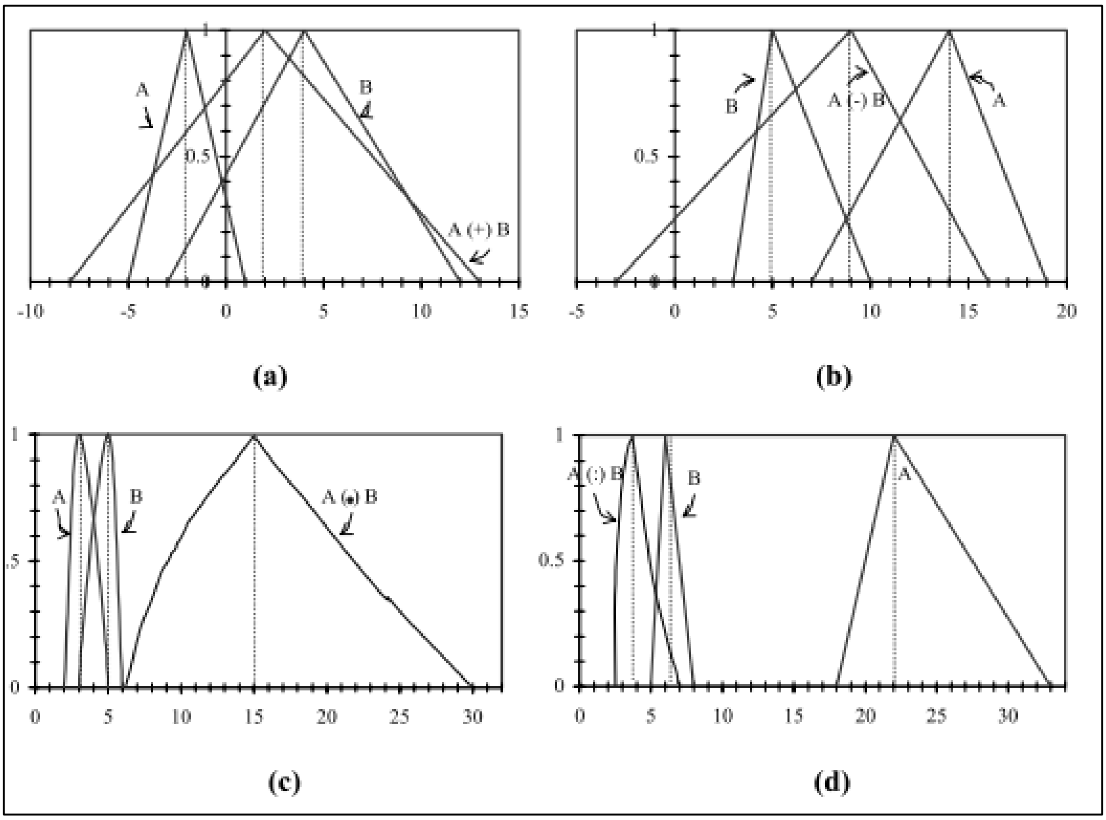


Figure 2.18 Fuzzy arithmetical operations: (a) addition, (b) subtraction, (c) multiplication, (d) division (Bhattacharyya, 2003)

2.8.3 Fuzzy Inference System

Fuzzy inference mechanism is defined by Daftaribesheli (2011) to be the computing framework that relies on fuzzy set theory, fuzzy if-then rules and fuzzy reasoning. It is the step in which inputs are processed to obtain an output value by making use of expert database. There are three components that a basic FIS structure contains: a rule base, a database that outlines the membership functions used in fuzzy rules and a reasoning mechanism, which performs inference procedure to give an output.

For fuzzy rule-based systems there are various mechanisms such as Mamdani, Tsukamoto and Sugeno systems. The difference between them lies in consequents, which means aggregation and defuzzification procedures are different. The mentioned inference mechanism wll be explained in the following titles

2.8.3.1 Mamdani Inference Mechanism

The Mamdani mechanism was first used in the control of a steam engine and boiler system by defining a set of linguistic variables with the help of experienced operators (Mamdani & Assilian, 1975). It is the most widely used algorithm in earth sciences. There are two main reasons of this situation. The first one is its simplicity of calculation. The second reason is due to its capability to deal with linguistic variables. Most geological processes are defined in linguistic terms. Mamdani and Assilian (1975) showed that fuzzy sets and fuzzy logic can be used to translate an entire set of unstructured set of linguistic heuristics into an algorithm. This reason makes it a suitable way to deal with complex geological processes.

In Mamdani mechanism fuzzy set operators are used to combine the rules. For example 'Min' is used for 'and' and 'Max' for 'or'. In spite of a wide scale of fuzzy relational compositions such as min-max, max-max, max-mean, etc… min-min and max-product are the most commonly used ones (Iphar & Goktan, 2005). An illustration of a two rule Mamdani FIS evaluation can be seen in Figure 2.19 in graphical format.

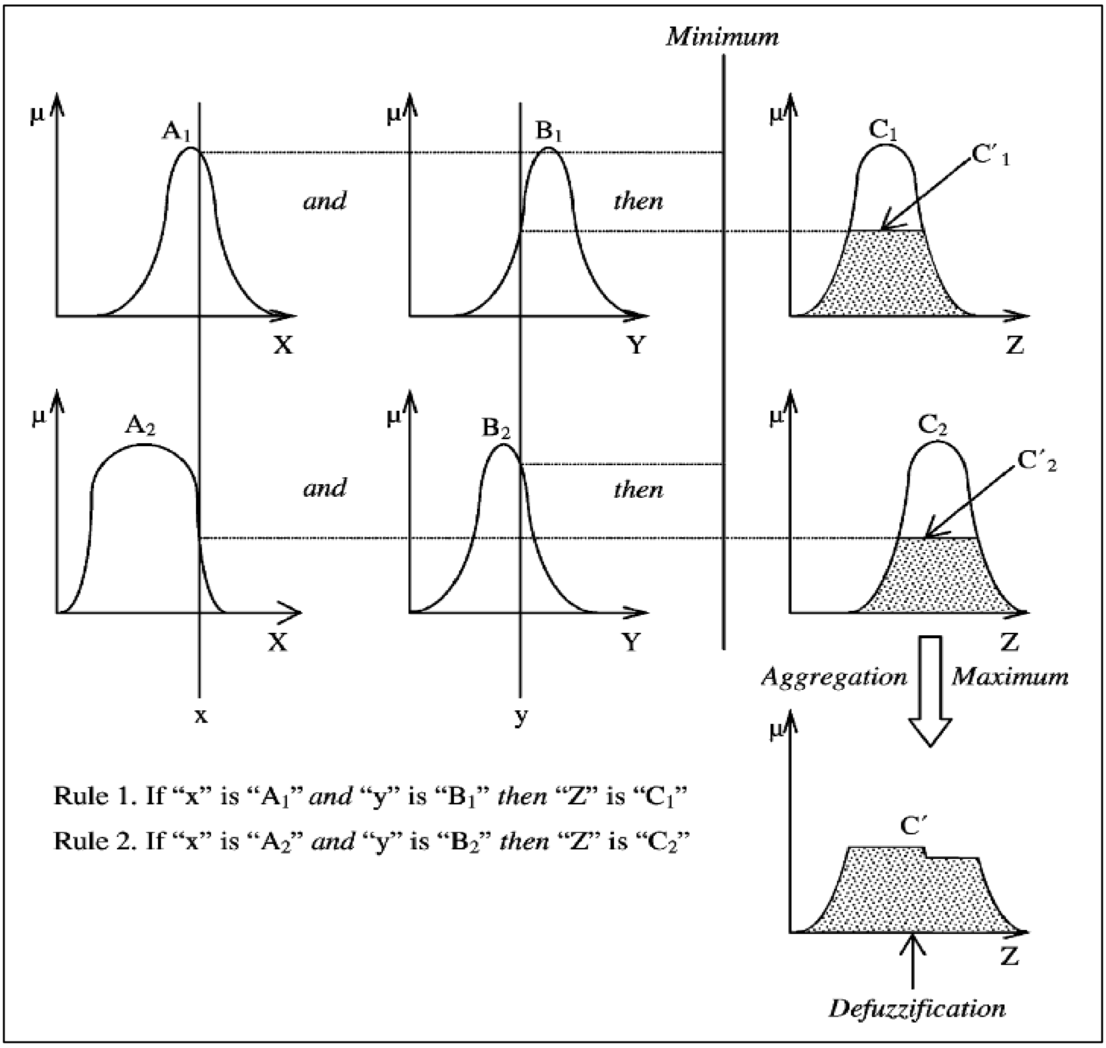


Figure 2.19 Mamdani inference mechanism (Iphar & Goktan, 2005)

2.8.3.2 Tsukamoto Inference Mechanism

In this type of inference mechanism, the consequents of each fuzzy if-then rule must be presented by a monotonic membership function (Tsukamoto, 1979). The output of each rule that is directly determined by the firing strength of the rule is in crisp value. The final output as being the single outcome of the inference mechanism is calculated by the weighted average of each rule's output. Due to the reason that each rule turns out a crisp value, Tsukamoto inference mechanism utilize weighted average method for aggregation. By this way, time-consuming defuzzification process can be skipped. A two input one output Tsukamoto inference mechanism example can be seen in Figure 2.20.

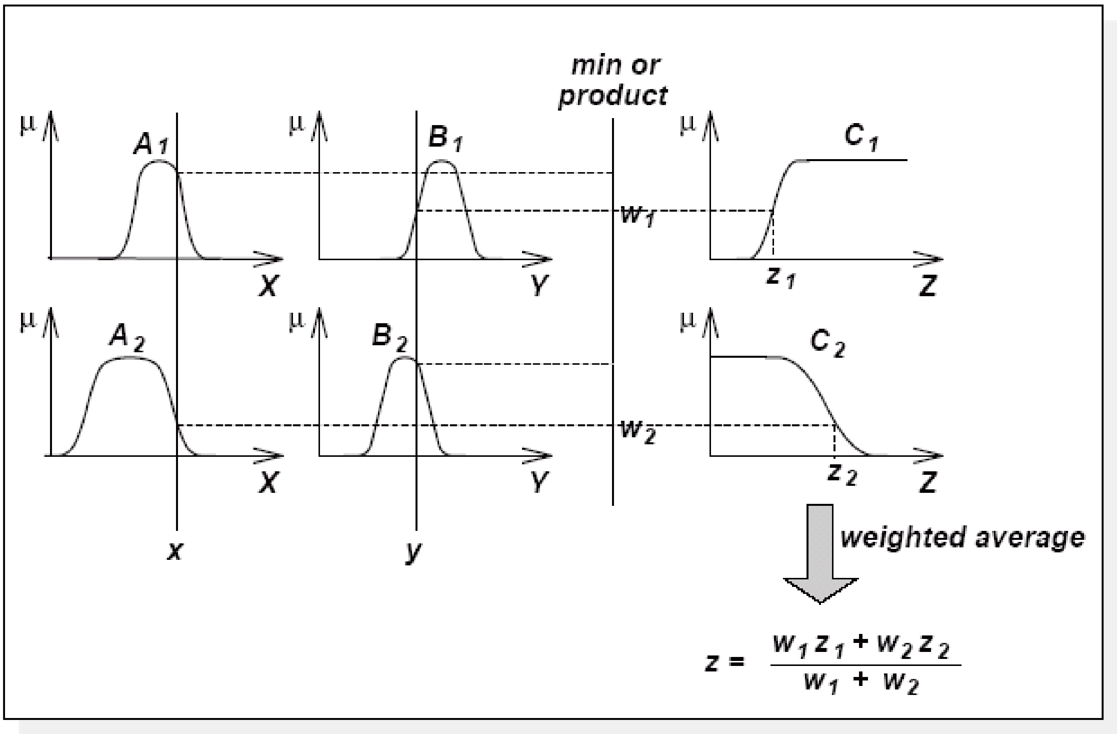


Figure 2.20 A two input one output Tsukamoto fuzzy model (Siddique, 2010)

2.8.3.3 Sugeno Inference Mechanism

This fuzzy model was invented in 1985 by Takagi, Sugeno & Kang in order to present a new method to generate fuzzy rules from any input-output data set (Siddique, 2010) and it is also known by the names of its inventers (TSK fuzzy model). The Sugeno inference mechanism is very similar to Mamdani mechanism. The main difference shows itself in the output consequence. In Mamdani system the output is computed by clipping a membership function at the rule strength. However, in Sugeno system, no output membership functions take place. The crisp number of output is calculated by multiplying each input by a constant and then summing them up. The evaluation procedure is illustrated in Figure 2.21 for a two input, two rule example. Degree of applicability stands for rule strength and the output is called as action. A typical rule for this mechanism can be seen below.

$$If\ x\ is\ A\ and\ y\ is\ B\ then\ z = f(x, y)$$

In this example rule A and B are fuzzy sets and f(x,y) is a crisp function. Commonly f(x,y) is a polynomial function; however, any function describing the output of the model in a convenient way can be of use. If f(x,y) is a first-order polynomial, the fuzzy model is called as first order Sugeno model. If it is a constant, then the fuzzy model is called as zero-order Sugeno model. The second type is a special case of Mamdani fuzzy model with consequents of fuzzy singleton for each rule or a special case of Tsukamoto fuzzy model with consequents of step function MF for each rule.

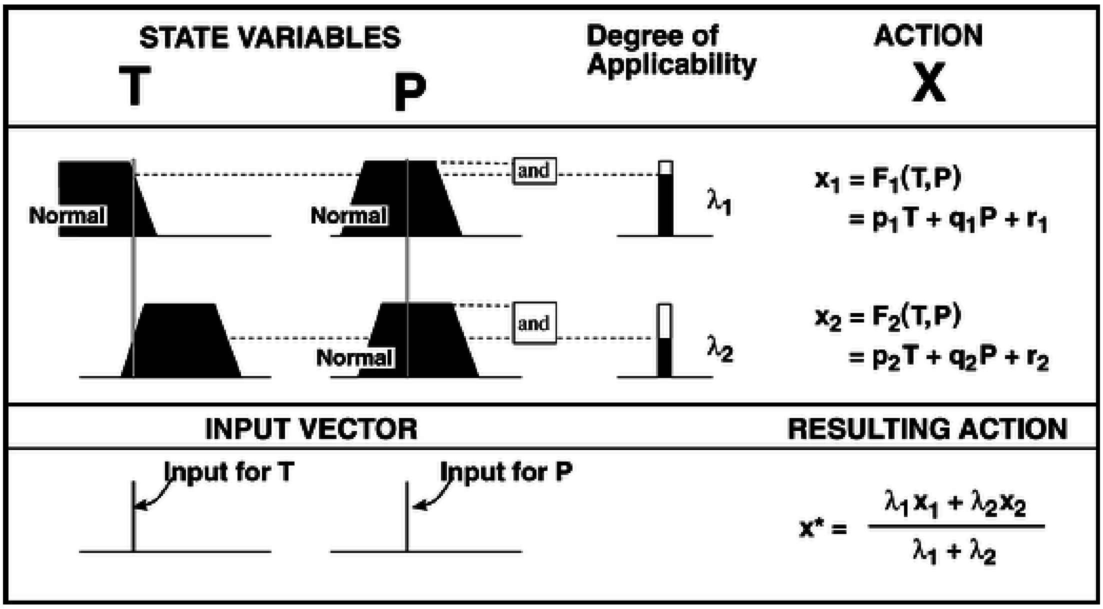


Figure 2.21 An example Sugeno FIS with two inputs and two rules (Knapp, 1996-2004)

The major problem of Sugeno FIS is the lack of a good and reliable method for the determination of p, q and r coefficients. While this is the case, the reason to use Sugeno FIS is the existence of algorithms for automatically optimization of the Sugeno FIS. One of these algorithms is ANFIS that is a type of combination of fuzzy sets and neural network.

2.8.4 Defuzzification

The final step in fuzzy evaluation is defuzzification in which fuzzy values are converted to crisp values. Considering the possible structures, FIS may be composed of a single input and a single output; in addition to this, multiple input variables may also be processed in FIS to obtain a single output as can be seen in Figure 2.19. In the case of multiple variables, FIS extracts a single value for each rule. If it is considered that even a simple FIS contains at least 2 rules and in earth science problems, the number of rules are generally very high, necessity of a system to extract a single value from all these evaluations can be obviously observed. It is stated by Nguyen and Walker (2000) that defuzzification is a transformation process with the purpose of obtaining a single output corresponding to input membership functions. Together with aggregation, it works effectively to obtain single outputs. There are various types of defuzzification methods according to the type of inference that is used to evaluate the fuzzy set, special points of the membership functions like maxima or minima, the area below the membership functions and other types. The most widely used ones are explained in the following part.

2.8.4.1 Center of Area Method (COA)

As being the most widely used method of defuzzification, this method is also called as center of gravity or centroid method. It is based on the equation 7

$$z^*_{COA} = \frac{\int_z \mu_A(z)z\,dz}{\int_z \mu_A(z)\,dz} \tag{7}$$

To be more obvious, the formula above finds the center of gravity of the aggregated area that is the result of FIS (Figure 2.22). The point standing for the COA in horizontal axis is the final crisp value. It is reported by Driankov et al. (1996) that this method is complex and slow in terms of computation.

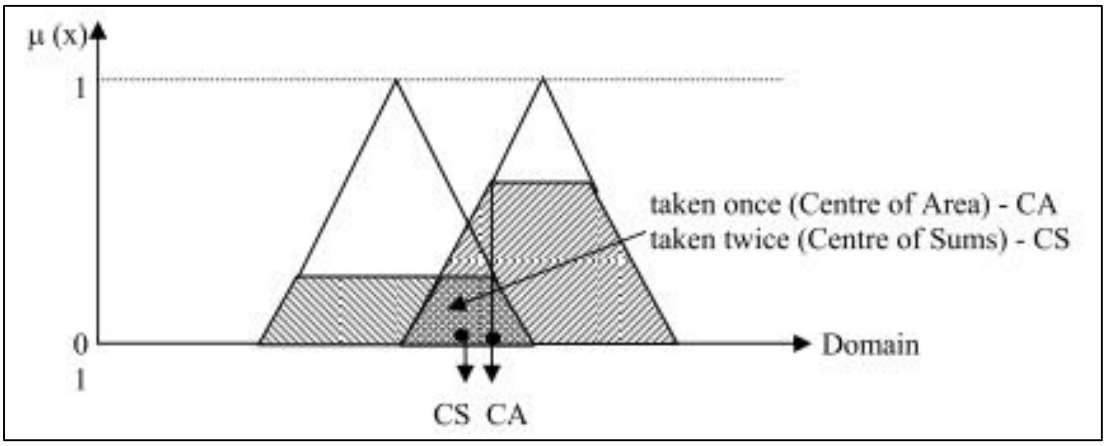


Figure 2.22 Graphical representation of the center of area and center of sums methods (Driankov, Hellendoorn, & Reinfrank, 1996)

2.8.4.2 Center of Sums Method

This method is rather similar to the COA method but its calculation is faster. The main difference is that this method takes each area individually, this results in overlapping areas (Driankov, Hellendoorn, & Reinfrank, 1996). Graphical representation can be seen in Figure 2.22.

2.8.4.3 Height Method

This method considers the peak values of each output fuzzy sets. Defuzzified value is calculated by the weighted sum of peak values. The illustration in Figure 2.23 shows the procedure of height defuzzification method.

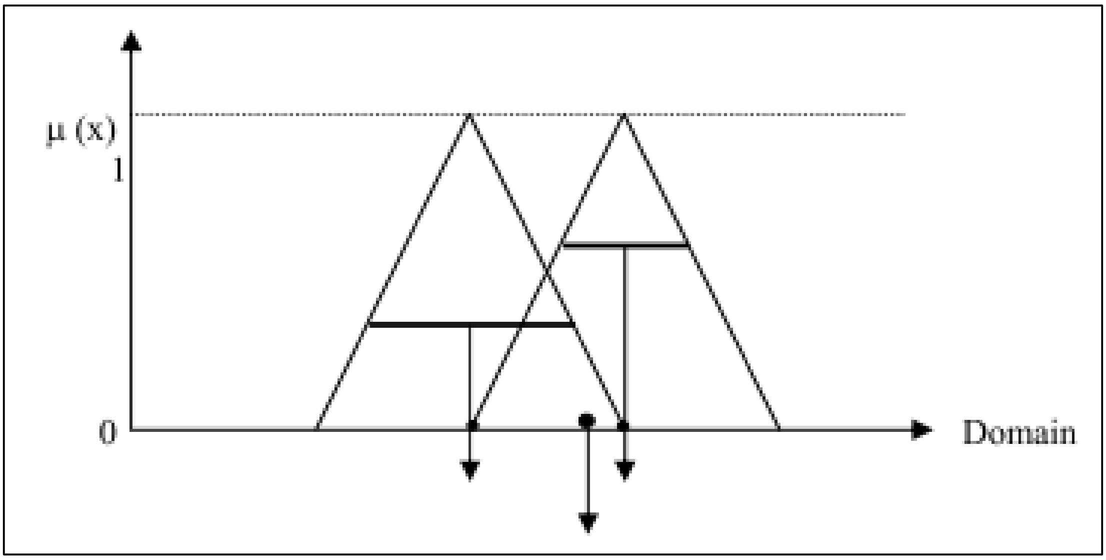


Figure 2.23 Illustration of height defuzzification method (Driankov, Hellendoorn, & Reinfrank, 1996)

2.8.4.4 Maxima Methods

Maxima defuzzification methods are composed of three types, which are first, last and middle maxima. First of maxima method (FOM), which is also called as left of maximum method (LOM) (Zimmerman, 2001), helps to determine the fuzzy rule with the highest effect on the result. The smallest value between the elements of the fuzzy set with the highest membership degree is determined in this method.

The second method is last of maxima method (LOM) or it is also known as right of maximum method (ROM). This method differs from the first of maxima by selecting the highest value between the elements of fuzzy set.

The last method that is middle of maxima (MOM) or center of maximum method (COM) makes use of the average values. The graphical interpretations of these three methods can be seen in Figure 2.24.

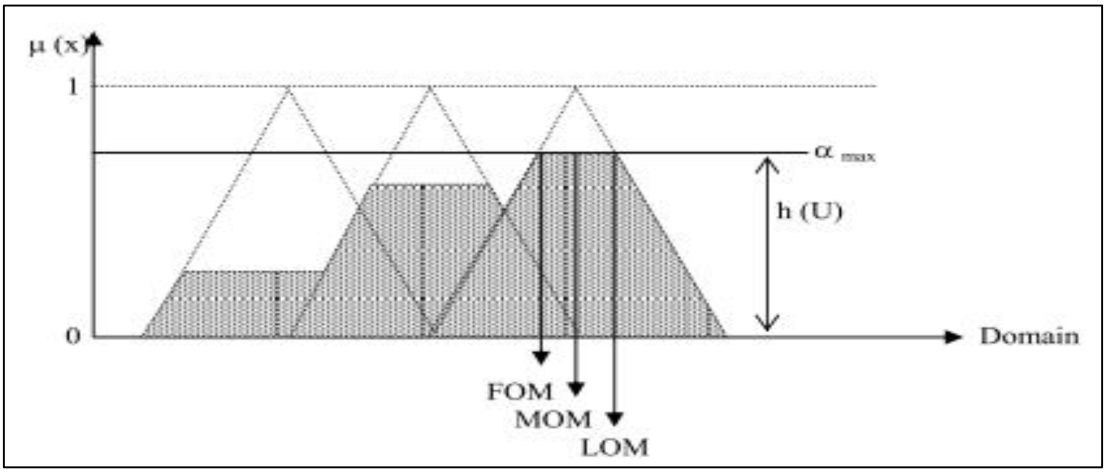


Figure 2.24 Illustration of FOM, MOM and LOM defuzzification methods (Virant, 2000)

2.8.5 Applications of Fuzzy Set Theory on RMR

Many classification methods for rock masses have been developed. The most common problem in classification is obtaining different results by evaluating the same rock mass with different methods. This inconsistency is due to classification systems' being based on subjective judgments that are variable for each researcher (Bhattacharyya, 2003). To handle the uncertain parameters a new methodology is required. Fuzzy set theory is a convenient way to cope with uncertain parameters. It is capable of quantifying the qualitative information and taking advantage of information sources such as expert opinion. Since its invention, fuzzy set theory has been applied to rock mass classification many times. In the following titles, four of the well-known fuzzy applications on RMR system will be explained.

2.8.5.1 Fuzzy RMR of Nguyen and Ashworth

The first attempt to use fuzzy set theory in classification was came from Nguyen (1985). Later, Nguyen and Ashworth (1985) developed the idea of use of fuzzy concept in rock classification. In this approach, fuzzy aggregation procedure lies on the procedure that was developed by Bellman and Zadeh (1970) for the purpose of multi-criteria decision modelling.

While rating the parameters of RMR, Bieniawski did not consider their nature. This leads to the rising importance of expert judgment and experience in the stage of classification. Nguyen and Ashworth (1985) realized that it is possible to include these subjective items into rock classification methods by the use of fuzzy set theory. First of all, they determined the membership degrees of each criterion for each rock class by benefiting from expert knowledge. In this way, a fuzzy binary relation is generated. Later, min-max operations of fuzzy mathematics is used to determine the optimum aggregated membership grades. In this approach, five parameters of RMR are evaluated.

2.8.5.2 Fuzzy RMR of Shimizu and Sakurai

In 1986, Shimizu and Sakurai published their fuzzy RMR system which makes use of fuzzy measure and fuzzy integral concepts to assess the subjective judgment of rock mass classification system. It is called as 'Rock Mass Classification by Fuzzy Set Theory (RMCF)". This approach is divided into the evaluation process in three steps.

1) By utilizing parameter classes, borders of numerical values or linguistic descriptions are determined.
2) Degree of importance for each parameter are determined.
3) Assessment of the parameters either by creating an artificial evaluation method or by using fuzzy measures and fuzzy integral, which are fuzzy mathematical operations.

Fuzzy integral is considered as an aggregation method in this approach. It seems reasonable because fuzzy integrals are used successfully in various multicriteria decision making processes and it takes the importance of parameters into account.

In this approach, all six parameters of RMR are evaluated; however, it is not logical to include discontinuity orientation to aggregation procedure. Another defect of this approach is its taking the same membership functions for all parameters. Finally, this method is complex and lengthy in terms of calculation (Bhattacharyya, 2003, p. 83).

2.8.5.3 Fuzzy RMR of Juang and Lee

This approach is based on a decision support system developed by Juang (1988) and presented in Juang and Lee (1990) for the purpose of evaluating 'Rock Mass Classification Index (RMCI)' by using fuzzy set theory. Fuzzy weighted average algorithm is utilized to obtain a resultant classification rating from individual ratings. This approach contains main and sub criteria that can be seen in Figure 2.25.

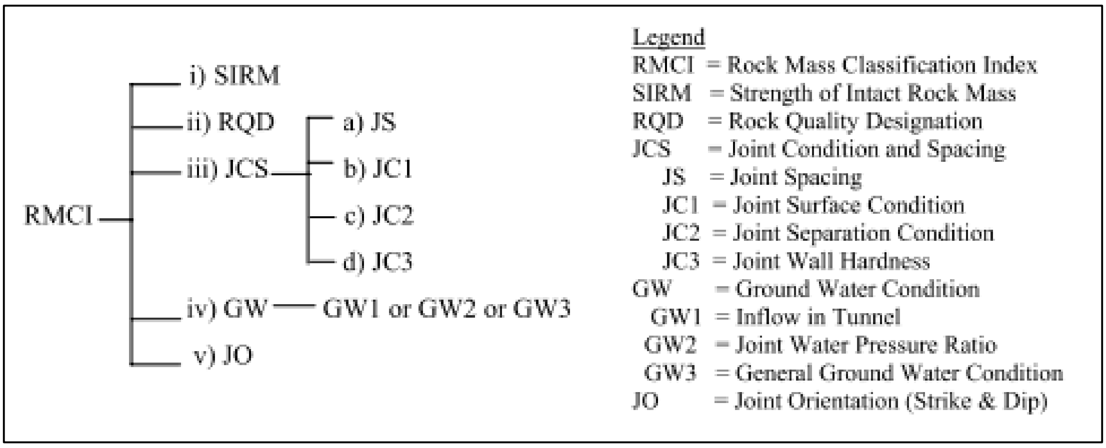


Figure 2.25 Decision tree of Juang and Lee (1990) fuzzy rock mass classification method

In this approach main and sub criteria are assigned ratings of 5 classes as being A, B, C, D and E. These ratings and weights are converted to fuzzy sets with five triangular membership functions with a domain from 1 to 17 (Figure 2.26). Fuzzification of input parameters can be seen between Table 2.9 - Table 2.11. In Table 2.12 mathematical descriptions of fuzzy membership functions, ratings, weights and designations can be seen. Finally, in Table 2.13, class and description information for RMCI intervals are presented in detail.

Fuzzy weighted average is advantageous because it is an aggregation method that takes the importance of each criterion into account. One of the defects of this approach is its taking the same domain for all weighting and rating scales that is between 1 – 17 Because range of classification parameters are different, this leads to problems. Also, there is an apparent overlap between the fuzzy sets of A, B, C, D and E.

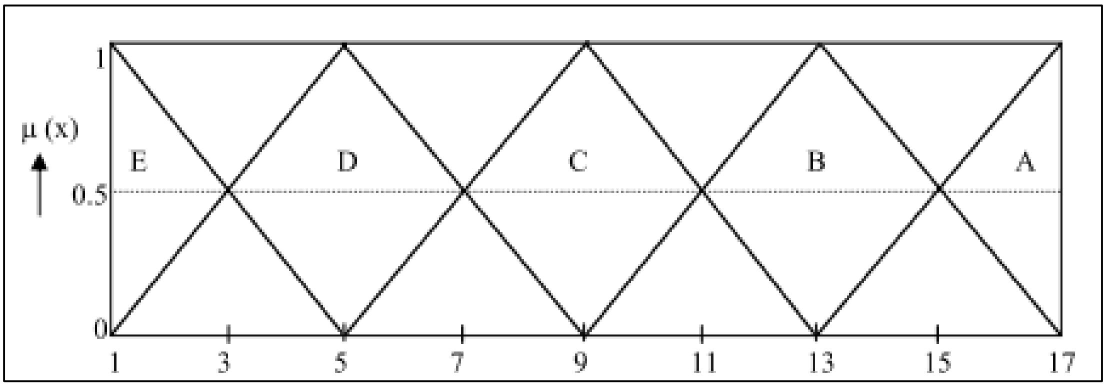


Figure 2.26 Fuzzy weight and ratings (Juang & Lee, 1990)

Table 2.9 Fuzzification of input values of Joint Condition and Spacing (JCS) (Juang & Lee, 1990)

JS (in m)	JC1	JC2 (in mm)	JC3	Rating
> 2	Very rough	0	Very hard	A
0.6 - 2	Rough	0 – 0.5	Hard	B
0.2 – 0.6	Slightly rough	0.5 – 1	Medium	C
0.06 – 0.2	Slickensided	1 – 5	Soft	D
< 0.06	Soft gouge	> 5	Very soft	E

Table 2.10 Fuzzification of input values of Ground Water Condition (GW) (Juang & Lee, 1990)

GW1 (l/min)	GW2	GW3	Rating
0	0	Completely dry	A
0 – 10	0 – 0.05	Moist	B
10 – 25	0.05 – 0.2	Damp	C
25 – 125	0.2 – 0.5	Water under moderate pressure	D
> 125	> 0.5	Severe water problem	E

Table 2.11 Fuzzification of input values of SIRM, RQD and JO (Juang & Lee, 1990)

SIRM (in MPa)	RQD	JO	Rating
> 200	90 – 100	Very favourable	A
100 – 200	75 – 90	Favourable	B
50 – 100	50 – 75	Fair	C
25 – 50	25 – 50	Unfavourable	D
0 – 25	0 - 25	Very unfavourable	E

Table 2.12 Fuzzy sets for linguistic descriptions of ratings and weights (Juang & Lee, 1990)

Rating	Weight	Designation	Fuzzy Set (Membership Functions)
Very good	Extremely important	A	f (x) = 0, 1 δ x < 13 = (x – 13) / 4, 13 δ x δ 17
Good	Very important	B	f (x) = 0, 1 δ x < 9 = (x - 9) /4, 9 δ x < 13 = 1 – (x – 13) / 4, 13 δ x δ 17
Fair	Important	C	f (x) = 0, 1 δ x < 5 = (x – 5) / 4, 5 δ x < 9 =1 – (x – 9) / 4, 9 δ x < 13 = 0, 13 δ x δ 17
Poor	Moderately important	D	f (x) = (x – 1) /4, 1 δ x < 5 = 1 – (x – 5) / 4, 5 δ x < 9 = 0, 9 δ x δ 17
Very poor	Unimportant	E	f (x) = 1 – (x - 1) / 4, 1 δ x < 5 = 0, 5 δ x δ 17

Table 2.13 RMCI Evaluation (Juang & Lee, 1990)

RMCI	Class	Description
1 – 20	I	Very poor
21 – 40	II	Poor
41 – 60	III	Fair
61 – 80	IV	Good
81 - 100	V	Very good

2.8.5.4 Fuzzy RMR of Habibagahi and Katebi

Fuzzy set theory was made use of by Habibagahi and Katebi (1996) to classify rock masses. The approach was mainly based on RMR. The first three RMR parameters with numerical values were presented by five trapezoidal membership functions. Fuzzy sets and their values in conventional RMR concept can be seen in Figure 2.27 -Figure 2.29. Boundaries of fuzzy sets were determined from the experience of conventional RMR system. The three preceding RMR parameters describe rock mass by linguistic terms by five triangular fuzzy sets (Figure 2.30 - Figure 2.32). Evaluation of RMR is similar to the conventional RMR computation; however, in this approach, each parameter is calculated by fuzzy membership functions. The ratings for the first five parameters are summed up and the rating for discontinuity orientation is subtracted.

This approach includes reliability analysis. Reliability of each parameter is denoted by linguistic terms (Figure 2.34). Reliability factors were determined by measurements and field experience (Bhattacharyya, 2003).

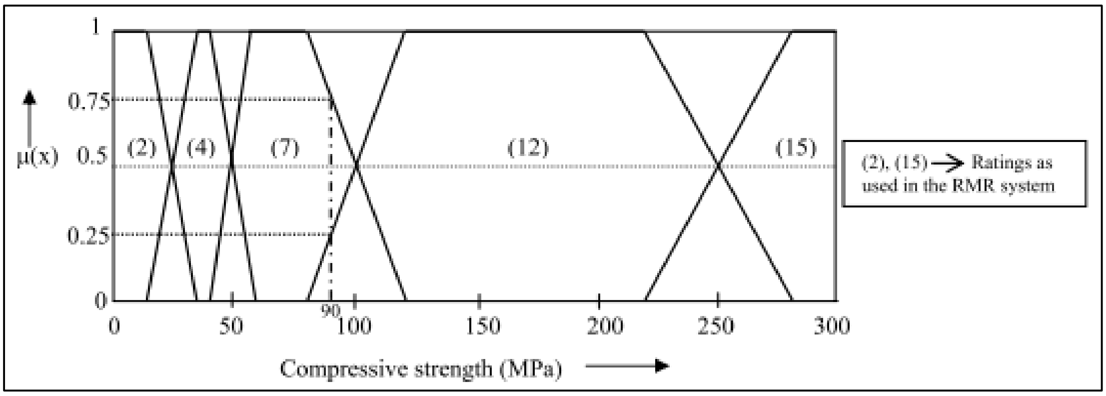


Figure 2.27 Fuzzy membership functions for strength of intact rock (Habibagahi & Katebi, 1996)

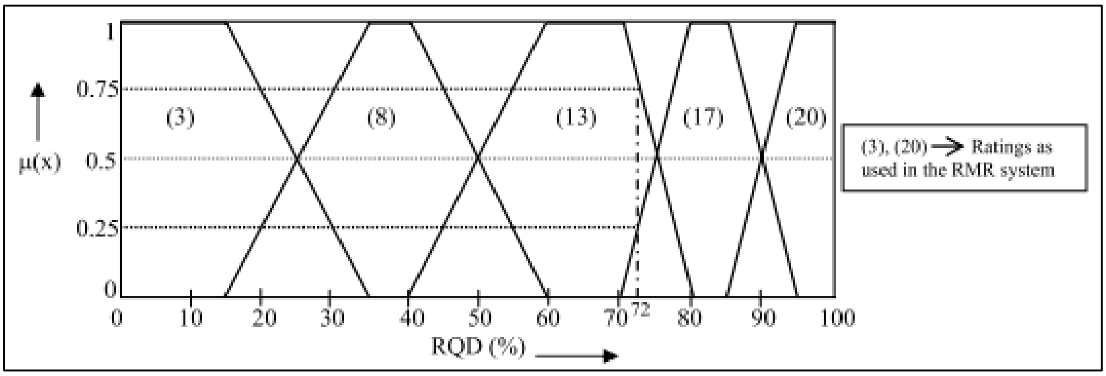


Figure 2.28 Fuzzy membership functions for RQD (Habibagahi & Katebi, 1996)

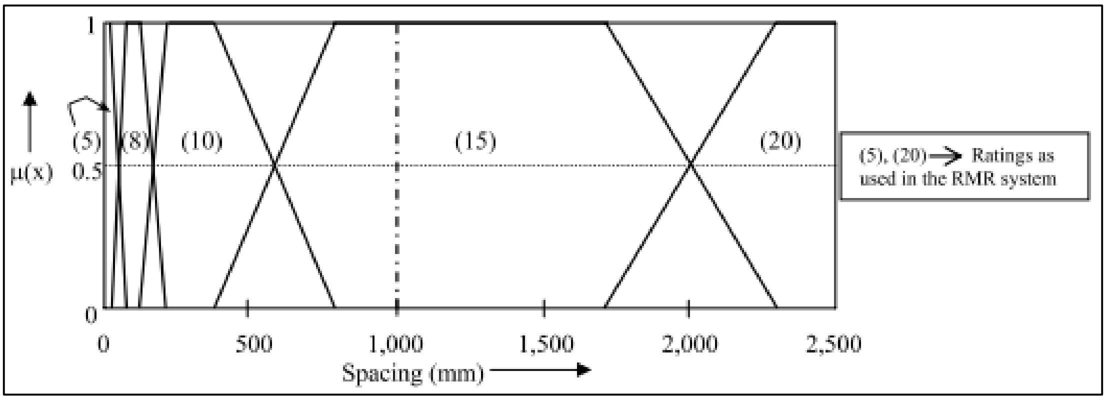


Figure 2.29 Fuzzy membership functions for spacing of discontinuities (Habibagahi & Katebi, 1996)

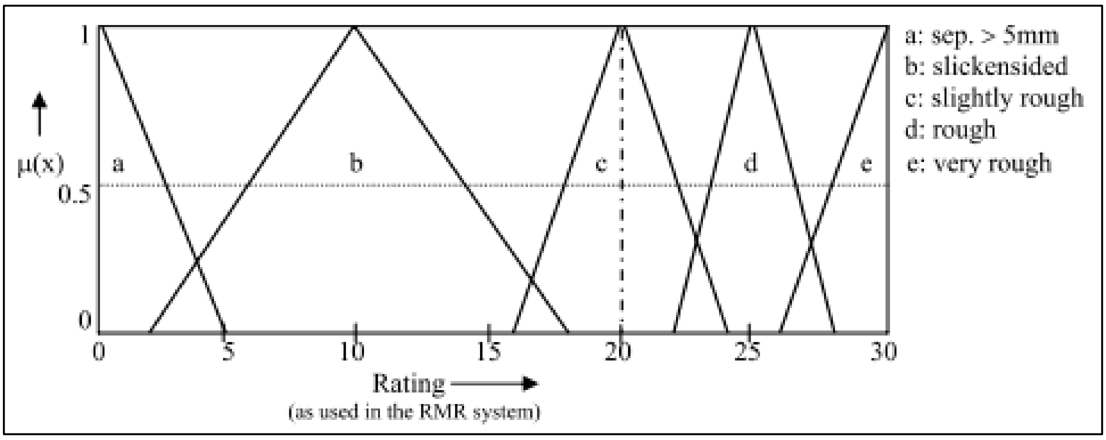


Figure 2.30 Fuzzy membership functions for discontinuity conditions (Habibagahi & Katebi, 1996)

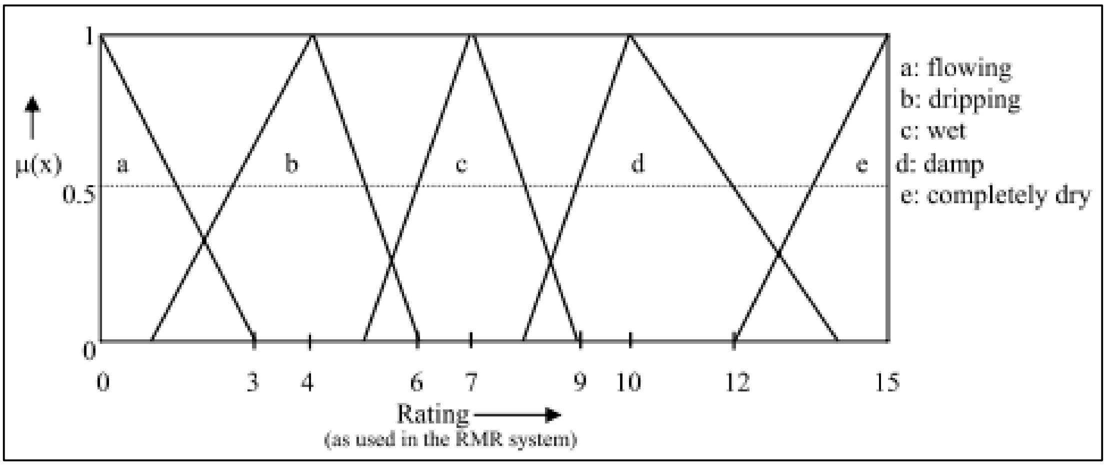


Figure 2.31 Fuzzy membership functions for groundwater condition (Habibagahi & Katebi, 1996)

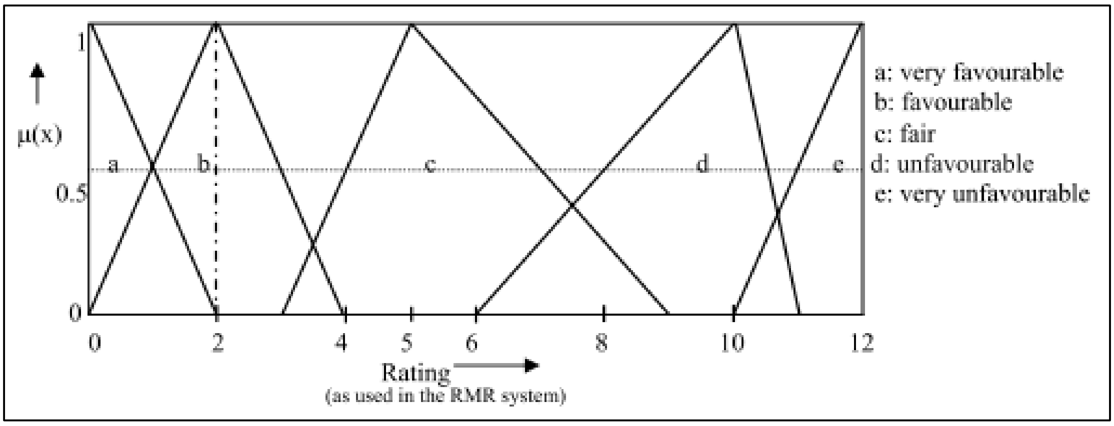


Figure 2.32 Fuzzy membership functions for discontinuity orientation (Habibagahi & Katebi, 1996)

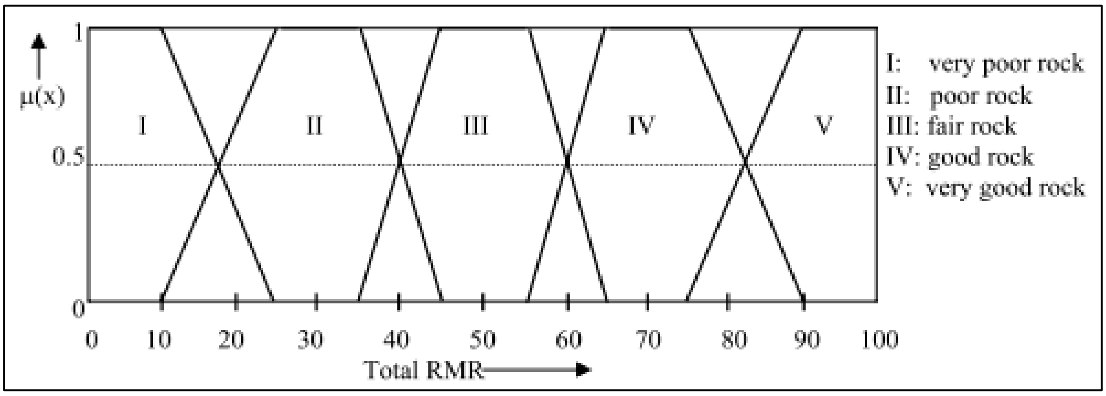


Figure 2.33 Fuzzy membership functions for rock mass classes (Habibagahi & Katebi, 1996)

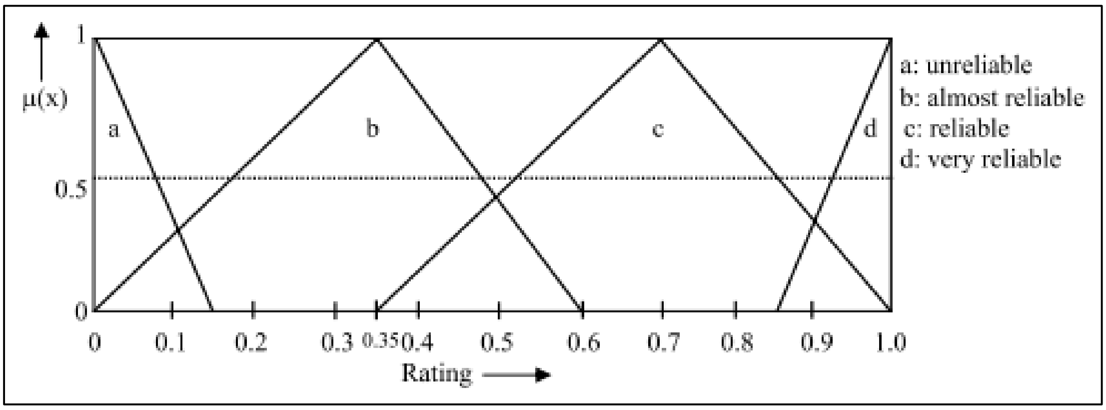


Figure 2.34 Reliability presentation using fuzzy sets (Habibagahi & Katebi, 1996)

In the approach of Habibagahi and Katebi (1996) all the six parameters of RMR were considered. However, fuzzy set theory was not applied in a complete manner for the last three parameters that were described linguistically. Also, in the calculation process, each parameter is evaluated in fuzzy algorithm. The first five parameters were summed up and the orientation parameter was subtracted. This means that, in evaluation process, instead of using fuzzy mathematics, conventional methods were used. In addition, reliability concept of this approach is problematic. Habibagahi and Katebi utilized weighted average concept to assess a reliability factor; however, foundations of selecting the weighting scale in that way is not described apparent (Bhattacharyya, 2003). Finally, the labels to describe rock class, such as I, II, etc…, are opposite of the conventional RMR system.

To sum up, fuzzy set theory has been studied by several researchers to be adapted for rock mass classification due to its capacity to handle uncertainty. However, as can be understood from the previous titles, the problem has not been fully solved yet. All of the researchers have used 5 or 6 parameters for the classification; however, none of them have studied on how many of parameters are required, in fact. In addition, aggregation methods have different effects on the final score.

CHAPTER 3

RESEARCH AREA AND PREVIOUS STUDIES AT THE SITES

3.1 TKI Orhaneli Lignite Mine

3.1.1 General Information about the Site

TKI Orhaneli Lignite Mine takes place in Orhaneli district, which is 65 km away from Bursa city of Turkey. It settles on a land of 9000 hectares. The mine administration is responsible for production in three sectors that are Gümüşpınar, Sağırlar and Çivili. Sağırlar sector had been operated by contractor until 1990 and still there is no activity in this sector (TKİ Bursa Linyitleri İşletmesi Müdürlüğü, 2013). Its altitude is 550 m and calorific value of its ore is around 3000kcal/kg. In Çivili sector there have never been any mining activities. The sector settles on a level of 600 m from the sea level and calorific value of its ore is 2000 kcal/kg. Currently, Gümüşpınar, which has an altitude of 500 m from the sea level, is the single sector that whole of the mining activities are continuing. Calorific values of the ore produced from this sector is between 2300 – 2600 kcal/kg (TKİ Bursa Linyitleri İşletmesi Müdürlüğü, 2013). Mining methods and corresponding proved reserves of three sectors can be seen in Table 3.1.

Table 3.1 Mining methods and corresponding proved reserves of three sectors in TKİ Orhaneli Lignite Mine (TKİ Bursa Linyitleri İşletmesi Müdürlüğü, 2013)

Sectors	**Surface Mining (tonnes)**	**Underground Mining (tonnes)**	**Total (tonnes)**
Gümüşpınar	17.358.972	5.355.000	22.713.972
Sağırlar	1.550.495	4.635.000	6.185.495
Çivili	2.610.000	8.037.000	10.647.000
TOTAL	21.519.467	18.027.000	39.546.467

Main purpose of the Sağırlar mine is to supply lignite coal for Orhaneli Thermal Power Plant that has an installed capacity of 210 MW.

3.1.2 Geology

Settling on the South Western Turkey expansion type neotectonic zone, Gümüşpınar coal basin is a graben that has a length of 7.5 – 5 km expanding in the NNE direction and a width of 2 km (Koçyiğit, 2005). The basin formed on ophiolitic units (serpentine, peridotite) in the west and north and jura cretaceous aged recrystallized limestone in the east and south during Early-Middle Miocene. East and west sides of the basin contain faults that were active in formation of the zone; however, they lost this mission, currently.

Koçyiğit (2005) gives the thickness of lignite bearing layer as 200m. He also stated that sedimentation of the fill had been in lake-river environment in assistance of an acidic volcanism. From their research it can be obviously seen that basin fill starts at the bottom with brown colored pebble stone in the west and continues with sandstone, tuff-tuffite, clay stone, coal, marl, tuff-tuffite, marl sequence through the up. In the upper layers dominance of pebble stone lenses with pink-brown tuff-tuffite and marl level rich in carbon can be seen. Sudden changes in facies, slumps show that the settling of coal containing basin was controlled by an active tectonism.

Rock types that are forming the basin fill shows a layering from lamina size to 1.5 – 2 m. Layer directions change between N36°W and N15°E and dip with an angle of 14° perpendicular to the strike in NE and SE directions. Generally, layers are dipping in the east direction and forming homoclinal structure. This structure is proven by the same directions and dips of layers, and deeper sitting of coal bearing layer in layer dip direction (around 140 - 150 m). The situation was proven by drill cores from the east of the basin (Kulaksız, et al., 1991).

Karpuz et. al. (2006) noted all the fault and joints by field observations and seismic exploration. They found six fault systems and named them as being FZ-1, … , FZ-6. According to their study fault zones have a width of 20 cm – 100 m and their slip amount are between 0.3 m – 7 m.

3.1.3 Studied Slopes

In the scope of this study ten slopes that are affected by faults are distinguished and fault orientations are presented in Table 3.3. Those slope properties and affecting faults are presented in Table 3.2. A large failure occurred at the Orhaneli open casts mine in 2004. Karpuz et. al. (2006) undertaken a research project to remedy the slopes at the mine. This failed slope was used for the purpose of validation. Material properties of this site were determined by back analysis of this failure and other nine slopes were analyzed using these parameters. Thus, the other nine slopes can also be used for validation purposes

Table 3.2 The orientation of the studied slopes and the affecting faults in TKI Orhaneli Lignite Mine (Karpuz, et al., 2006)

Slope	Dip Direction/ Dip (°)	Height (m)	Affecting Faults
Slope 1	094/36	100	Fault G10
Slope 2	341/32	100	Fault 16, Fault 3
Slope 3	335/36	100	Fault 3
Slope 4	055/36	100	Fault 13
Slope 5	023/26	100	Fault 12
Slope 6	289/24	115	Fault 11, Fault 12
Slope 7	226/32	100	Fault 11
Slope 8	227/36	100	Fault 8
Slope 9	234/36	100	Fault 8
Slope 10	259/30	100	Fault 1, Fault 2

Orientation relationships of the faults and the names of slopes they affect can be seen in Table 3.3. These relations will be later used in calculation of slope mass rating. Also, they have been utilized in the stage of analytical stability analysis.

Table 3.3 Directional relations of the faults in TKI Orhaneli Lignite Mine

Fault	Affected Slope	Dip Direction/Dip (°)
Fault G10	Slope 1	145/53
Fault 16	Slope 2	217/52
Fault 3	Slope 2	118/52
Fault 3	Slope 3	156/60
Fault 13	Slope 4	053/74
Fault 12	Slope 5	014/68
Fault 11	Slope 6	233/52
Fault 12	Slope 6	004/68
Fault 11	Slope 7	216/52
Fault 8	Slope 8	215/56
Fault 8	Slope 9	220/56
Fault 1	Slope 10	202/58
Fault 2	Slope 10	006/58

3.1.4 Back Analysis of Large Slope Failure at Orhaneli Lignite Mine

In 2006, Karpuz et al. carried out a study to investigate the failed slope of Orhaneli Lignite Mine in order to determine rock mass properties and design stable slopes for a safe production operation. The failed slope is named as 'Slope 6'. The large failure was initiated by a wedge failure and propagated by planar and circular types of failures. Because of this reason, kinematical analysis does not represent a pure wedge failure (Figure 3.1). They conducted both 2D and 3D analyses on the failure. First, 2D analyses were carried out to obtain frictional properties assuming FOS as one. Later, detailed investigation of the failure have been studied in 3D analyses.

A simplified 2D model investigating the failure has been prepared for the purpose of obtaining the frictional properties of discontinuities. This model was designed to carry out analyses on cross-sections for a composite plane by using Janbu slice method in SLIDE software of Rocscience Company. Siltstone - claystone intercalations were modelled with the current groundwater conditions.

First, cohesion of discontinuity planes have been kept constant as '0' in order to observe the effect of fault friction angle on the factor of safety. It was concluded that friction angles of discontinuities do not have major effects on failure mechanisms because faults are close to vertical. The main actor is the cohesion of siltstone – claystone intercalation.

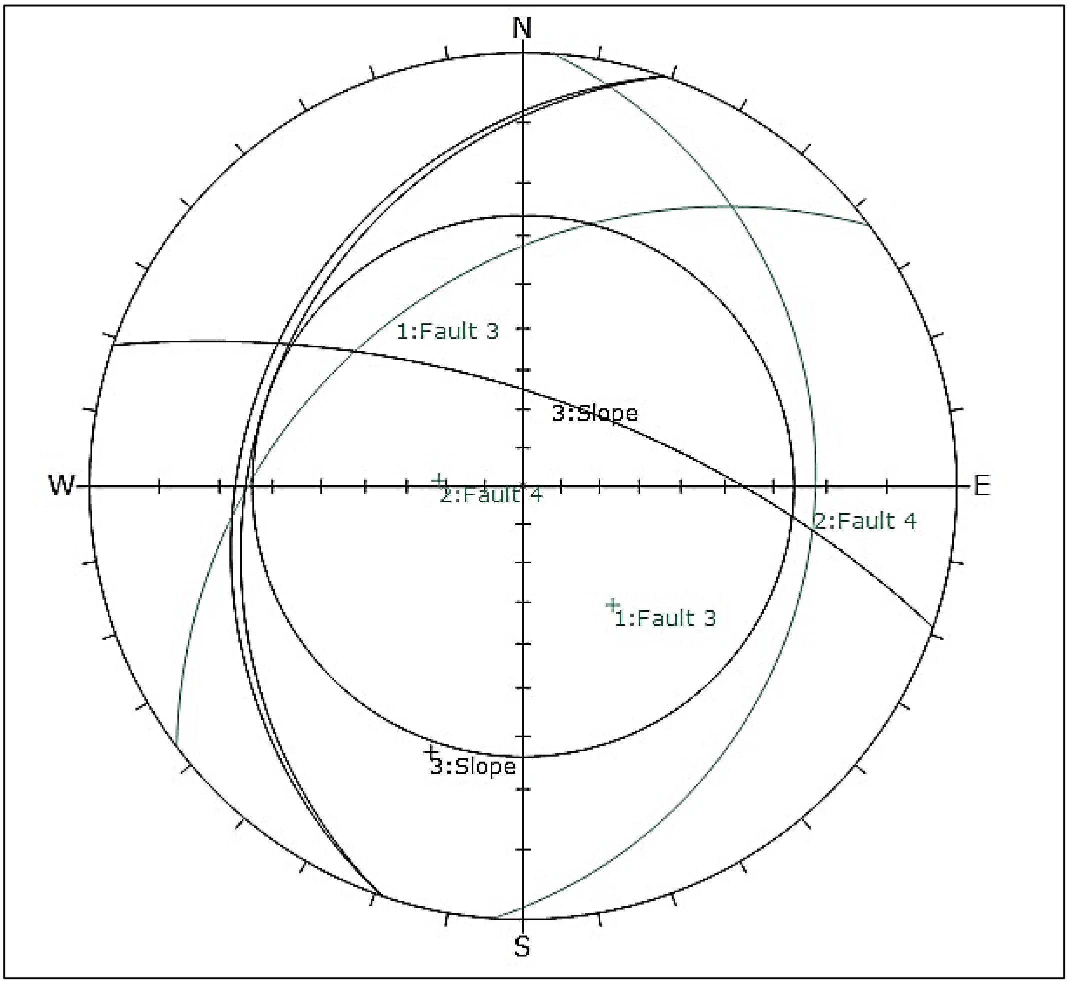


Figure 3.1 Kinematic analysis of the failed slope in Orhaneli Mine (Rocscience Dips)

Karpuz et al. (2006) observed that 2D analyses does not reflect the real behavior of the failure due to its lack of including compressive forces in the third dimension and decided to use 3D modelling by 3DEC software (3 Dimensional Distinct Element Code v3.0) of Itasca Company. 3DEC Software has been developed by Itasca Consulting and Software Company as a distinct element code for the stability analysis of materials with discontinuities. Discontinuous materials are simulated by joining different blocks of materials. This software makes it possible to analyze geotechnical problems with large strain and moment. Each block can be defined to be rigid or deformable. Deformable can be divided into finite difference elements and deformations on points can be recorded. Discontinuities like faults and joints can be defined inside the software. The software is time-marched and stress, strain and other parameters can be observed in desired computation times. The computation can be paused whenever it is desired. By this way, the step of calculation in which the problem is in balance can be determined. If desired, the computation can be continued.

The failure was modelled and the shear parameters of the dominant strata in the region, which is silty – clayey levels, were calculated.

Figure 3.2 View of failure zone in Orhaneli Lignite Mine (Karpuz, et al., 2006)

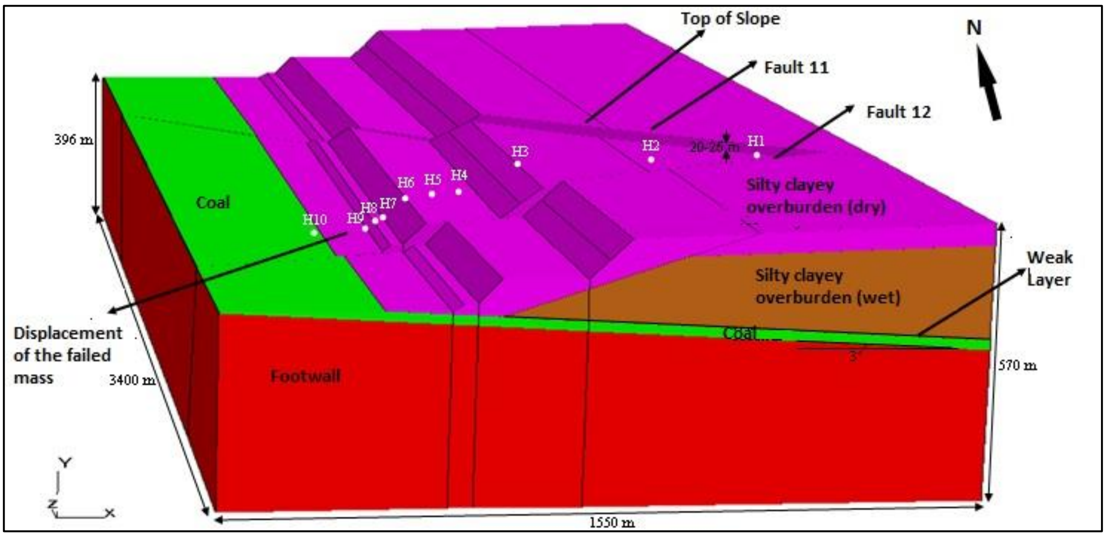


Figure 3.3 3D model of failure in Slope 6 and locations of the points on the failed mass to track displacements (Karpuz, et al., 2006)

The silty – clayey layer was defined as a layer with thickness in some parts of the model and included into the finite difference mesh. In other parts, it was defined as a discontinuity due to its avoidable thickness.

To sum up, as a result of 3D model of the failure in the mine it was found that two intersecting and wedge forming discontinuities generate a failed block of rock mass that moves 20 m downwards and triggers the large failure. This moving block results in turning effect on the silty clayey layer that is placed on the front. Because the software cannot simulate cracks, they cannot be shown; however, in reality rock mass has been sliced on the front due to the separation as a result of failure.

Cohesion of the silt-clay intercalation was determined to be 100 kPa. This can be explained with a drop to residual values of cohesion following the failure. Friction angle of silt- clay intercalation was determined to be 26° and no correlation has been detected between the results of models and the friction angle (Karpuz, et al., 2006).

Table 3.4 Material properties of rock mass of Orhaneli Mine from back analysis of the failure

Material	**Elastic Modulus (MPa)**	**Poisson Ratio**	**Cohesion (kPA)**	**Internal Friction Angle (°)**
Siltstone - claystone intercal.	100	0.2	100	26
Lignite	500	0.2	500	25
Foot wall (andesite & tuff int.)	2000	0.2	5000	35
Discontinuity Planes	**Normal Stiffness (MPa/m)**	**Shear Stiffness (MPa/m)**	**Cohesion (kPa)**	**Internal Friction Angle (°)**
Fault 11 & 12	160	160	5	20

3.2 TKI Çan Lignite Mine

3.2.1 General Information about the Site

TKI Çan Lignite Mine is located in the west of Çan district that is 55 km away from the Çanakkale City of Turkey. Lignite formation in the region that can be seen in Figure 3.4 has been discovered in 1940 and operated by private sector until its nationalization in 1979. Since then, the mine is operated for the purpose of providing energy demand of the industry. Most of the reserve contains sulphur in high amounts. Because of this reason, the main customer of the product is Çan Thermal Power Plant, which has an installed capacity of 2 x 160MW. At the same time, sale for the purpose of heating can be done. 90 % of the production is consumed for thermal power plant while 10 % is for heating.

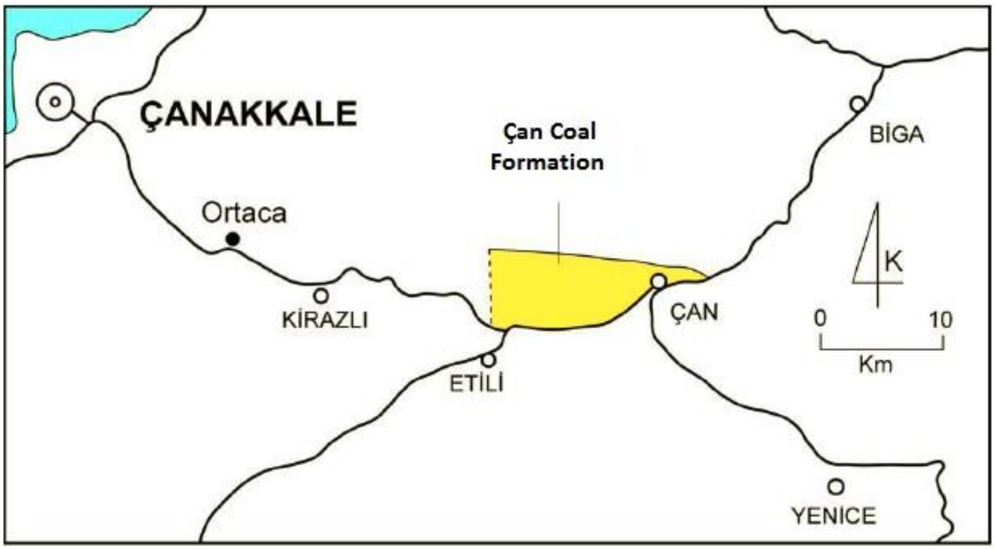


Figure 3.4 Location of Çan coal formation on the map

Çan Lignite Mine, operating with the government license of IR-3378, settles on 2,437.02 hectare area. Mining activities continue on an area of 19,000 acres. The mine has a proven reserve of 80,302,588 tonnes and 59,182,958 tonnes of it is producible (Çan Linyitleri İşletmesi Müdürlüğü, 2013).

3.2.2 Geology

The first geological survey of Çan coal region was carried out by General Directorate of Mineral Research and Exploration (MTA) by Hezerfan in 1976. As a result of this study, 24 pages of text, a geological map of 1/5000 scale and 29 geological cross-sections based on drillhole data were published. This report was informing about the rock types of the coal bearing bed sediments, thickness of the coal, discontinuities.

Karpuz et. al. (2005) stated that late Eocene-Oligocene aged Çan coal basin had been formed on a base of vulcanite (andesite, andesitic pyroclasts) and basalt, basaltic pyroclasts in control of faulting. They state that faults are observed in the Northeast and South sides of the basin and the basin had been formed in the control of these faults. In the basin there are two fillings that are separated from each other with an angle. The filling taking place at the bottom contains pebble stone, coal in varying thicknesses (up to 65 m), clay stone, agglomerate, clay stone with thin coal veins and agglomerate in order. Coal bearing volcano sedimentary layer that is 482 m thick contains shale that is rich in organic matter. The top layer has been formed in control of slip faults and this formation is still in progress.

Karpuz et al. (2005) informed that Çan coal region has a shape of triangle or wedge and deformed in the time period following the formation of the region. Development of the coal bearing old aged filling of the basin is in a good condition and shows preserved layering. Layer slopes change between 15°-76° and the average slope is around 30°-35°.

In the region two types of faults have been noted by Karpuz et al. (2005), which are growth faults and tectonic faults. Growth faults are formed by tectonic movements that were dominant during sedimentation of the coal. They have lengths up to 100 m. Faults are the dominant actors of the formation of coal and basin geometry. There are two major tectonic faults namely Kocabaş and Bağbaşı.

3.2.3 Studied Slopes

Çan 5 panel slope data given in Table 3.5 is utilized for the analysis since it has been failed along a dominant layering. Directional relations of studied slopes and the names of faults affecting those slopes can be seen in Table 3.6.

Table 3.5 Directional relations of slopes and their affecting faults in TKI Can Lignite Mine

Slope	Dip Direction (°)	Dip Amount (°)	Height (m)	Defects
Can 5	180	17	120	Weak Layer

Directional relationships of the weak layer and the affected slope can be seen in Table 3.6. These relations will be later used in calculation of slope mass rating. They have been used in the stage of analytical stability analysis.

Table 3.6 Directional relations of the faults in TKI Can Lignite Mine

Defects	Affected Slope	Dip Direction (°)	Dip Amount (°)
Weak Layer	Can 5	180	7

3.2.4 Back Analysis of Failed Slope in TKİ Çan Lignite Mine

Çan 5 slope of Çan Lignite Mine has experienced a large failure and Karpuz et al. (2005) benefited from this ‘open air rock mechanics experiment’ to predict mechanical properties (c and ϕ) of the failed rock mass by back analysis. Types of rocks and the slope geometry during the failure can be observed in Figure 3.5. Planar type of failure occurred in the slope and this can be purely observed in the kinematical analysis (Figure 3.6)

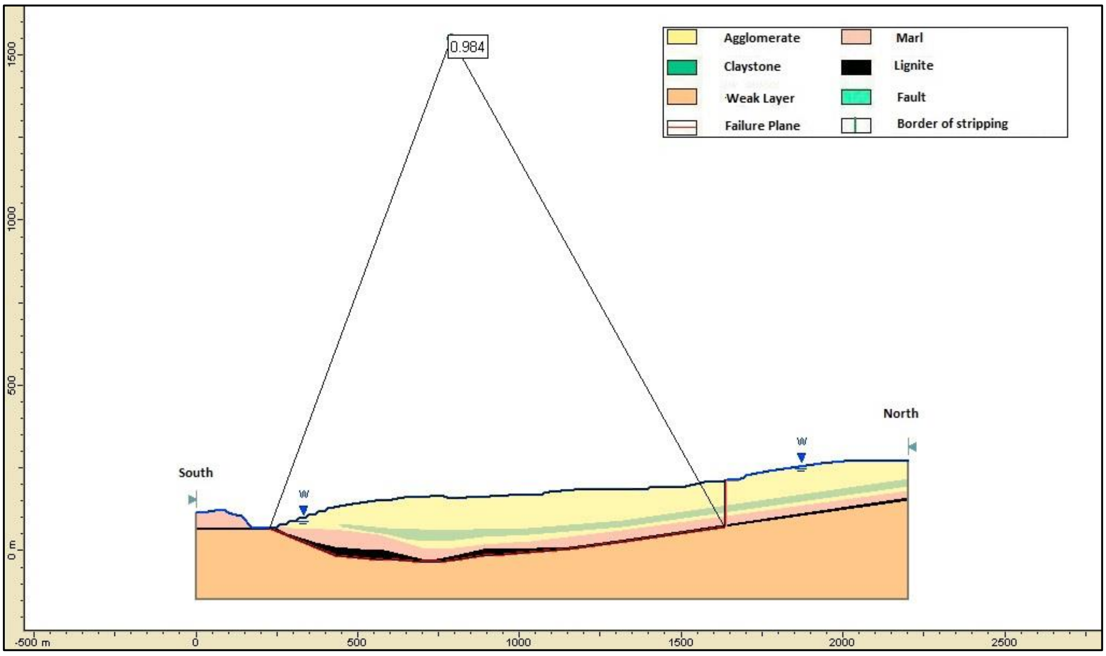


Figure 3.5 Geometry of Çan 5 slope in the meantime of failure generated in Rocscience SLIDE software (Karpuz et.al, 2005)

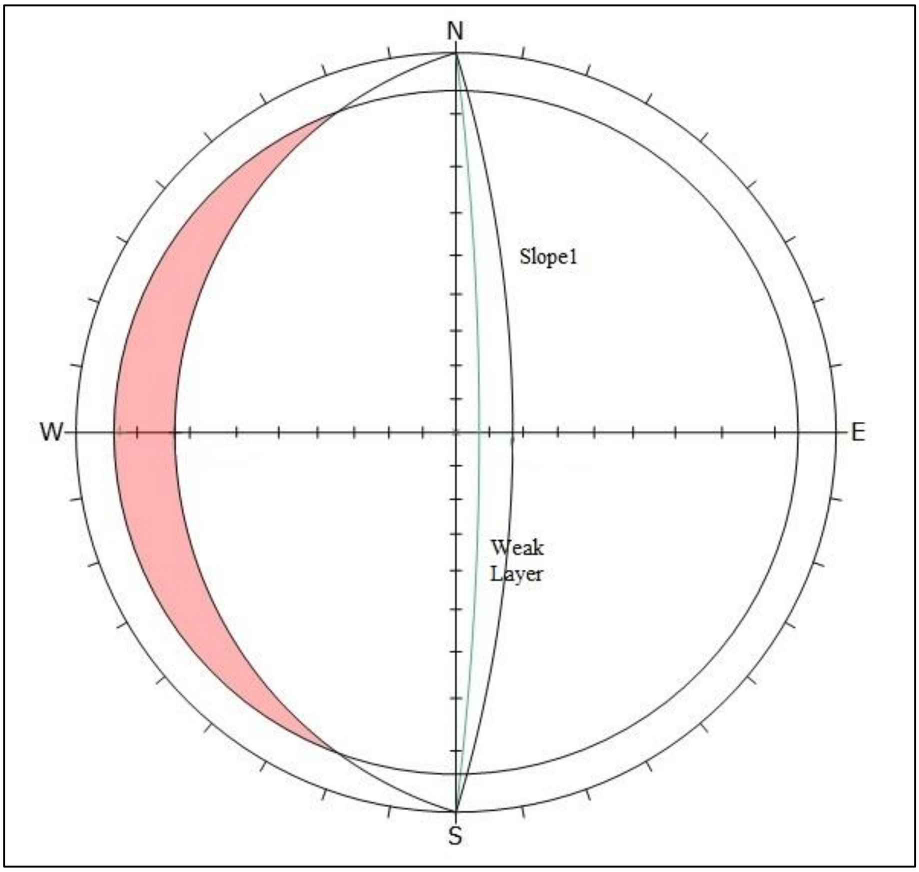


Figure 3.6 Kinematic analysis of the failed slope in Çan Mine (Rocscience Dips)

To predict the failure mechanisms and rock material properties, two software packages, which are SLIDE and FLAC were used. These two softwares can conduct 2D analysis. In this problem, no need for 3D analysis was observed because there is no importance of the third dimension. The failure of this slope happens on a weak layer of silt-clay intercalation and it can be represented by a cross-section. It is just a special type of plane failure.

In SLIDE software, to analyze non circular failures 'Ordinary Method of Slices' gives better results; thus, it was used in this problem.

Location of the tension crack was noted and introduced to the program. In the weak layer, because cohesion is not as effective as friction angle, it was assumed to be fix and 9.87 kPa. Groundwater was defined into the footwall and the failed surfaces. A failure plane that is parallel to the base of lignite was fixed in cohesion and by changing the friction angle, the value in the meantime of FOS of 1 was determined. The effective friction angle during the failure was found to be 6.1°. To find this value it was assumed that the tension crack is full of water and in the whole lignite bed the weak layer lying under it was very thick. In reality, the thickness of this layer is between 2 – 10 m. Results found from SLIDE shows a wide change according to the state of water. For example, if the tension crack is dry, the FOS rises up to 1.51. To have a failure in this case, the friction angle of the layer should be 4°, which is not realistic because even in the cross-section that was used for the back analyses, the most steep portion has an angle of 7° and there is no failure if no excavation is done in front of the slope. SLIDE is a software that works more efficiently for circular failure analysis and it may not be appropriate to use it in this case where friction angle of slip surface is important. For this reason, it was decided by Karpuz et. al. (2005) to study the failure mechanism in FLAC models (Itasca Consulting&Software Co.).

FLAC is a finite difference code of Itasca Consulting and Software Company that can be used to simulate large deformation as in this case. The failure geometry was prepared in the software. By alternating the friction angle of weak layer down the lignite bed, the failure in Çan 5 slope was simulated.

FLAC software is a time-marched solution program. This means that, the problem is solved in steps and each step is a solution time.

In the analysis, friction angle of weak layer was dropped from 14° to 2° and each time 5800 cycles of solution was done. By decreasing the friction angle, geometry of the failed mass has been revealed. It was realized that the point of the initiation of circular movement on the top of the slope is intersecting with the tension crack observed in the field. This proves the success of FLAC software in the analysis of slope instability.

To conclude, the critical friction angle for initiation of the failure in silt – clay intercalation was observed to be between 6° - 8° and the cohesion is 9.87kPa.

Table 3.7 Material properties of rock mass of Çan Mine from back analysis of the failure

Material	**Elastic Modulus (MPa)**	**Poisson Ratio**	**Cohesion (kPa)**	**Internal Friction Angle (º)**
Agglomerate Tuff Intercal.	100	0.2	12.93	17
Lignite	100	0.2	9.87	8
Foot Wall (Andesite&Tuff Int.)	100	0.2	14	16
Discontinuity Plane	**Normal Stiffness (MPa/m)**	**Shear Stiffness (MPa/m)**	**Cohesion (kPa)**	**Internal Friction Angle (°)**
Weak layer (Siltstone claystone int.)	120	120	9.87	6

CHAPTER 4

PRELIMINARY SLOPE DESIGN USING CONVENTIONAL AND FUZZY RATINGS

4.1 Determination of Rock Mass Rating (RMR)

The first step of empirical slope design is to determine basic Rock Mass Rating values of the interested rock masses in conventional meaning. According to Bieniawski (1989) rock mass should be divided into structurally uniform regions. In Orhaneli Lignite Mine, the rock mass on which slopes will be cut is named as intercalation of siltstone and claystone. These layers are so thin to be defined as individual structural layers; therefore, their sequence is described as a combined structural class. In Çan Lignite Mine, the slopes will be cut on silt – clay intercalation. RMR can either be calculated based on borehole cores or by directly field observation. After defining rock types, rock masses can be rated for the parameters that are given in the RMR table. Since drilling has been carried out for the purpose of exploration of lignite coal and there has been no geotechnical logging in Orhaneli and Çan Lignite Mines, the rock mass and material properties determined by Paşamehmetoğlu et. al. (1988) is utilized for the determination of RMR values of rock units. Detailed information about the values and ratings of each parameter are given in Table 4.1 for Orhaneli and Çan Mines. Heterogeneous rock types were rated uniquely and their averages were taken. As a result of rating not only single values of RMR obtained but result intervals were found.

In the scope of this study for the purpose of being on the safe side, minimum values of RMR were considered. Average RMR values considered in slope designs of Orhaneli and Çan Lignite Mines are taken as 37 and 34, respectively. According to RMR table (Table 2.2) these rock masses are described as "poor rock" and the rock mass class is "IV".

4.2 Determination of Fuzzy Rock Mass Rating (FRMR)

4.2.1 General Information about FRMR

Fuzzy logic has three steps that are fuzzification, inference and defuzzification. The inference system, three main elements of which are rule-base, database and reasoning mechanism, is the computing framework that derives adequate conclusions from input data. There are many models developed for fuzzy inference. In this study, fuzzy rule-based system will be used. Also, for rule-based systems, many mechanisms such as "Mamdani Inference Mechanism", "Tsukamoto Inference Mechanism", "Sugeno Inference Mechanism" and "Larsen Inference Mechanism" were developed. In many geotechnical studies "Mamdani Mechanism" is preferred due to its simplicity and capability of dealing with linguistic variables (Adoko & Wu, 2011). Considering its advantages and popularity, "Mamdani Mechanism" is used in this study.

Table 4.1 The determined RMR 79 values at Orhaneli and Çan Lignite Mines for intercalation of siltstone claystone ((Paşamehmetoğlu, et al., 1988))

				RMR 79 LOG OF TKİ ORHANELI LIGNITE MINE FOR INTERCALATION OF SILTSTONE CLAYSTONE			RMR 79 LOG OF TKİ ÇAN LIGNITE MINE FOR AGGLOMERATE		
Discontinuity Type				Siltstone claystone intercal. including set 1	Siltstone claystone intercal. including set 2		Siltstone claystone intercal. including set 1	Siltstone claystone intercal. including set 2	
INTACT ROCK STR.	UCS (MPa)			10	10		10	10	
	Rating			**2**	**2**		**2**	**2**	
RQD (%)				25- 50	25- 50		0-20	0-20	
Rating				**8**	**8**		**5**	**5**	
Discontinuity spacing (m)				0.01-1.0	0.2-0.5		0.01-1.0	0.2-0.5	
Rating			min	**5**	**8**		**5**	**8**	
			max	**15**	**10**		**15**	**10**	
CONDITION of DISCONTINUITIES	Persistence (m)			<1	<2		<1	<2	
	Rating			**6**	**4**		**6**	**4**	
	Aperture (mm)			>5	>5		>5	>5	
	Rating			**0**	**0**		**0**	**0**	
	J.R.	(VR, R, SR, S, SS)		S	S		S	S	
	Rating			**1**	**1**		**1**	**1**	
	Weathering	(UW, SW, MW, HW, D)		MW	SW- MW		MW	SW-MW	
	Rating		min	**5**	**3**		**5**	**3**	
			max	**5**	**5**		**5**	**5**	
	F.C.	Filling Hardness (S, H)		S	N		S	N	
		Filling Thickness (mm)		>5			>5		
		Infilling Rate		0	6		0	6	
Groundwater				W	W	**Avg.**	W	W	**Avg.**
Rating				**7**	**7**		**7**	**7**	
RMR			**min**	**34**	**38**	**37**	**31**	**35**	**34**
			max	**39**	**39**	**38**	**36**	**36**	**35**

UCS=Uniaxial Compressive Strength
J.R. = Joint Roughness
F.C. = Filling Characteristics
VR = Very Rough
R = Rough
SR = Slightly Rough
S = Smooth
SS = Slickensided
S = Soft
H = Hard
UW = Unweathered
SW = Slightly Weathered
MW = Moderately Weathered
HW = Highly weathered
D = Decomposed

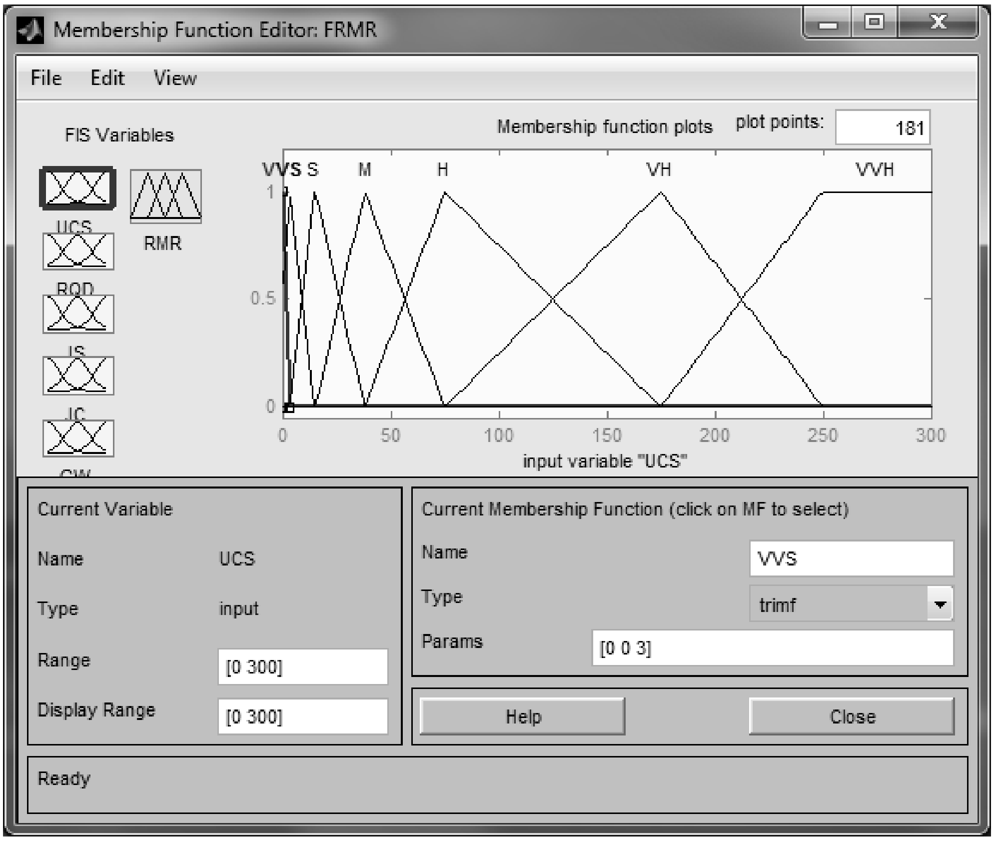
4.2.2 Fuzzification

RMR basic has five parameters and values of each parameter were recorded in field studies. These values are in the form of crisp values. To process them in fuzzy inference system, they need to be fuzzified. To accomplish this, linguistic variables should be defined in order to divide data into clusters such as “good”, “bad”, etc. Linguistic terms are also useful in stage of rating. After that, membership functions must be determined. There are many types of functions such as triangular, trapezoidal, gaussian, etc. Although it is possible to determine the exact complex shape of the function, it requires very much effort and does not result in significant difference. Thus, simplified functions are preferred. The two most commonly used function types are triangular and trapezoidal functions.

As mentioned before there are two options for defining membership functions. In the first option, huge amount of data used by artificial learning methods and mathematical relation of the variable will be predicted. The second option is determining weightings, boundaries and the function shapes by benefiting from expert opinion. The second option requires less data; thus, it is preferable in case of lack of high amounts of data. In the scope of this study, the second option is going to be made use of. In basic RMR there are five parameters that are UCS, RQD, JS, JC, and GW. UCS, RQD and JS are very suitable to be fuzzified because they are defined by linguistics variables each of which represents an interval. However, JC and GW represent single values; thus, it is the main problem to fuzzify these two variables for the researchers who studied on this subject. In the scope of this study, membership functions for RMR basic variables are determined according to the study of Jalalifar (2011) that pays special attention to the JC and GW parameters. He determines a new scale between 0-1 and 0-0.8 for them and divides the variables into five subclasses. In their study of “Assessment of Slope Stability Using Fuzzy Sets and System” (2012) Başarır and Saiang also preferred similar functions for UCS, RQD and J, JC and GW. In their effort to reveal effects of “Fuzzy Set Theory” on slope mass rating Daftaribesheli et al. (2011) defined very similar boundaries and functions for UCS, RQD and JS. However, they did not consider JC and GW for evaluation of Fuzzy RMR. In this study, boundaries of functions and function types will be based on these three studies with some modifications for the current study area. As an example, membership function types and boundaries for UCS parameter of RMR can be seen in Table 4.2. In this table, linguistic variables to define the intervals, boundary values for each fuzzy set, and types of membership functions can be seen. The membership functions of the other input parameters are given in Table A.1 - Table A.5.

Table 4.2 Membership functions for "Uniaxial Compressive Strength" (The MathWorks, Inc., 2012)

UCS			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Very Small	VVS	Triangular	[0 0 3]
Very Small	VS	Triangular	[-4 3 15]
Small	S	Triangular	[3 15 38]
Medium	M	Triangular	[15 38 75]
High	H	Triangular	[38 75 175]
Very High	VH	Triangular	[75 175 250]
Very Very High	VVH	Trapezoidal	[175 250 300 300]



4.2.3 Fuzzy Inference System

According to Başarır & Saiang (2012)"Fuzzy Inference system" is the task of formulating input fuzzy set to an output fuzzy set using fuzzy logic. Before, it was mentioned that there are many models for this input – output relationship. The most widely used ones are Mamdani and Takagi-Sugeno-Kang (TSK) systems. Due to its capability to handle non-linearity in an effective way, dynamic behavior and widespread use in civil and mining engineering projects, "Mamdani Algorithm" was selected.

Mamdani algorithm contains “If-Then” relations mapping inputs to outputs. These relations are called as “Fuzzy Rules”. Just as membership functions, there are two ways to determine fuzzy rules. The first one is to use huge amounts of data for artificial learning. The second way is to take opinion of experts. Fuzzy rules of this study are generated by benefiting from expert view. RMR79 rating is taken as the basis of rule generation. The subclasses of variables were rated for each possible combination. It can easily be calculated that there are totally 7x5x5x5x5=4375 combinations. Figure 4.1 shows the summary of results for FRMR rule base that is used in this study. According to this graph, 20% of the rules are for RMR values of smaller than 40. Total number of rules for this range is 904. In their study Daftaribesheli et al. (2011) generated 825 rules for whole of the RMR range (between 0 – 100). Also, Jalalifar et al. (2011) stated that they used 125 rules for model A and 375 rules for model B for whole of the range. Compared to these studies, sufficient number of rules were used in this study. Deeper analysis about the performance of fuzzy rules will be made later by comparing the conventional and fuzzy RMR values.

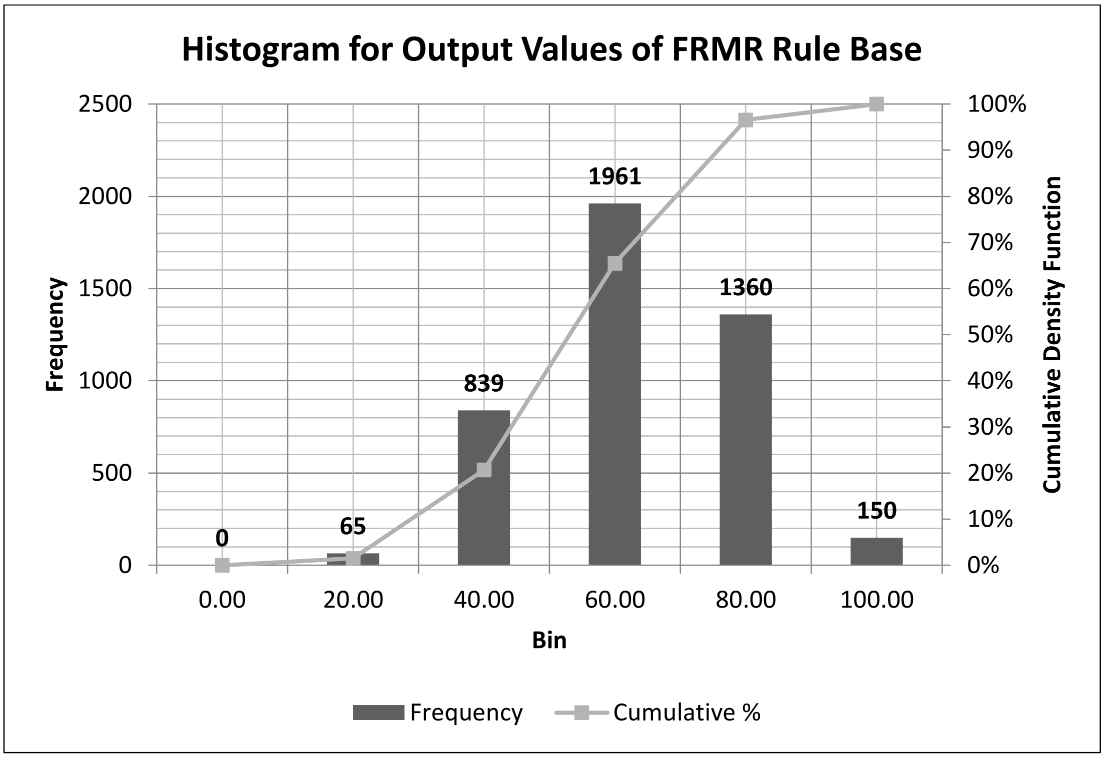


Figure 4.1 Histogram for output values of FRMR rule base

4.2.4 Defuzzification

After evaluating the fuzzy variables, they must be turned into crisp values. To do this, there are many methods such as centroid of area (COA), mean of maximum (MOM) and smallest of maximum (SOM), methods. The most widely used one is centroid of area (COA) method due to its simplicity in calculation. Also, its most remarkable advantage is that defuzzification process includes all the activated membership functions (Daftaribesheli, Ataei, & Sereshki, 2011). In this study, for defuzzification of RMR, centroid of area (COA) method is used.

4.2.5 Results of FRMR Evaluation

Conventional RMR ratings were given in details for Orhaneli and Çan Lignite Mines in Table 4.1. Based on the principles explained in the previous sections FRMR calculated for these two mines and two example evaluations of FRMR for siltstone claystone intercalation in Matlab Fuzzy Toolbox are presented in Figure 4.2 and Figure 4.3 and summary of results can be seen in Table 4.3.

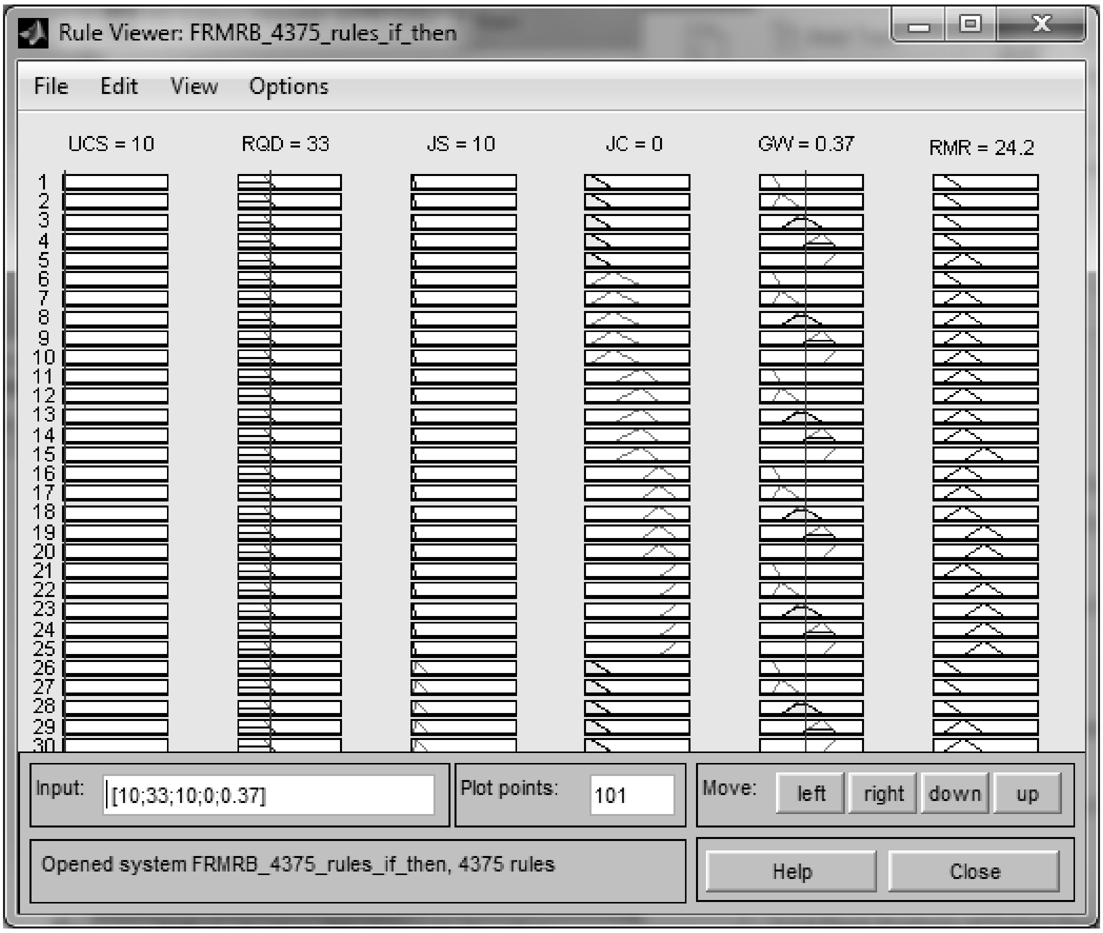


Figure 4.2 Evaluation of FRMR for Orhaneli Lignite Mine (The MathWorks, Inc., 2012)

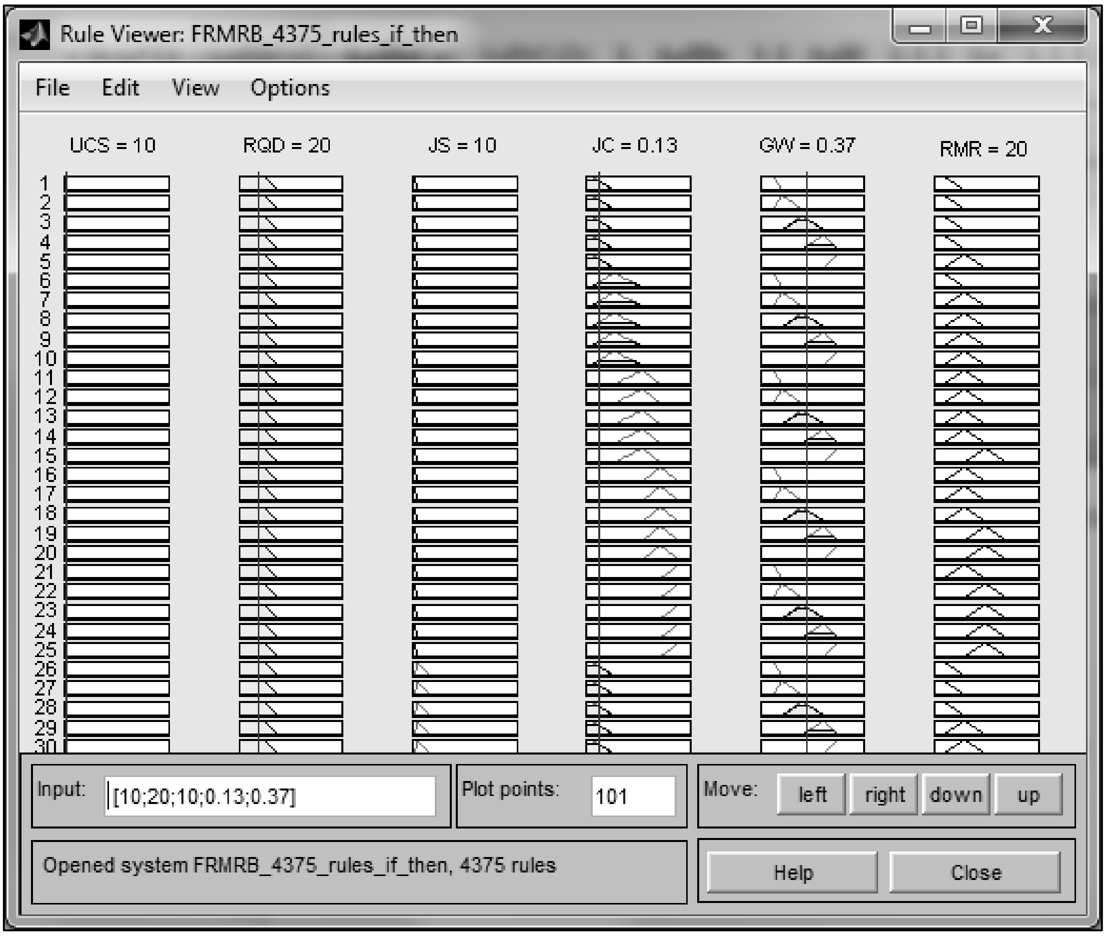


Figure 4.3 Evaluation of FRMR for Çan Lignite Mine (The MathWorks, Inc., 2012)

Table 4.3 CRMR and FRMR results for two mines

Location	Rock Type	CRMR	Rock Class	FRMR	Rock Class	Desc.
TKİ Orhaneli Lignite Mine	Siltstone-claystone intercalation	37	IV	24.2	IV	Poor
TKİ Çan Lignite Mine	Siltstone-claystone intercalation	34	IV	20	V	Very Poor

As it is seen from Table 4.3, there are obviously remarkable decreases in CRMR scores of the rock masses of the two lignite mines. In the first one, the decrease is 12.8 point that is 34.6% of decrease. The second one has a change of 14 points and 41.2%. These low FRMR values seems to be logical because these rock masses belong to lignite bearing formations having dominant stratification and under the effect of tectonism. Hence, these rock masses having dominant bedding and intersected by faults can be defined as weak rock. Also, the rock mass shows nearly soil behavior that is defined as weak rock. In addition, both of the slope cut these rock masses have failed slopes in their history and this situation supports the low prediction of RMR of fuzzy set theory.

4.3 Evaluation of Slope Angles from Slope Performance Chart

Slope performance charts are useful tools to be used in preliminary slope design. As mentioned in section 2.6, many researchers developed similar charts for certain locations and some of them were claimed to be used for global by their authors. In this study, slope performance chart of Bieniawski is used. This chart has three curves for RMR less than 20, close to 30 and close to 50 values (Figure 4.4).

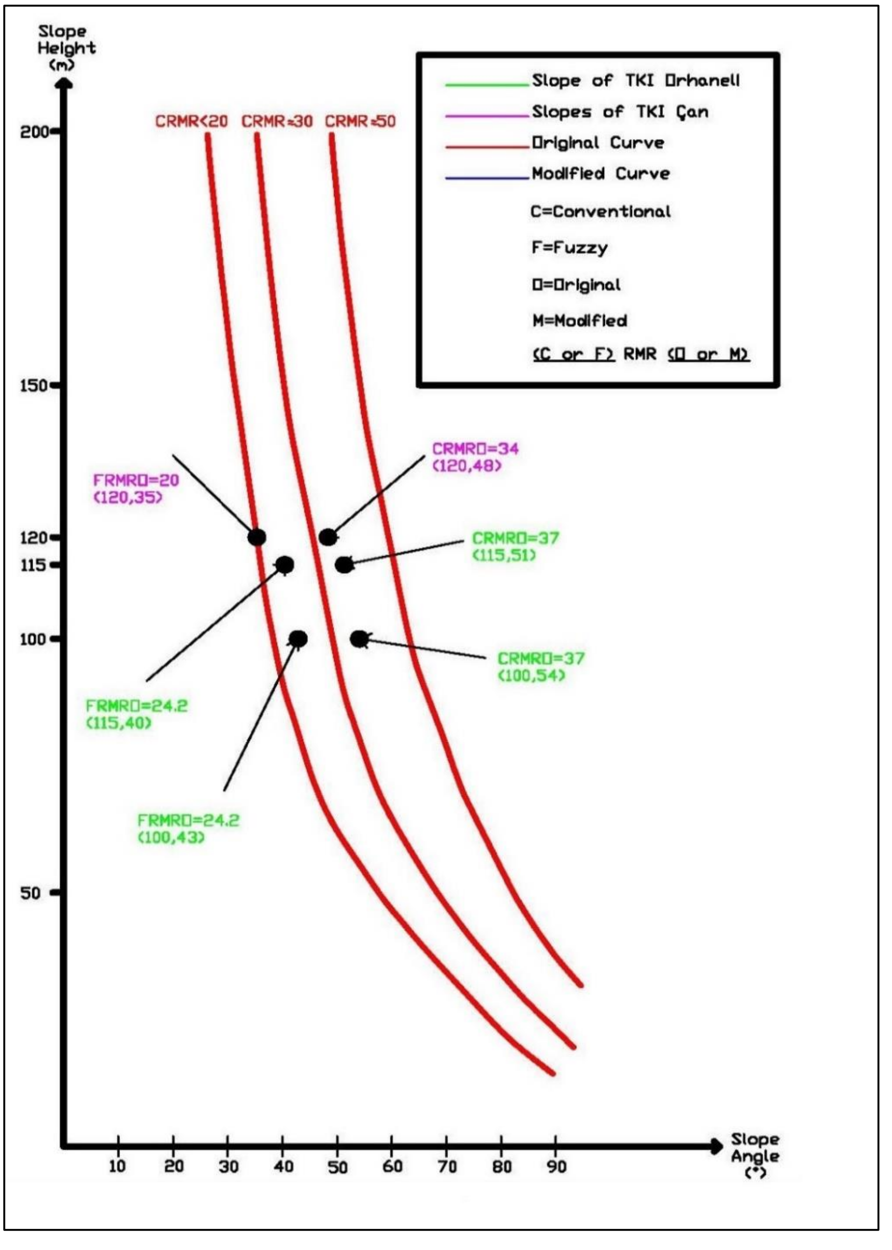


Figure 4.4 Evaluation of preliminary slope angles from Bieniawski's slope performance chart using CRMR and FRMR

RMR ratings of the rock masses were carried out before and they were 37 for Orhaneli and 34 for Çan. Also, slope heights are known to be 100,115 and 120 m in different parts of the mines. Using these input values preliminary safe slope angles were calculated for three different RMR values using the chart in Figure 4.4 (Table 4.4).

Table 4.4 Safe slope angles from Bieniawski's slope performance chart for CRMR, FRMR and numerical method

Location	**Slope Name**	**RMR**	**FRMR**	**Slope Height (m)**	**Safe Slope Angle for Conventional RMR from The Original Chart (°)**	**Safe Slope Angle for Fuzzy RMR from The Original Chart (°)**	**Critical Slope Angle from Analytical Analysis** (Karpuz, et al., 2006) **(°)**
TKİ Orhaneli Lignite Mine	Slope 1	37	24.2	100	54	43	36
	Slope 2	37	24.2	100	54	43	32
	Slope 3	37	24.2	100	54	43	36
	Slope 4	37	24.2	100	54	43	36
	Slope 5	37	24.2	100	54	43	26
	Slope 6	37	24.2	115	51	40	22
	Slope 7	37	24.2	100	54	43	32
	Slope 8	37	24.2	100	54	43	36
	Slope 9	37	24.2	100	54	43	36
	Slope 10	37	24.2	100	54	43	30
TKİ Çan Lignite Mine	Çan 5	34	20	120	48	35	17

At first glance, the estimated slope angles are considerably high for the rock masses present in mines. Thus, evaluation method of RMR obviously requires either a new approach or some modifications. Although the RMR evaluation system is modified by fuzzy system, still performance chart of Bieniawski predicts high values. This may probably be due to nature of rock mass used for the generation of this chart. In construction of this chart, it is highly possible that good or medium quality rock masses had been used. This leads to the necessity to modify the performance chart, also. To obtain more plausible slope angles from the chart, RMR values should be decreased. It was mentioned before that these rock masses are expected to have lower RMR values due to field observations and the reason of this high RMR values is the problem in conventional evaluation system for weak rock conditions. Thus, fuzzy set theory is used in evaluation stage. Using the FRMR values, slope angles were evaluated again and a noticeable decrease in each of the cases can be observed in Table 4.4.In spite of the lowering effect of FRMR, the slope angles are still high by considering the failure in the area and the detailed stability analysis carried out for the slopes above. Therefore, the performance chart obviously needs to be modified for weak rock conditions.

4.4 Determination of Slope Mass Rating (SMR)

In order to predict failure mechanisms of slopes, it was before stated that SMR is used in this study. SMR is a modification of RMR that adds four factors to the RMR basic. As mentioned before, three factors represent geometrical relationships between slope and discontinuities. The last one represents type of excavation. Directional relations of the slopes of TKI Orhaneli and Can Lignite Mines can be seen in Table 3.2 - Table 3.6. Slope directions were already certain; however, slope angles should have been determined. For this purpose, RMR scores and slope performance chart of Bieniawski have been used. Also, for the purpose of validation, failed slopes in the area have been examined and validated using back-analysis of the previous failure and the other slopes were designed analytically using rock mass parameters (c, Φ) obtained from the back analysis of the previous failures. Orientation properties and the SMR table were used in order to determine SMR scores of each slope. For each case, scores of parameters and orientation information for slopes and discontinuities can be seen in Table A.15-Table A.46. Final SMR scores for each slope in variable combinations of CRMR, FRMR and analysis results can be seen in Table A.47-Table A.51.

As an example of SMR evaluation for Slope 6 of Orhaneli Lignite Mine Table 4.5 is presented. In the evaluation table, failure types are represented by 'P' for plane failure, 'T' for toppling failure and 'W' for wedge failure. For each discontinuity set, the evaluation was done. Because two discontinuity sets exist, evaluation for their intersections were also done. Since there are two discontinuity sets wedge analysis was also carried out.

Since SMR is capable of analyzing the possibility of variable failure mechanisms, such as plane, toppling, wedge and circular failures, each of the mechanisms should be rated and compared to each other to find the most probable one. In order to decide the type of failure, SMR contains modifications for each type of failure mechanisms. Rating for plane and toppling failures should be done for each joint set one by one. Wedge failure rating is carried out for the intersection of two discontinuity sets and it is done for each intersection. Hence, an SMR score for each mechanism and each joint set and intersection is obtained. By comparing them with each other, the most probable failure considering the least score is determined from the mechanism with the least score.

Table 4.5 Conventional and Fuzzy SMR ratings of Slope 6 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering FZ3 and slope	P	|αj-αs|	56	0.15	|βj|	52	1.00	|βj-βs|	1	-6	-0.90	0.93	0.95	-56.79	-50.61	0
	T	|αj-αs-180|	236	0.15	1		1.00	|βj+βs|	103	0	0.00	0.14	1.00	-17.99	-2.60	
Considering FZ4 and slope	P	|αj-αs|	75	0.15	|βj|	68	1.00	|βj-βs|	17	0	0.00	0.94	0.95	-27.07	-24.23	
	T	|αj-αs-180|	105	0.15	1		1.00	|βj+βs|	119	-6	-0.90	0.14	1.00	-11.63	-1.68	
Considering the plunge and trend of line of intersection of FZ3 and FZ4 and the slope	W	|αi-αs|	165	0.15	|βi|	35	0.70	|βi-βs|	16	0	0.00	0.95	0.73	-27.02	-18.83	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
FZ3	233	143	52
FZ4	4	274	68
		Trend (αi)	**Plunge (βi)**
FZ3 FZ4 Intersection		34	35
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Failure	289	199	51

4.5 Determination of Fuzzy Slope Mass Rating (FSMR)

4.5.1 General Information about FSMR

In the preliminary design stage for the purpose of predicting stability conditions of slopes, SMR is a practical method. Because it is based on easily obtainable parameters from rock mass, it is practical to use. As being a classification method, it suffers the common problems of classification methods mentioned before. Uncertainty is the main point leading to over or under estimations and "Fuzzy Set Theory" is a tool to overcome these problems.

There are various approaches for the calculation of FSMR. Daftaribesheli et al. (2011) processed all three SMR adjustment factors in a single inference mechanism and summed up the F_4 factor, which cannot be fuzzified (Figure 4.5). Later, Başarır and Saiang (2012) preferred to evaluate each SMR adjustment factors in individual inference mechanisms and summed up the F_4 factor. In this study, approach of Başarır and Saiang (2012) is used.

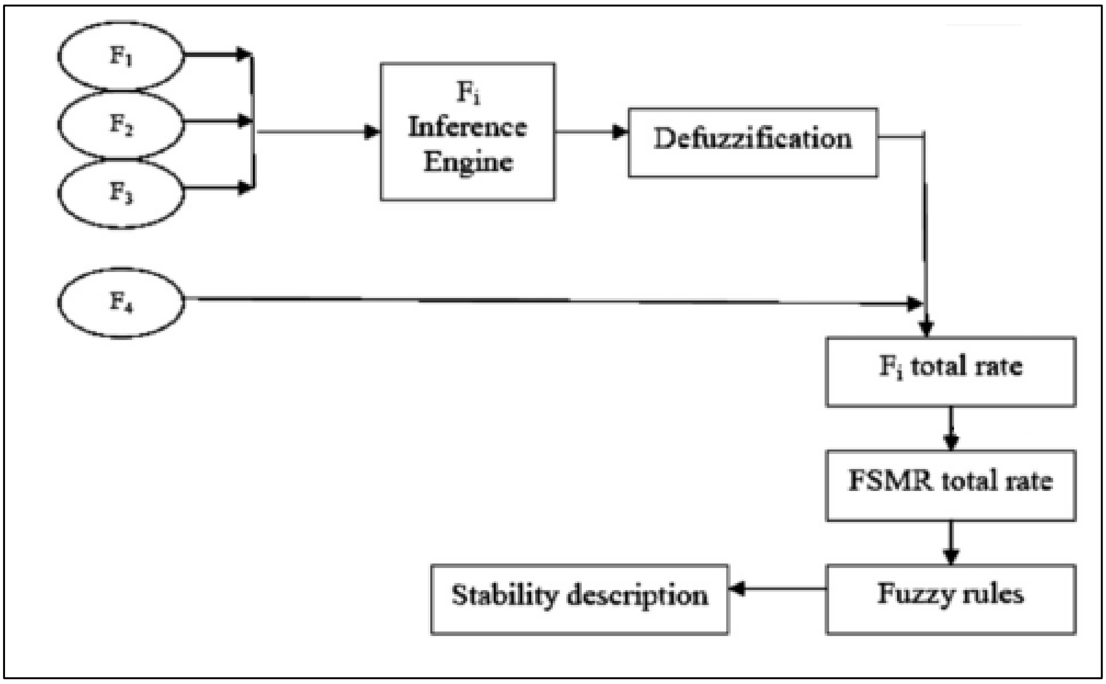


Figure 4.5 Flow chart of SMR calculation of Daftaribesheli et. al. (2011)

To calculate Fuzzy SMR, crisp value of FRMR is summed up with the defuzzified value of F_1, F_2 and F_3 factors and later F_4 factor is added. The equation 8 below represents the FSMR calculation process.

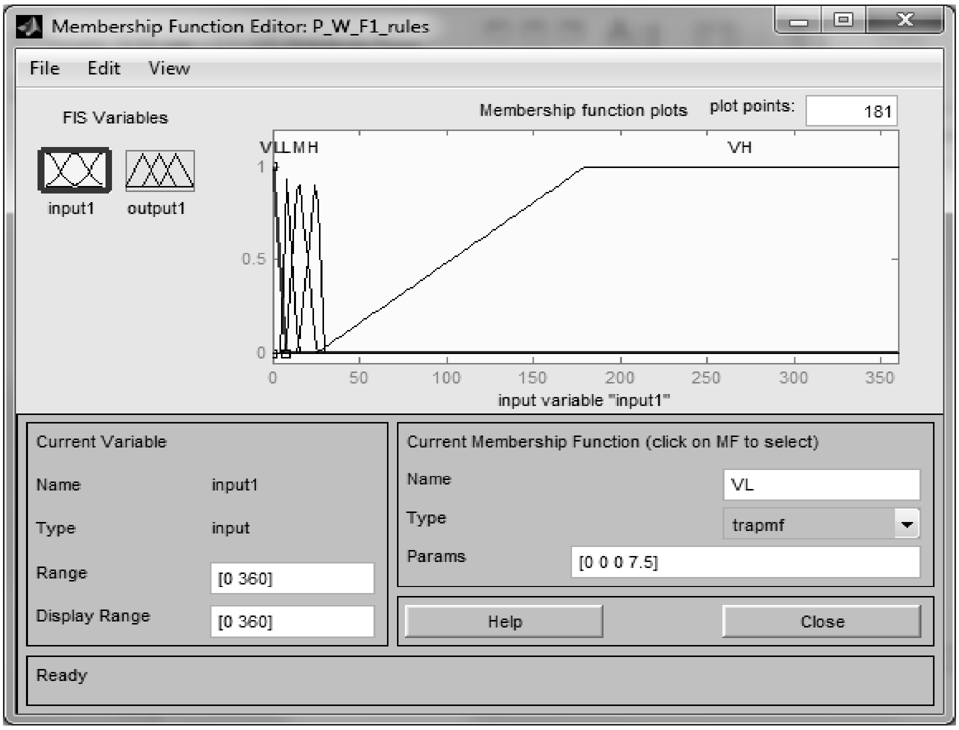
$$FSMR = FRMR + (F_1.F_2.F_3) + F_4 \tag{8}$$

4.5.2 Fuzzification

In fuzzification stage, although there are four parameters of SMR, five inference mechanisms were generated. First of all, inference mechanisms were produced for F_1, F_2, and F_3 parameters. There is no inference mechanism for F_4 parameter because it is a certain variable that points just a single item with the rating and these items do not have middle situations. The reason of five mechanisms for three parameters is that each parameter must be rated for three possible failure mechanisms that are plane, wedge and toppling failures. Plane and wedge failures use the same mechanisms for F_1, F_2 and F_3 parameters; for toppling a different mechanisms was generated for F_1 and F_3. In the case of F2 no mechanisms is required because its value was determined to be 1.0 by Romana. Membership functions and boundaries of these mechanisms in this study for planar and wedge failure can be seen for F_1 parameter in Table 4.6. In this table, linguistic variables to define the intervals, boundary values for each fuzzy set, and types of membership functions can be seen. Rest of the membership functions of SMR can be seen in Table A.6 - Table A.14.

Table 4.6 Membership functions for "F_1"parameter for the case of planar and wedge type failures (The MathWorks, Inc., 2012)

F_1 (Planar and Wedge Type Failures)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Low	VL	Trapezoidal	[0 0 0 7.5]
Low	L	Triangular	[5 7.5 15]
Medium	M	Triangular	[7.5 15 25]
High	H	Triangular	[15 25 30]
Very High	VH	Trapezoidal	[25 180 360 360]



4.5.3 Fuzzy Inference System

Similar to FRMR, in the inference system of FSMR, Mamdani algorithm is used due to the advantages mentioned before. Because Mamdani algorithm makes use of "If – Then Rules", a rule base is required to be established. For five mechanisms of FSMR, there are two dominant states which are five rules case and three rules case. Rules for F_1 and F_2 parameters for the case of planar and wedge failures can be seen in Table 4.7. Fuzzy rules for F_3 parameter in the case of toppling failure are given in Table 4.8.

Table 4.7 Fuzzy rules of "F_1" and "F_2" parameters for the case of planar and wedge type failures and "F_3"parameter for the case of toppling failure

	Rules	
No	**Verbose**	**Indexed**
1	If (input1 is VL) then (output1 is VL) (1)	1, 1 (1) : 1
2	If (input1 is L) then (output1 is L) (1)	2, 2 (1) : 1
3	If (input1 is M) then (output1 is M) (1)	3, 3 (1) : 1
4	If (input1 is H) then (output1 is H) (1)	4, 4 (1) : 1
5	If (input1 is VH) then (output1 is VH) (1)	5, 5 (1) : 1

Table 4.8 Fuzzy rules of "F_3"parameter for the case of toppling failures

	Rules	
No	**Verbose**	**Indexed**
1	If (input1 is L) then (output1 is L) (1)	1, 1 (1) : 1
2	If (input1 is M) then (output1 is M) (1)	2, 2 (1) : 1
3	If (input1 is H) then (output1 is H) (1)	3, 3 (1) : 1

4.5.4 Defuzzification

In order to turn the fuzzy values of parameters back into crisp values, centroid of area (COA), method was used.

4.5.5 Results of FSMR Evaluation

FSMR scores for each of the slopes in Orhaneli and Çan Lignite Mines were evaluated. An example evaluation table in conventional and fuzzy methods for Slope 6 of Orhaneli Lignite Mine can be seen in Table 4.5. and the results can be seen in Table A.47-Table A.51. The result table for Çan Lignite Mine can be seen in Table 4.9 for the slope angle determined from CRMR and slope performance chart. Lowering effect of Fuzzy on scores can be obviously observed in the above mentioned tables. Although detailed analysis of the results will be later given, the early comment about the situation can be its better prediction of failure mechanisms with respect to the conventional SMR and the slope angles evaluated from performance chart using conventional and fuzzy RMR's still result in high values compared to the validation data. Thus, it is obviously a necessity to modify the slope performance chart of Bieniawski in order to reflect the failures occurred in the studied areas.

Table 4.9 Conventional and Fuzzy SMR scores at slopes of Çan Lignite Mine

Performance Chart for Slopes (CRMR = 34, Slope Angle = 46°)												
Slope	**Discontinuity**	**Failure Type**	**Conventional RMR**	**Fuzzy RMR**	**Conventional RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Conventional RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**
Çan 5	Weak Layer	P	34	20	34.00	**IVa**	33.76	**IVa**	20.00	**Va**	19.76	**Va**
Çan 5	Weak Layer	T	34	20	34.00	**IVa**	31.11	**IVa**	20.00	**Va**	17.11	**Va**

CHAPTER 5

MODIFICATION OF BIENIAWSKI'S SLOPE PERFORMANCE CHART

In preliminary design of slopes, use of performance chart is a practical and useful method in the way of detailed stability analysis. In spite of its advantages, performance chart is not a tool to be used for final slope design. It is just an initial step that needs to be corrected with analytical analyses. Throughout this study, for determination of slope angles, slope performance chart of Bieniawski is taken as basis.

Various slope performance charts have been prepared by many authors. They were created either from geotechnical data of different rock types of different sites or a single site. Ones created from single site data make these charts represent local conditions. Although the other types seem to be more global, they cannot be claimed to be the absolute solution for global problems. For different rock conditions, performance charts may be misleading. The case in this study is a good example to illustrate this situation. Performance chart of Bieniawski was created from rocks of different properties. It mostly represents medium to hard rock conditions. However, in the case of this study, the slopes will be cut in weak rock conditions and the original chart with conventional RMR values resulted in extremely high slope angles. Before, it has been proven by real failure data that the relatively high RMR values from conventional evaluation (see Table 4.1) does not reflect the real conditions; therefore, RMR evaluation system requires to be modified for weak rock units. “Fuzzy Set Theory” is used and better represent the weak rock condition and significant decrease in scores were obtained (see Table 4.4). By comparing with the site conditions, the FRMR values seems to be more close to the real case, so it can be said that some of the problems in the evaluation of RMR has been overcome. On the other side, there is still another problem that is determining representative slope angles. In spite of the dramatic decreases, slope angles are still high when the evaluation is done with FRMR scores. Additionally, the suggested safe slope angles of the chart was validated by the data obtained from back analysis of two large slope slides occurred on these sites. The process of validation will be later given in detail. To modify the Bieniawski’s slope performance chart, slope heights and angles of already failed slopes were used. In the original chart, in order to take place on the safe side FOS was 1.3. In modified case, the slope height and angle at the moment of failure is used and it stands for a FOS of 1. Thus modified chart predicts critical slope angle instead of safe slope angle which is the case of the original chart. In the modified chart, FOS of 1 is used. Normally, increase in slope angle results in decrease of FOS. In this modification, the FOS of curves drops from 1.3 to 1 and predicted slope angles also drop. It is important to stress up that slope height and angle found from the graph represents the critical heights and angles. In other word, they are estimated considering FOS as one.

For the modification of the chart, two types of data has been made use of. The first type is slope height and angle obtained from the real failure cases at Orhaneli Slope 6 and Çan 5 slopes used to analyze other slopes in the area. Later on, slope angle were determined using CRMR and FRMR and the data obtained from back analyses (Figure 5.1 and Figure 5.2). A combined plot was presented in Figure 5.3. The original curves are red and modified curves are in blue color. Compared to the curves of Bieniawski, the same values of RMR takes place closer to the origin of the graph and the trend changes between slope heights of 100m - 120m. Later, slope angles decreasingly increase as the slope heights decrease. For the lower portions of the graph that are for low slope heights, analysis results have been used from the slope design studies of Karpuz et al for Orhaneli (2006) and Çan (2005) Lignite Mines. Obviously, the difference shows itself in the lower portion of the graph that is the slope heights of lower than 100m. The original chart tends to evaluate slope angles that increase in this portion. This behavior may be logical for the medium to hard rock conditions. However, weak rock does not expected to behave this way. This situation is proven by the new curves, which are drawn using the real filed data.

Critical slope angles determined from conventional and fuzzy RMR values using modified slope performance chart presented in Table 5.1. Compared to the slope angles that are given before in Table 4.4, values obtained from modification of the chart seems to be more realistic. Compared to the slope angles found from failures, CRMR still results in higher values. The difference is between 9° - 13°, on the critical side. The slope angles obtained from modified chart is lower than original chart values but they are still high. Obviously it needs an improvement. Slope angles of FRMR are equated to the slope angles where real failure took place. Slope angles obtained using back analysis data are in the same range. The difference is in between 0° - 6°. When it is considered that these angles represent the case of FOS of 1.3 and the modified chart is prepared for the critical slope angle that is of FOS of 1 these differences seem to be tolerable.

Table 5.1 Critical slope angles determined from Bieniawski's modified slope performance chart.

Location	**Zone**	**Slope Height (m)**	**RMR**	**FRMR**	**Critical Slope Angle for CRMR from The Modified Chart (°)**	**Critical Slope Angle for FRMR from The Modified Chart (°)**	**Slope Angle from Analytical Analysis** (Karpuz, et al., 2006) **(°)**
TKİ Orhaneli Lignite Mine	Slope 1	100	37	24.2	41	30	36
	Slope 2	100	37	24.2	41	30	32
	Slope 3	100	37	24.2	41	30	36
	Slope 4	100	37	24.2	41	30	36
	Slope 5	100	37	24.2	41	30	26
	Slope 6	115	37	24.2	34	22	22
	Slope 7	100	37	24.2	41	30	32
	Slope 8	100	37	24.2	41	30	36
	Slope 9	100	37	24.2	41	30	36
	Slope 10	100	37	24.2	41	30	30
TKİ Çan Lignite Mine	Çan 5	120	34	20	30	17	17

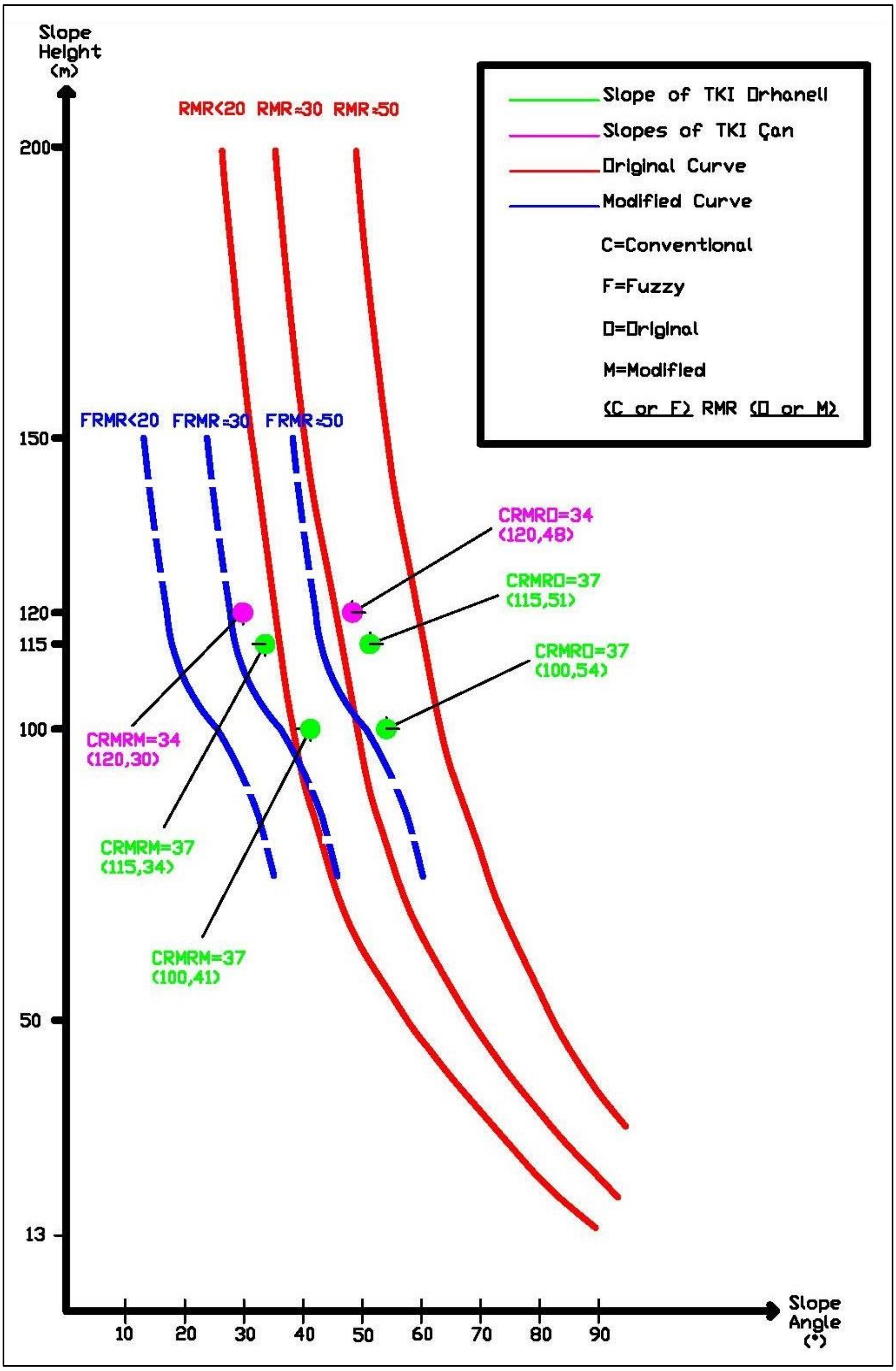


Figure 5.1 Plotting of critical slope angles by using CRMR for studied slopes on the original and modified slope performance charts of Bieniawski

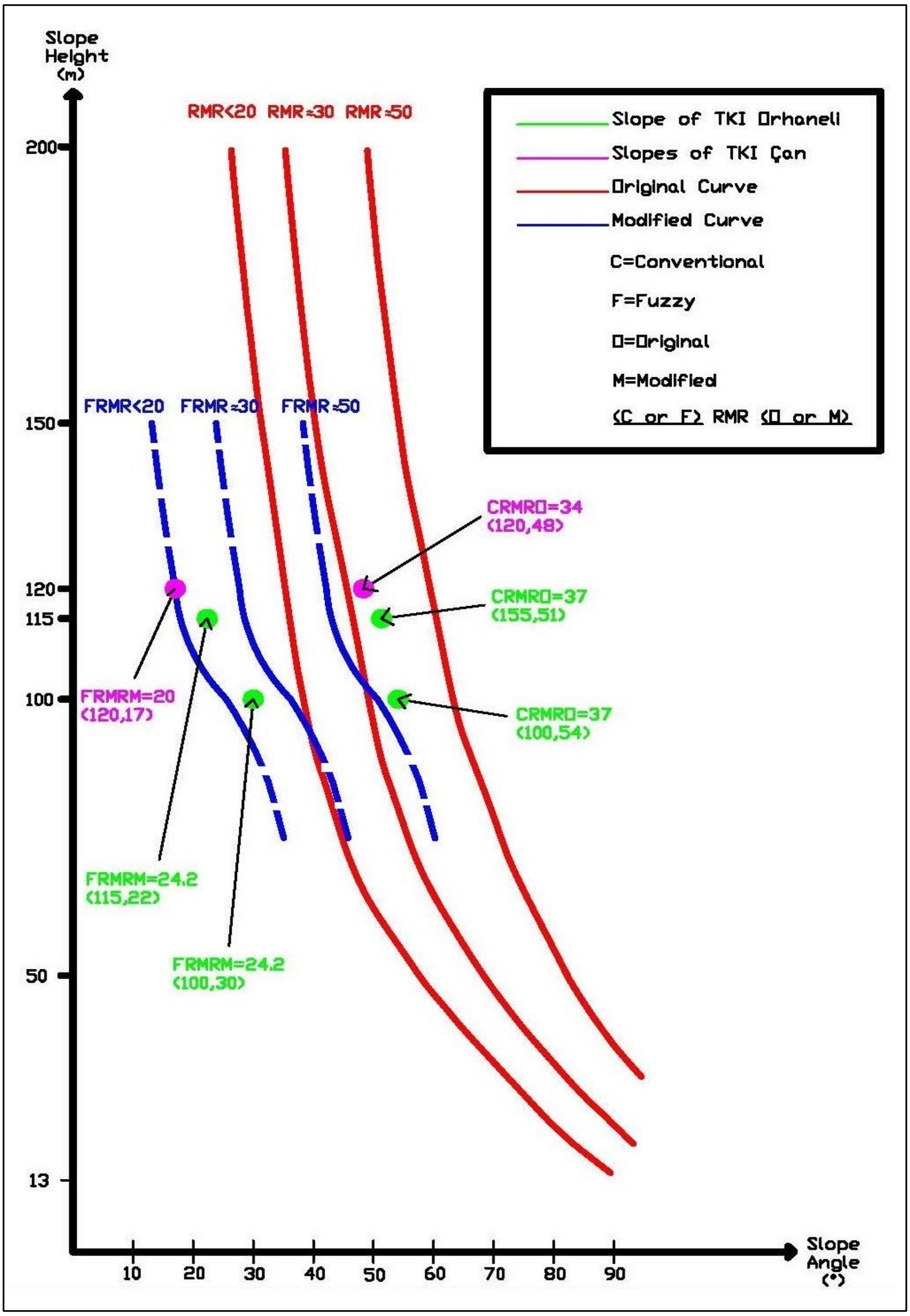


Figure 5.2 Plotting of critical slope angles by using FRMR for studied slopes on the original and modified slope performance charts of Bieniawski

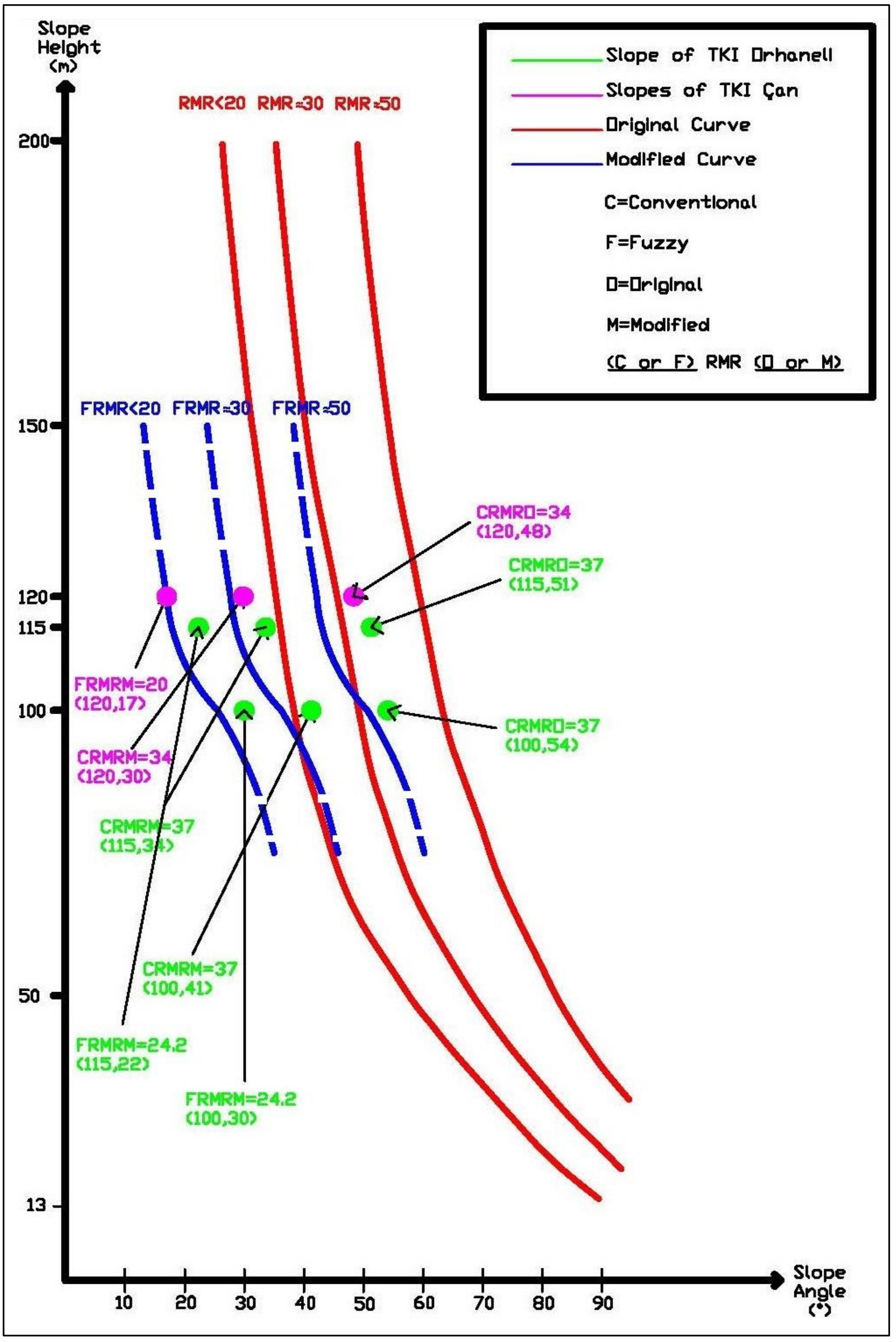


Figure 5.3 Combined plot of determination of critical slope angles from CRMR and FRMR together for studied slopes on the original and modified slope performance charts of Bieniawski

Mathematical equations for the curves of modified slope performance chart were determined by using curve fitting tool box of Matlab 2012a software. According to this,

Equation (9) for modified curve for RMR<20;

$$y = -0.01762x^3 + 1.362x^2 - 36.19x + 428.1 \qquad (9)$$

Equation (10) for modified curve for RMR=30;

$$y = -0.01904x^3 + 2.065x^2 - 75.7x + 1037 \qquad (10)$$

Equation (11) for modified curve for RMR=50;

$$y = -0.01871x^3 + 2.848x^2 - 145.6x + 2597 \qquad (11)$$

where;

x = slope angle

y = slope height

CHAPTER 6

DISCUSSION

The slope angle obtained from the modified slope performance chart for Slope 1 with a CRMR of 37 is 54°. The probable failure types were determined to be plane failure. Although the SMR table recommends wedge and circular failures, they were eliminated due to their impossibility to occur. Wedge failure is not possible because there is only one discontinuity set. Toppling failure cannot be expected because the discontinuity angle is less than slope angle, so the necessary conditions do not exist. In this case all four combinations of RMR and SMR adjustment factors predict the same planar failure type which is the real expected failure type. The safe slope angle for this slope was determined to be 36°. Thus, above this angle the only possible failure types are plane, toppling and circular failures. Toppling failure was eliminated due to the reason mentioned before. Finally, in terms of failure mechanism prediction, there seems to be no apparent difference between the conventional and fuzzy approaches for this slope. However, investigating the SMR scores, fuzzy SMR obviously decreases the rock class from 'IVb' to 'Vb'. Because this is a failing slope, this decrease in rock class and stability condition is plausible. For the slope angle 43° from the modified slope performance chart and FRMR of 24.2, probability of plane failure is eliminated because the discontinuity angle is more than slope angle. The expected failure type is circular failure and it was predicted by CRMR+ FSMR factors and FRMR + FSMR factors combinations. The other combinations cannot even make any failure prediction. Finally, for the slope angle of 36° found from analytical analysis, the plane and toppling failures were eliminated again. The only possible failure type is circular failure. Again, the CRMR+ FSMR factors and FRMR + FSMR factors combinations predict the same and plausible failure mechanism. In Slope 7, similar situations can be seen.

In the case of Slope 2, there are two discontinuity sets, so probability of wedge failure comes up. For a CRMR of 37 the slope angle was found to be 54°. All four combinations predict plane failure and eliminate wedge failure probability which seems problematic. The expected failure type from is wedge failure from analytical analysis. For an FRMR of 24.2 the slope angle was found to be 43°. CRMR+ FSMR factors and FRMR + FSMR factors combinations predict wedge failure which is the expected result. From the stability analysis, a slope angle of 32° was determined and the predicted failure mechanism is wedge for all four combinations. Investigating the numerical values of SMR, CRMR+ FSMR factors and FRMR + FSMR factors combinations shows their sensibility of geometry. The other combinations give the similar or close result for each failure type investigation. The slope 10 has a similar behavior in terms of failure prediction systems from SMR for conventional and fuzzy approaches.

Slope 3 has a slope angle of 54° for a CRMR of 37. Circular failure was expected in each combination, which seems to be the only possible mechanism. The plane failure is impossible because dip of discontinuity is greater than the slope angle. For an FRMR of 24.2 the slope angle was found to be 43°. Expected failure types are circular, again. The analysis results in a slope angle of 36° and it results in an expected failure type of circular. Investigating the numerical scores of RMR, sharp change in slope class can be seen. Similar stability situations and conventional fuzzy RMR and SMR relations can be observed for Slopes 4, 5, 8 and 9.

Slope 6 was before analyzed; however, here, it will be investigated for the purpose of validation. It was failed with a CRMR of 37 and a slope angle of 24°. For the last case that was calculated with failure data, four of the combinations predict wedge failure, which was the real occurred mechanism. However, CRMR+ FSMR factors and FRMR + FSMR factors combinations predict the wedge failure more neatly. In the case of slope angle from FRMR of 24.2, all the combinations predict the wedge failure. However, the first case, where the slope angle was determined to be 51° from the chart, the predicted failure mechanisms is of circular type and CRMR+ CSMR factors and FRMR + CSMR factors combinations could not even predict any possible failures.

To summarize, results of this study showed that FRMR makes better predictions for weak rock conditions. Also, FSMR resulted in better predictions of stability conditions and failure mechanisms compared to the conventional methods. Modified slope performance chart predicts slope angles that are appropriate to for the preliminary stage of stability analysis.

Similar situations are also the case for Çan 5 slope. Here, fuzzy logic helps to decrease slope class from 'IVa' to 'Va'. This slope failed in planar mechanism. By looking at SMR scores it can be seen that the predicted mechanism changes from planar to big planar failure, which means that the mechanism is predicted better. In the first case wedge failure would not have been predicted by FSMR. Here, it can be concluded that there is a problem in wedge failure cases. This is also noted by Daftaribesheli et al. (2011).

Commonly in most of the cases SMR calculated from FRMR and conventional adjustment factors does not show considerable change when compared to the cases of different slope angle. It is usually slightly lower in the slope angle from CRMR cases. This situation makes this combination useless. When fuzzy adjustment factors are taken into consideration, noticeable changes occurred. This obviously shows the positive effect of fuzzy logic on prediction mechanism.

In every case, it is seen that fuzzy scores are less than conventional scores. This is logical if the weak rock conditions are considered. Also, it can be concluded that failure mechanism predictions are mostly trustable for plane and circular failure cases. However, wedge failure prediction is problematic as reported by other authors, before. The trustable predicted parameters are slope class, stability condition and failure probability.

To conclude, fuzzy system was observed to be predicting better result for SMR scores. By this way, failure mechanisms and stability conditions of slopes are possible to be predicted more accurately for the scale of preliminary analysis.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This study presents the result of the preliminary slope design in weak rock for lignite mines using slope performance chart and slope mass rating by applying fuzzy logic and expert experience in order to overcome some of the common problems of classification systems to obtain better scores. For this purpose, two lignite mines, which are TKİ Orhaneli and Çan Mines of Turkey, were selected. Two failure cases in these mines were back analyzed to determine mechanical parameters of rock masses. In order to determine safe slope angles considering rock mass failure for being an input parameter of SMR, slope performance chart of Bieniawski was used. Soon, it was realized that this chart better represents the classification of good quality rock masses and it needs modification. By using failure data, the chart has been modified. In addition, to be able to use this chart more efficiently, RMR evaluation system was enhanced by making use of fuzzy logic. Finally, the other failure mechanisms like plane, toppling and wedge failures were examined by slope mass rating (SMR) method. It was realized that slope mass quality scores were high for the cases in this study. This problem was also due to the common problems of classification systems. By making a brief investigation, results of these analyses were decided to be directly used in this study. Because safe slope angles were known for all the studied slopes from the previous studies made on these sites that were mentioned before, they were only compared with the results obtained from SMR predictions.

The main purpose of this study was to enhance and modify the existing methods of preliminary slope design to be more convenient for weak rock conditions in lignite mines. The following main conclusions are drawn.

1. As it is known, conventional RMR is problematic. It may sometimes yield same scores for rock masses of different properties. The fuzzy approach overcome some of these problems suggesting more realistic values based on back analysis data.

2. Although slope performance chart is a practical tool, the one of Bieniawski’s cannot be used for weak rock conditions in lignite mines; its utilization results in dramatically high slope angles. The chart must have been modified. It is done by making use of actual failure data and its usefulness was proven for weak rock conditions.

3. Bieniawski’s slope performance chart dominantly better represents the medium to hard rock. It is modified for the weak rock properties. Modified chart results in better slope angle predictions than conventional chart.

4. Fuzzified Slope mass rating (FSMR) suggested by Romana to predict corresponding safe slope angles and type of failures result in better predictions for weak rock properties.

5. The modified version of slope charts and fuzzified forms of RMR and SMR systems were applied to 11 different slopes present in Orhaneli and Çan Mines and their stabilities were analyzed.

6. Negatively produced SMR scores were not overcome in the fuzzified SMR either. Hence, the approach which considers the smaller score for failure type adjustment was utilized to predict the final failure mechanism

According to the mentioned conclusions, following items were recommended.

1. Use of experience enhances empirical scoring systems; however, they cannot said to be globally correct because the knowledge database presents the conditions of a limited area and needs to be updated for different site conditions.

2. Methods in this study can only be used for the preliminary design of slopes in weak rock conditions for lignite mines. These preliminary analysis methods are useful to get an idea about the situation in the site for the very beginning of any design job. They always need to be corrected by detailed analytical analyses.

3. Fuzzy logic, basically used in this study is a type of expert system and hence these systems depends on the experience on any site. When site conditions are noticeably different, fuzzy system should be updated to reflect the site conditions.

4. The developed slope performance charts are applicable till 120 m high slopes; however, deeper slopes need special attention.

5. Slope performance chart is based on case histories and this makes it a useful tool to predict rock mass failures. However, in the existence of structural defect, it needs an auxiliary tool to assess other failure mechanisms. SMR was determined to be a reliable one for this purpose.

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APPENDIX A

TABLES

Table A.1 Membership functions for “Rock Quality Designation” (The MathWorks, Inc., 2012)

RQD			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Weak	VW	Trapezoidal	[0 0 25 38]
Weak	W	Triangular	[25 38 62]
Medium	M	Triangular	[38 62 82]
Strong	S	Triangular	[62 82 95]
Very Strong	VS	Trapezoidal	[82 95 100 100]

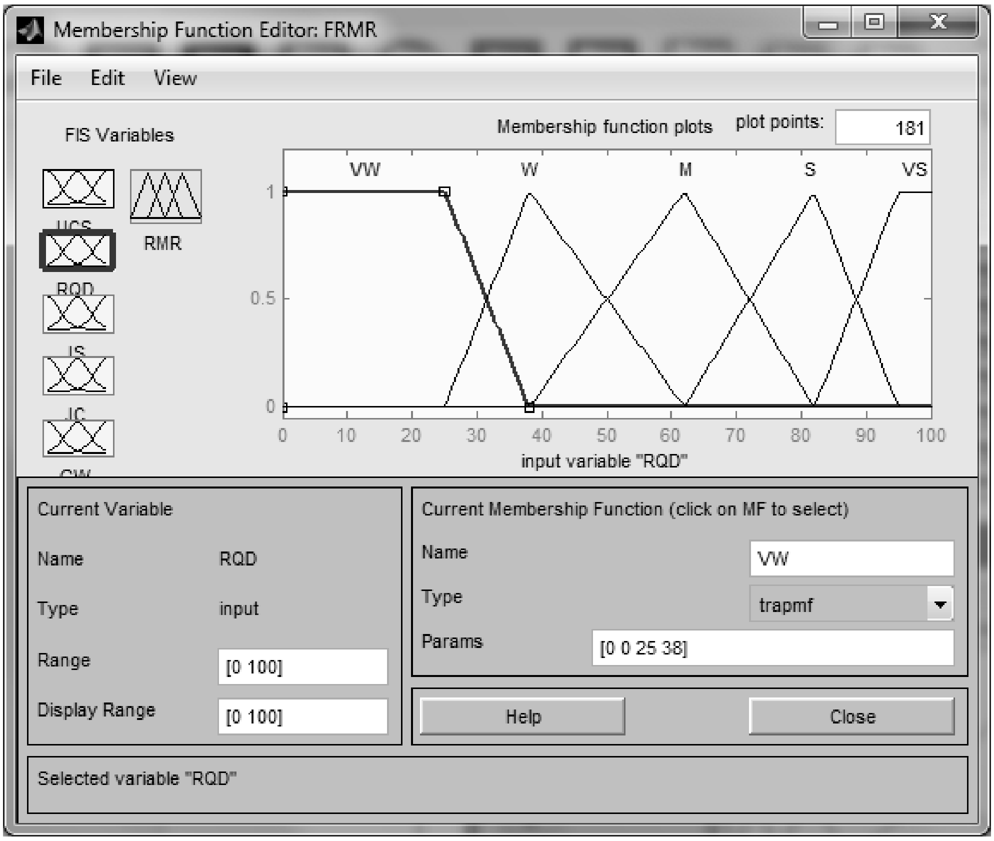

Table A.2 Membership functions for “Joint Spacing” (The MathWorks, Inc., 2012)

JS			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Close	VC	Trapezoidal	[0 0 57 130]
Close	C	Triangular	[52 130 404]
Medium	M	Triangular	[130 404 1300]
Wide	W	Triangular	[404 1300 2000]
Very Wide	VW	Trapezoidal	[1300 2000 2500 2500]

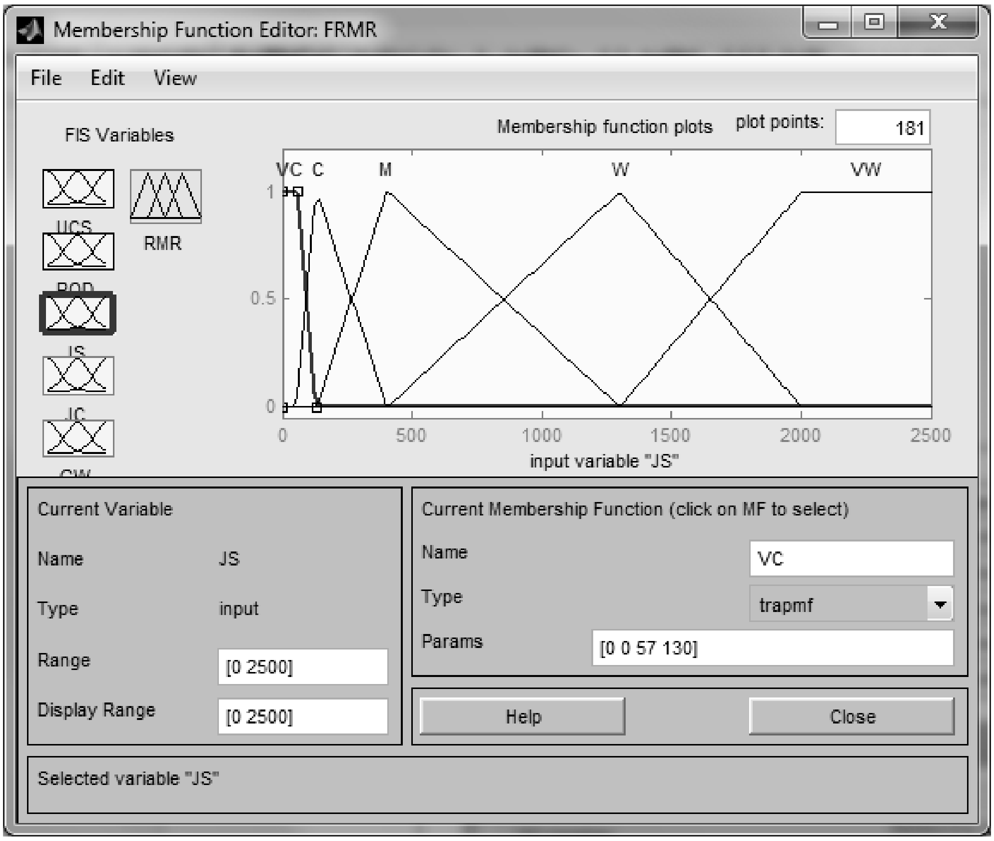

Table A.3 Membership functions for “Joint Condition” (The MathWorks, Inc., 2012)

JC			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Soft	VS	Trapezoidal	[0 0 0.05 0.28]
Soft	S	Triangular	[0.05 0.28 0.55]
Medium	M	Triangular	[0.28 0.55 0.72]
Rough	R	Triangular	[0.55 0.72 0.9]
Very Rough	VR	Trapezoidal	[0.72 0.9 1 1]

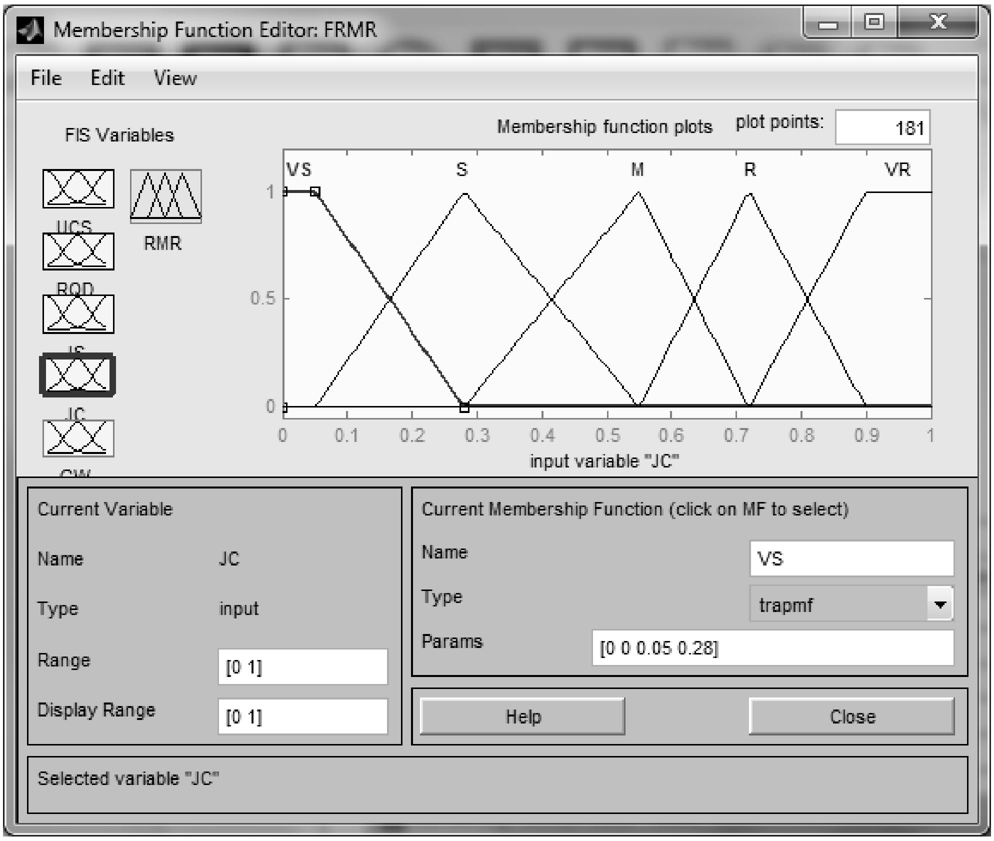

Table A.4 Membership functions for "Groundwater" (The MathWorks, Inc., 2012)

GW			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Flowing	F	Trapezoidal	[0 0 0.1 0.17]
Dripping	DR	Triangular	[0.1 0.17 0.33]
Wet	W	Triangular	[0.171 0.331 0.501]
Damp	DA	Triangular	[0.33 0.5 0.6]
Completely Dry	CD	Trapezoidal	[0.5 0.6 0.8 0.8]

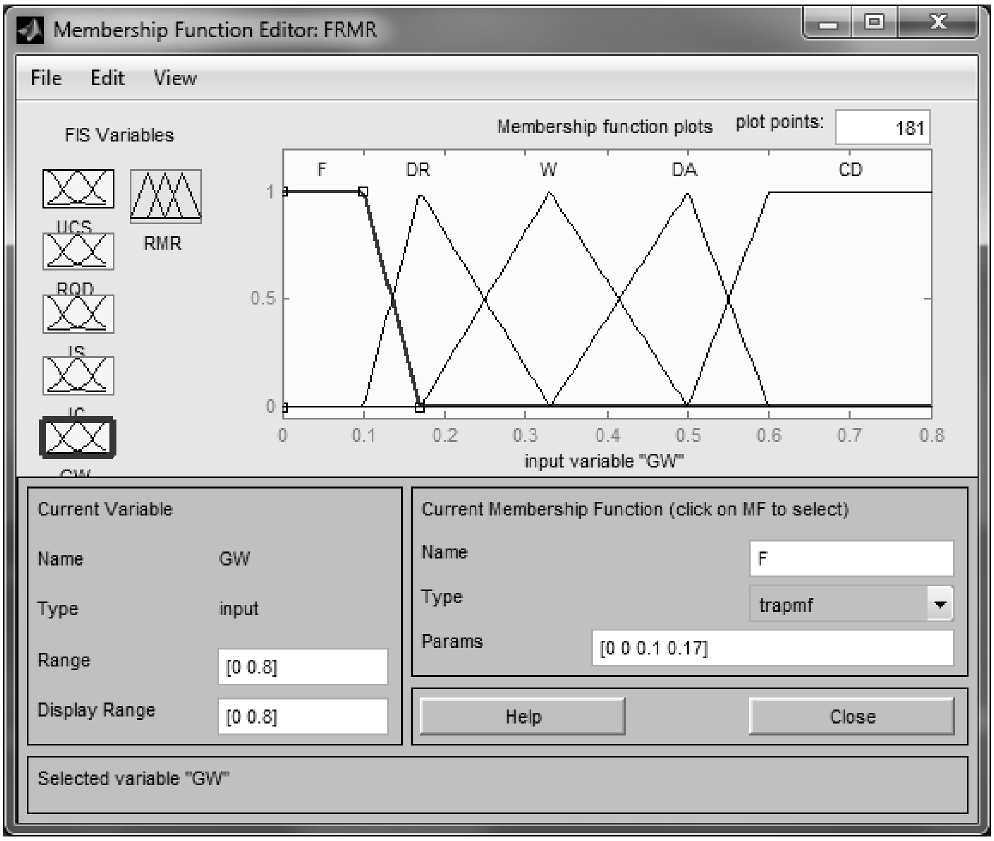

Table A.5 Membership functions for "Rock Mass Rating" (The MathWorks, Inc., 2012)

RMR			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Weak	VW	Trapezoidal	[0 0 10 30]
Weak	W	Triangular	[10 30 50]
Medium	M	Triangular	[30 50 70]
Strong	S	Triangular	[50 70 90]
Very Strong	VS	Trapezoidal	[70 90 100 100]

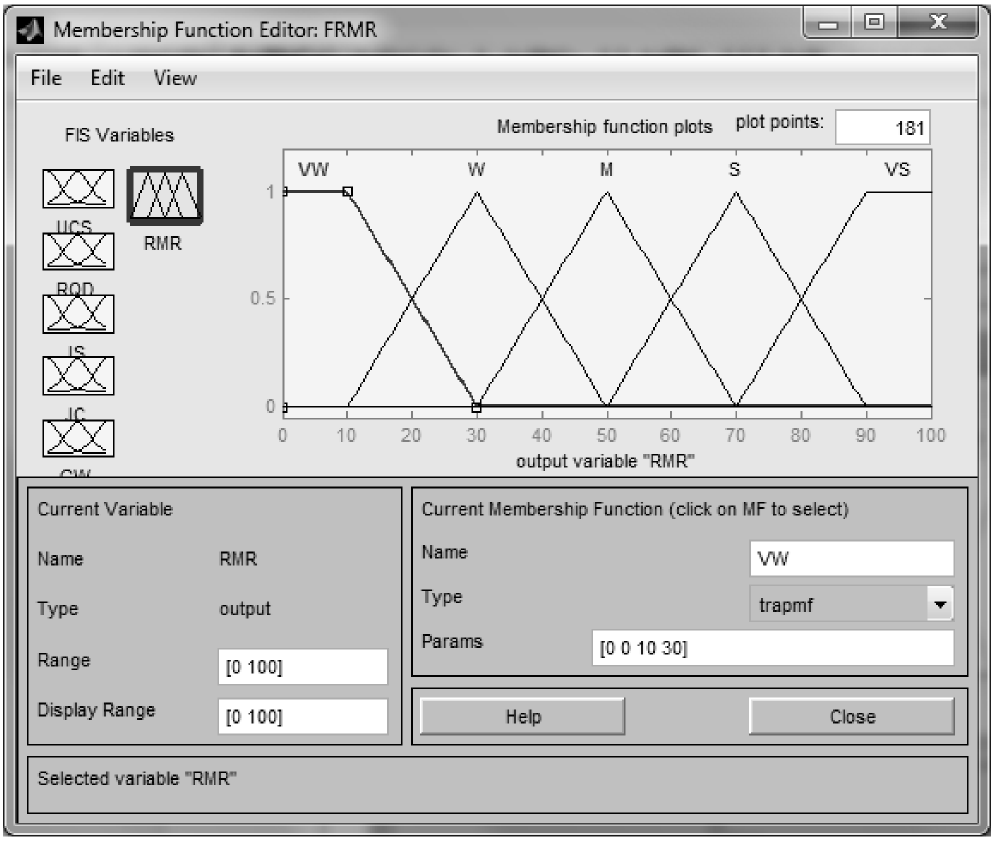

Table A.6 Membership functions for output of "F_1"parameter for the case of planar and wedge type failures (The MathWorks, Inc., 2012)

Output of F_1 (Planar and Wedge Type Failures)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Low	VL	Trapezoidal	[0 0 0.15 0.4]
Low	L	Triangular	[0.15 0.4 0.7]
Medium	M	Triangular	[0.4 0.7 0.85]
High	H	Triangular	[0.7 0.85 1]
Very High	VH	Trapezoidal	[0.85 1 1 1]

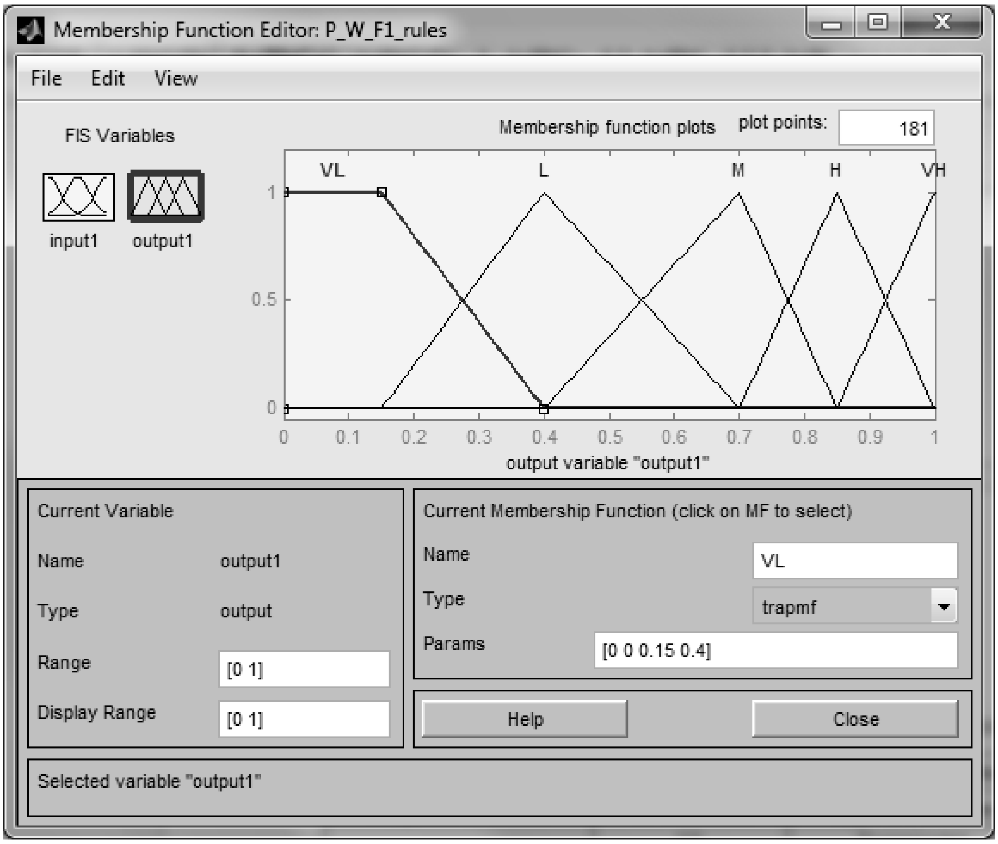

Table A.7 Membership functions for "F_1" parameter for the case of toppling failure (The MathWorks, Inc., 2012)

F_1 (Toppling Failure)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Low	VL	Trapezoidal	[0 0 5 7.5]
Low	L	Triangular	[5 7.5 15]
Medium	M	Triangular	[7.5 15 25]
High	H	Triangular	[15 25 30]
Very High	VH	Trapezoidal	[25 90 540 540]

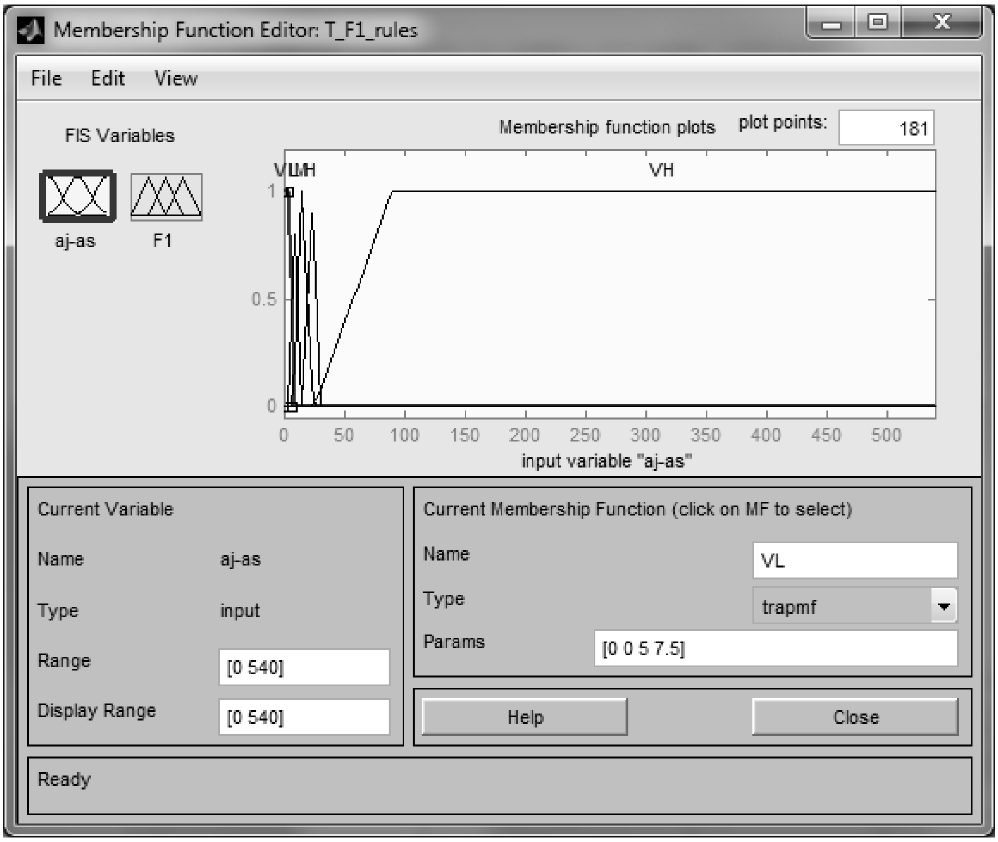

Table A.8 Membership functions for output of "F$_1$" parameter for the case of toppling failure (The MathWorks, Inc., 2012)

Output of F$_1$ (Toppling Failure)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Low	VL	Trapezoidal	[0 0 0.15 0.4]
Low	L	Triangular	[0.15 0.4 0.7]
Medium	M	Triangular	[0.4 0.7 0.85]
High	H	Triangular	[0.7 0.85 1]
Very High	VH	Trapezoidal	[0.85 1 1 1]

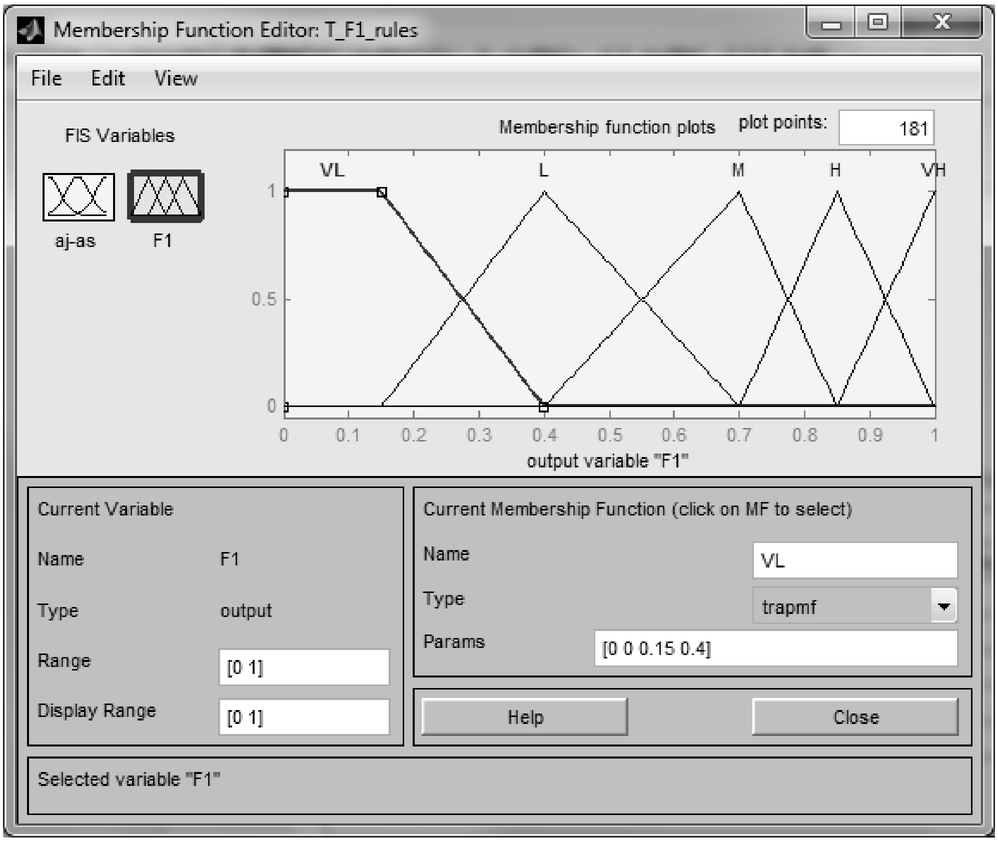

Table A.9 Membership functions for “F_2” parameter for the case of planar and wedge type failures (The MathWorks, Inc., 2012)

F_2 (Planar and Wedge Type Failures)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Low	VL	Trapezoidal	[0 0 20 25]
Low	L	Triangular	[20 25 32]
Medium	M	Triangular	[25 32 37]
High	H	Triangular	[32 37 45]
Very High	VH	Trapezoidal	[37 45 90 90]

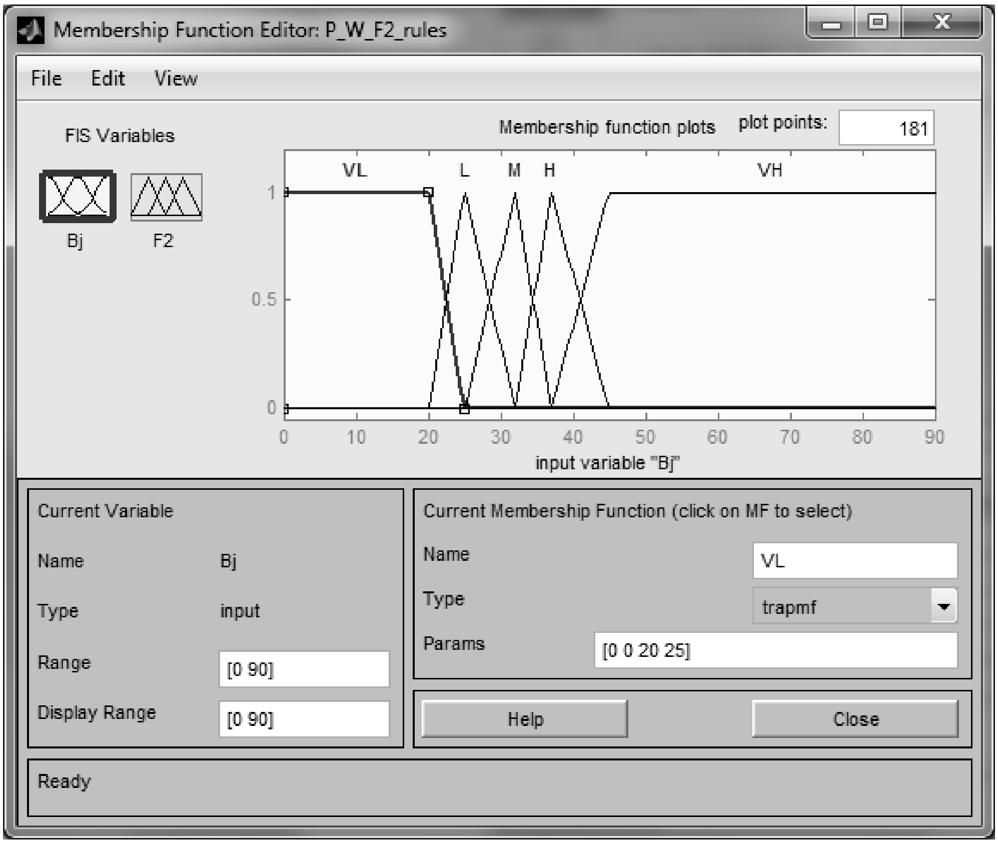

Table A.10 Membership functions for output of "F_2" parameter for the case of planar and wedge type failures (The MathWorks, Inc., 2012)

Output of F_2 (Planar and Wedge Type Failures)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Low	VL	Trapezoidal	[0 0 0.15 0.4]
Low	L	Triangular	[0.15 0.4 0.7]
Medium	M	Triangular	[0.4 0.7 0.85]
High	H	Triangular	[0.7 0.85 1]
Very High	VH	Trapezoidal	[0.85 1 1 1]

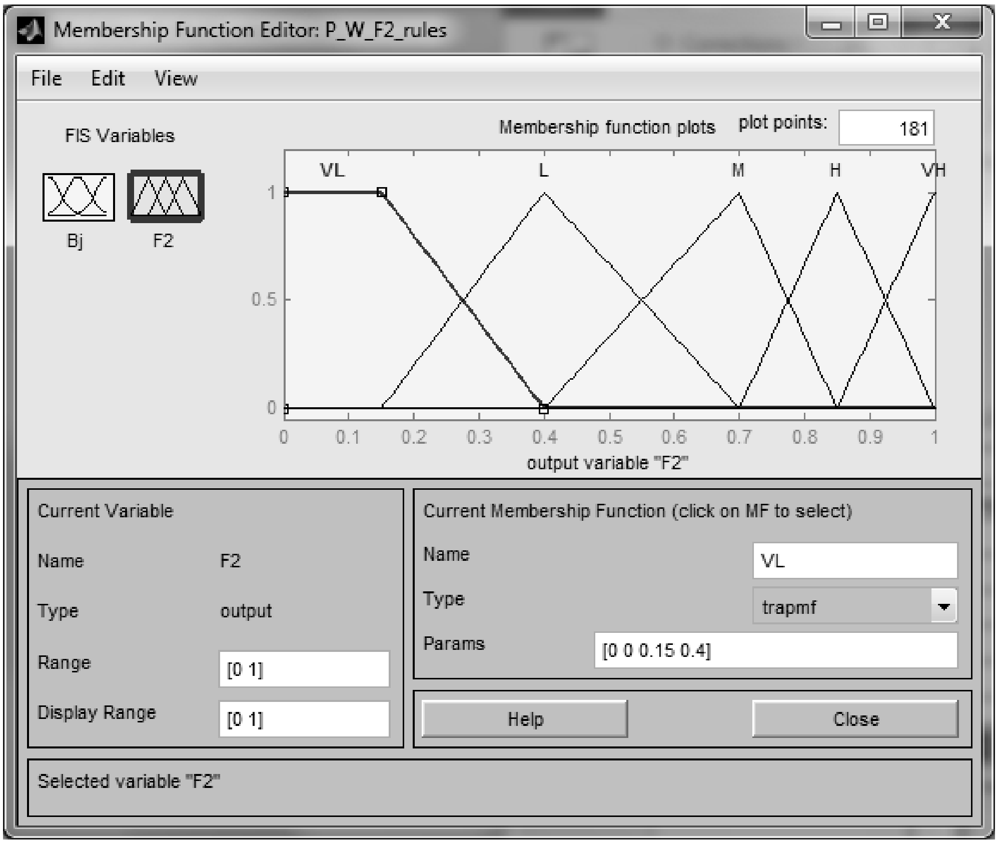

Table A.11 Membership functions for “F_3” parameter for the case of planar and wedge type failures (The MathWorks, Inc., 2012)

F_3 (Planar and Wedge Type Failures)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Low	VL	Trapezoidal	[0 0 0 7.5]
Low	L	Triangular	[5 7.5 15]
Medium	M	Triangular	[10 15 25]
High	H	Triangular	[20 25 45]
Very High	VH	Trapezoidal	[40 45 90 90]

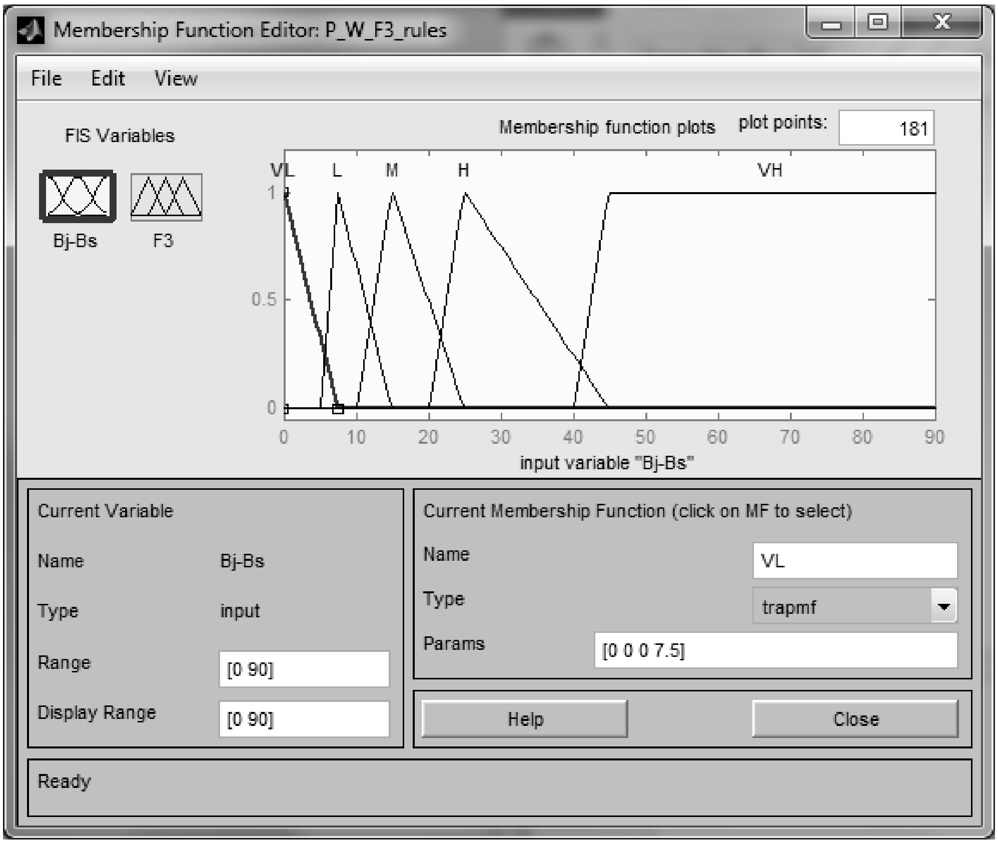

Table A.12 Membership functions for output of "F_3" parameter for the case of planar and wedge type failures (The MathWorks, Inc., 2012)

Output of F_3 (Planar and Wedge Type Failures)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Very Low	VL	Trapezoidal	[-60 -60 -60 -50]
Low	L	Triangular	[-60 -50 -25]
Medium	M	Triangular	[-50 -25 -6]
High	H	Triangular	[-25 -6 0]
Very High	VH	Trapezoidal	[-6 0 0 0]

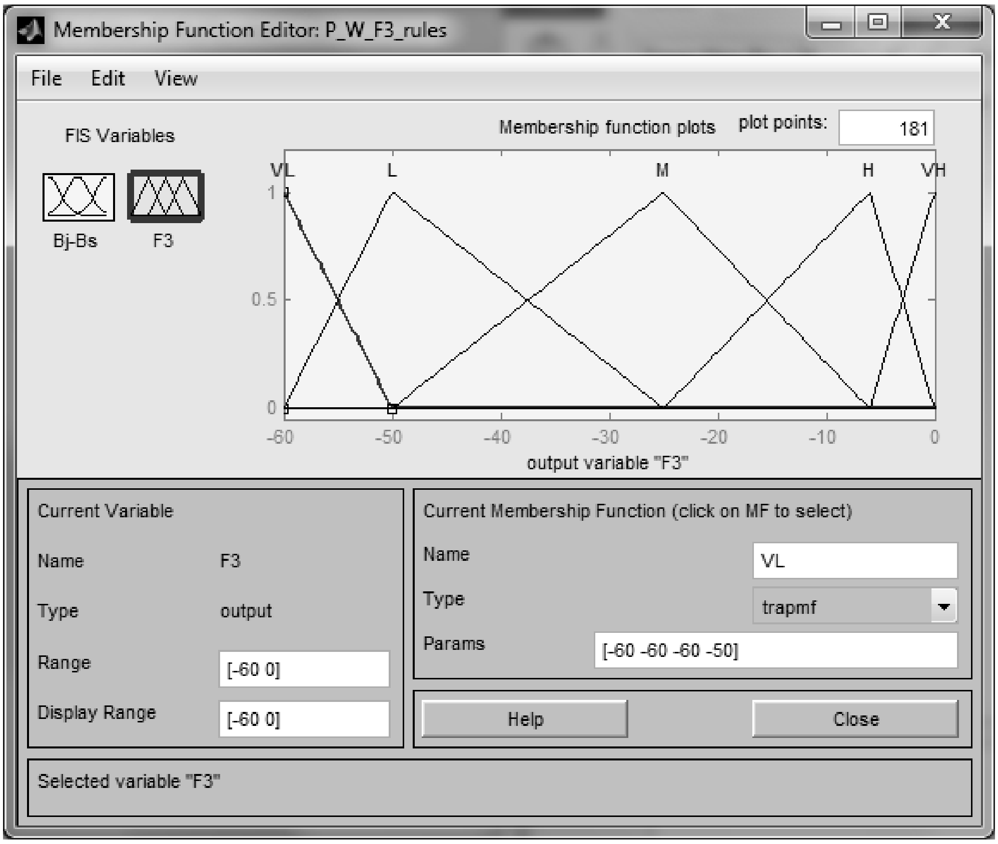

Table A.13 Membership functions for “F_3” parameter for the case of toppling failure (The MathWorks, Inc., 2012)

F_3 (Toppling Failure)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Low	L	Trapezoidal	[0 0 50 110]
Medium	M	Triangular	[105 115 125]
High	H	Trapezoidal	[120 150 180 180]

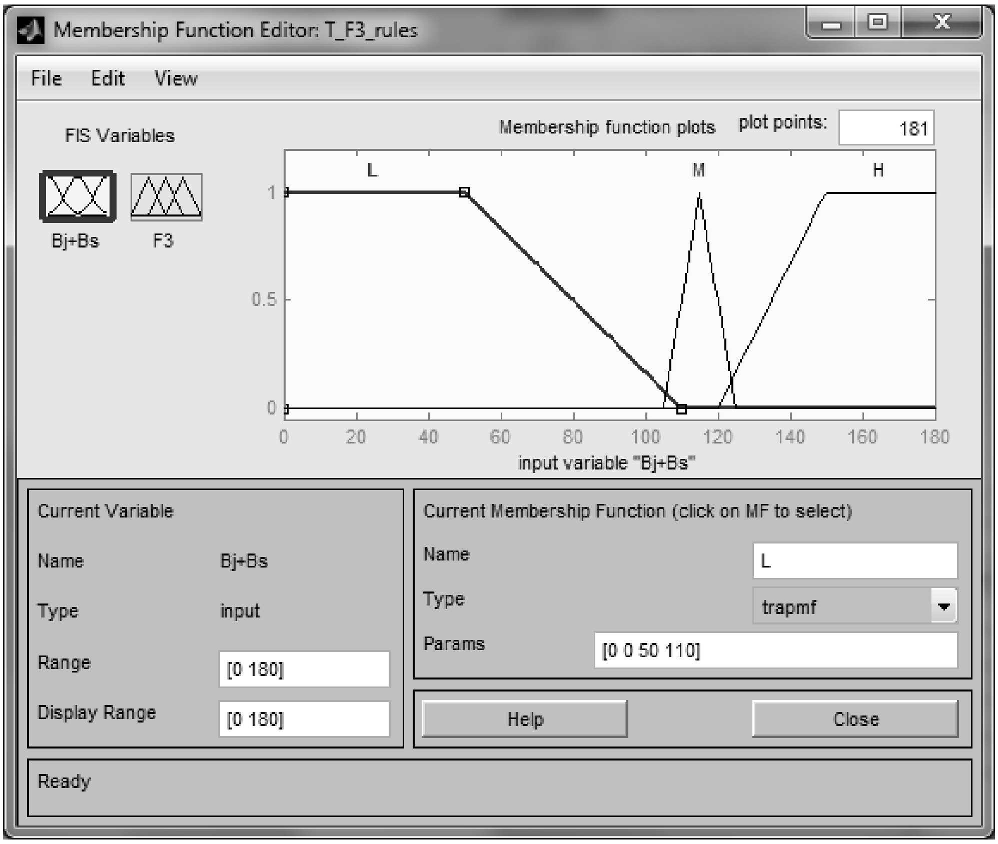

Table A.14 Membership functions for output of "F_3" parameter for the case of toppling failure (The MathWorks, Inc., 2012)

Output of F_3 (Toppling Failure)			
Linguistic Variable	**Abbreviation**	**Type of Function**	**Boundaries**
Low	L	Trapezoidal	[-25 -25 -10]
Medium	M	Triangular	[-20 -12 -3]
High	H	Trapezoidal	[-10 0 0]

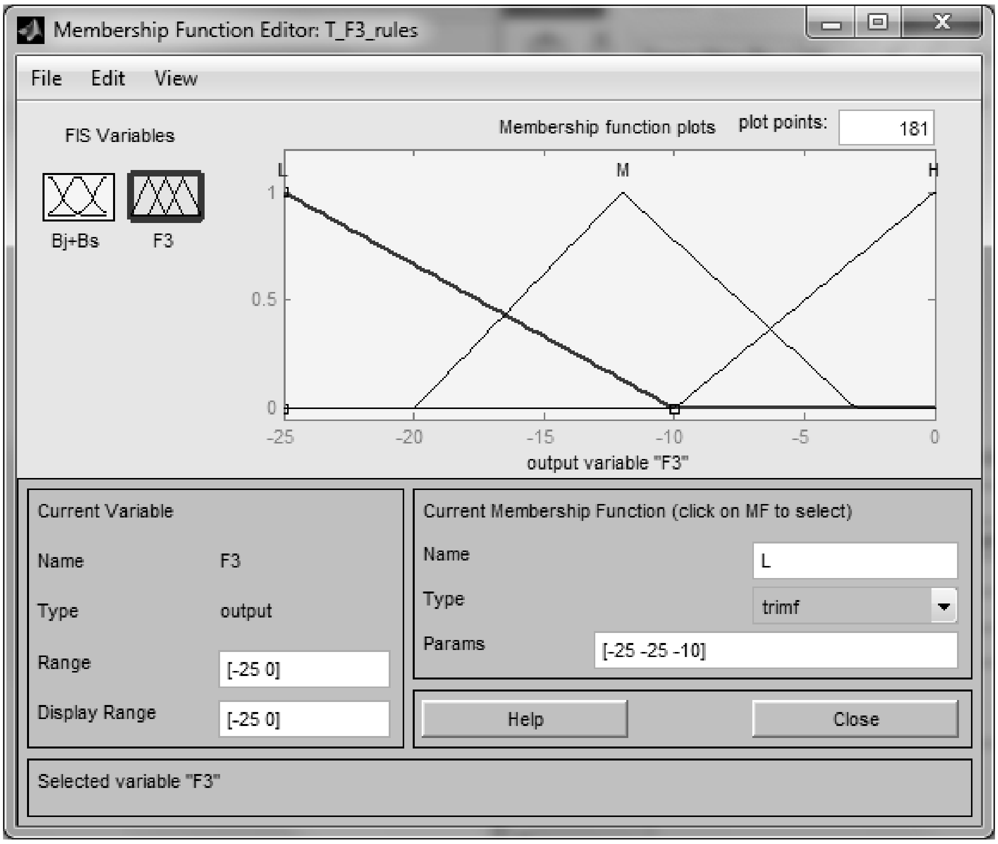

Table A.15 Conventional and Fuzzy SMR ratings of Slope 1 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering G10 and Slope 1	P	│αj-αs│	51	0.1	│βj│	45	0.85	│βj-βs│	9	-6	-0.77	0.93	0.95	-44.83	-39.91	0
	T	│αj-αs-180│	129	0.15	1		1	│βj+βs│	99	0	0.00	0.14	1.00	-18.23	-2.63	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
G10	145	55	45

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 1	94	4	54

Table A.16 Conventional and Fuzzy SMR ratings of Slope 1 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering G10 and Slope 1	P	│αj-αs│	51	0.15	│βj│	45	0.85	│βj-βs│	2	-6	-0.77	0.93	0.95	-56.64	-50.43	0
	T	│αj-αs-180│	129	0.15	1		1	│βj+βs│	88	0	0	0.14	1.00	-18.84	-2.72	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
G10	145	55	45

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 1	94	4	43

Table A.17 Conventional and Fuzzy SMR ratings of Slope 1 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering G10 and Slope 1	P	│αj-αs│	51	0.15	│βj│	45	0.85	│βj-βs│	9	-6	-0.77	0.93	0.95	-44.83	-39.91	0
	T	│αj-αs-180│	129	0.15	1		1	│βj+βs│	81	0	0	0.14	1.00	-19.18	-2.77	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
G10	145	55	45

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 1	94	4	36

Table A.18 Conventional and Fuzzy SMR ratings of Slope 2 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor (F_1.F_2.F_3)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor (F_1.F_2.F_3)**	**F_4**
Considering Fault 16 and slope	P	|αj-αs|	124	0.15	|βj|	52	1.00	|βj-βs|	2	-6	-0.90	0.95	0.95	-56.64	-51.19	0
	T	|αj-αs-180|	304	0.15	1		1.00	|βj+βs|	106	0	0.00	0.14	1.00	-13.51	-1.95	
Considering Fault 3 and slope	P	|αj-αs|	223	0.15	|βj|	52	1.00	|βj-βs|	2	-6	-0.90	0.95	0.95	-56.64	-51.48	
	T	|αj-αs-180|	403	0.15	1		1.00	|βj+βs|	106	0	0.00	0.14	1.00	-13.51	-1.95	
Considering intersection of Fault 16 and Fault 3 and the slope	W	|αi-αs|	173	0.15	|βi|	40	0.85	|βi-βs|	14	0	0.00	0.95	0.86	-28.80	-23.66	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
16	217	127	52
Fay 3	118	28	52
		Trend (αi)	**Plunge (βi)**
16 Fay 3 Intersection		78	40
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 2	341	251	54

Table A.19 Conventional and Fuzzy SMR ratings of Slope 2 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering Fault 16 and slope	P	$\lvert \alpha j-\alpha s \rvert$	124	0.15	$\lvert \beta j \rvert$	52	1.00	$\lvert \beta j-\beta s \rvert$	9	-6	-0.90	0.95	0.95	-44.83	-40.51	0
	T	$\lvert \alpha j-\alpha s-180 \rvert$	304	0.15	1		1.00	$\lvert \beta j+\beta s \rvert$	95	0	0.00	0.14	1.00	-18.46	-2.66	
Considering Fault 3 and slope	P	$\lvert \alpha j-\alpha s \rvert$	223	0.15	$\lvert \beta j \rvert$	52	1.00	$\lvert \beta j-\beta s \rvert$	9	-6	-0.90	0.95	0.95	-44.83	-40.74	
	T	$\lvert \alpha j-\alpha s-180 \rvert$	403	0.15	1		1.00	$\lvert \beta j+\beta s \rvert$	95	0	0.00	0.14	1.00	-18.46	-2.66	
Considering intersection of Fault 16 and Fault 3 and the slope	W	$\lvert \alpha i-\alpha s \rvert$	173	0.15	$\lvert \beta i \rvert$	40	0.85	$\lvert \beta i-\beta s \rvert$	3	-6	-0.77	0.95	0.86	-56.44	-46.36	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
16	217	127	52
Fay 3	118	28	52
		Trend (αi)	**Plunge (βi)**
16 Fay 3 Intersection		78	40
Slope 2	341	251	43

Table A.20 Conventional and Fuzzy SMR ratings of Slope 2 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering Fault 16 and slope	P	$\lvert αj-αs \rvert$	124	0.15	$\lvert βj \rvert$	52	1.00	$\lvert βj-βs \rvert$	20	0	0.00	0.95	0.95	-27.34	-24.70	0
	T	$\lvert αj-αs-180 \rvert$	304	0.15	1		1.00	$\lvert βj+βs \rvert$	84	0	0.00	0.14	1.00	-19.04	-2.75	
Considering Fault 3 and slope	P	$\lvert αj-αs \rvert$	223	0.15	$\lvert βj \rvert$	52	1.00	$\lvert βj-βs \rvert$	20	0	0.00	0.95	0.95	-27.34	-24.84	
	T	$\lvert αj-αs-180 \rvert$	403	0.15	1		1.00	$\lvert βj+βs \rvert$	84	0	0.00	0.14	1.00	-19.04	-2.75	
Considering intersection of Fault 16 and Fault 3 and the slope	W	$\lvert αi-αs \rvert$	173	0.15	$\lvert βi \rvert$	40	0.85	$\lvert βi-βs \rvert$	8	-6	-0.77	0.95	0.86	-44.98	-36.94	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
16	217	127	52
Fay 3	118	28	52
		Trend (αi)	**Plunge (βi)**
16 Fay 3 Intersection		78	40
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 2	341	251	32

Table A.21 Conventional and Fuzzy SMR ratings of Slope 3 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering Fay 3 and Slope 3	P	$\lvert \alpha j-\alpha s \rvert$	179	0.15	$\lvert \beta j \rvert$	60	1.00	$\lvert \beta j-\beta s \rvert$	6	-6	-0.90	0.95	0.95	-44.23	-40.20	0
	T	$\lvert \alpha j-\alpha s-180 \rvert$	359	0.15	1		1.00	$\lvert \beta j+\beta s \rvert$	114	-6	-0.90	0.14	1.00	-11.66	-1.68	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
Fay 3	156	66	60

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 3	335	245	54

Table A.22 Conventional and Fuzzy SMR ratings of Slope 3 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering Fay 3 and Slope 3	P	$\|\alpha j-\alpha s\|$	179	0.15	$\|\beta j\|$	60	1.00	$\|\beta j-\beta s\|$	17	0	0.00	0.95	0.95	-27.07	-24.60	0
	T	$\|\alpha j-\alpha s-180\|$	359	0.15	1		1.00	$\|\beta j+\beta s\|$	103	0	0.00	0.14	1.00	-17.99	-2.60	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
Fay 3	156	66	60

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 3	335	245	43

Table A.23 Conventional and Fuzzy SMR ratings of Slope 3 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering Fay 3 and Slope 3	P	$\lvert \alpha j-\alpha s \rvert$	179	0.15	$\lvert \beta j \rvert$	60	1.00	$\lvert \beta j-\beta s \rvert$	24	0	0.00	0.95	0.95	-14.91	-13.55	0
	T	$\lvert \alpha j-\alpha s-180 \rvert$	359	0.15	1		1.00	$\lvert \beta j+\beta s \rvert$	96	0	0.00	0.14	1.00	-18.40	-2.65	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
Fay 3	156	66	60

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 3	335	245	36

Table A.24 Conventional and Fuzzy SMR ratings of Slope 4 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 13 and Slope 4	P	│αj-αs│	22	0.4	│βj│	74	1.00	│βj-βs│	20	0	0.00	0.75	0.95	-27.34	-19.51	0
	T	│αj-αs-180│	202	0.15	1		1.00	│βj+βs│	128	-25	-3.75	0.14	1.00	-4.30	-0.62	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
13	53	303	74

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 4	55	325	54

Table A.25 Conventional and Fuzzy SMR ratings of Slope 4 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 13 and Slope 4	P	│αj-αs│	22	0.4	│βj│	74	1.00	│βj-βs│	31	0	0.00	0.75	0.95	-10.64	-7.59	0
	T	│αj-αs-180│	202	0.15	1		1.00	│βj+βs│	117	-6	-0.90	0.14	1.00	-11.66	-1.68	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
13	53	303	74

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 4	55	325	43

Table A.26 Conventional and Fuzzy SMR ratings of Slope 4 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 13 and Slope 4	P	$\lvert \alpha j-\alpha s \rvert$	22	0.4	$\lvert \beta j \rvert$	74	1.00	$\lvert \beta j-\beta s \rvert$	38	0	0.00	0.75	0.95	-11.45	-8.18	0
	T	$\lvert \alpha j-\alpha s-180 \rvert$	202	0.15	1		1.00	$\lvert \beta j+\beta s \rvert$	110	-6	-0.90	0.14	1.00	-11.61	-1.68	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
13	53	303	74
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 4	55	325	36

Table A.27 Conventional and Fuzzy SMR ratings of Slope 5 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 12 and Slope 5	P	│αj-αs│	9	0.85	│βj│	68	1.00	│βj-βs│	14	0	0.00	0.45	0.95	-28.80	-12.48	0
	T	│αj-αs-180│	189	0.15	1		1.00	│βj+βs│	122	-25	-3.75	0.14	1.00	-11.07	-1.60	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
12	14	284	68

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 5	23	293	54

Table A.28 Conventional and Fuzzy SMR ratings of Slope 5 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 12 and Slope 5	P	│αj-αs│	9	0.85	│βj│	68	1.00	│βj-βs│	25	0	0.00	0.45	0.95	-10.34	-4.48	0
	T	│αj-αs-180│	189	0.15	1		1.00	│βj+βs│	111	-6	-0.90	0.14	1.00	-11.63	-1.68	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
12	14	284	68
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 5	23	293	43

Table A.29 Conventional and Fuzzy SMR ratings of Slope 5 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 12 and Slope 5	P	│αj-αs│	9	0.85	│βj│	68	1.00	│βj-βs│	42	0	0.00	0.45	0.95	-9.29	-4.03	0
	T	│αj-αs-180│	189	0.15	1		1.00	│βj+βs│	94	0	0.00	0.14	1.00	-18.51	-2.67	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
12	14	284	68

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 5	23	293	26

Table A.30 Conventional and Fuzzy SMR ratings of Slope 6 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering FZ3 and slope	P	$\vert\alpha j-\alpha s\vert$	56	0.15	$\vert\beta j\vert$	52	1.00	$\vert\beta j-\beta s\vert$	12	0	0.00	0.93	0.95	-33.86	-30.18	0
	T	$\vert\alpha j-\alpha s-180\vert$	236	0.15	1		1.00	$\vert\beta j+\beta s\vert$	92	0	0.00	0.14	1.00	-18.62	-2.69	
Considering FZ4 and slope	P	$\vert\alpha j-\alpha s\vert$	75	0.15	$\vert\beta j\vert$	68	1.00	$\vert\beta j-\beta s\vert$	28	0	0.00	0.94	0.95	-10.42	-9.33	
	T	$\vert\alpha j-\alpha s-180\vert$	105	0.15	1		1.00	$\vert\beta j+\beta s\vert$	108	0	0.00	0.14	1.00	-12.00	-1.73	
Considering intersection of FZ3 and FZ4 and the slope	W	$\vert\alpha i-\alpha s\vert$	165	0.15	$\vert\beta i\vert$	35	0.70	$\vert\beta i-\beta s\vert$	5	-6	-0.63	0.95	0.73	-55.93	-38.97	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
FZ3	233	143	52
FZ4	4	274	68
		Trend (αi)	**Plunge (βi)**
FZ3 FZ4 Intersection		34	35
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Failure	289	199	40

Table A.31 Conventional and Fuzzy SMR ratings of Slope 6 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering FZ3 and slope	P	│αj-αs│	56	0.15	│βj│	52	1.00	│βj-βs│	28	0	0.00	0.93	0.95	-10.42	-9.29	0
	T	│αj-αs-180│	236	0.15	1		1.00	│βj+βs│	76	0	0.00	0.14	1.00	-19.41	-2.80	
Considering FZ4 and slope	P	│αj-αs│	75	0.15	│βj│	68	1.00	│βj-βs│	44	0	0.00	0.94	0.95	-4.96	-4.44	
	T	│αj-αs-180│	105	0.15	1		1.00	│βj+βs│	92	0	0.00	0.14	1.00	-18.62	-2.69	
Considering intersection of FZ3 and FZ4 and the slope	W	│αi-αs│	165	0.15	│βi│	35	0.70	│βi-βs│	11	0	0.00	0.95	0.95	-10.38	-9.42	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
FZ3	233	143	52
FZ4	4	274	68
Description		**Trend (αi)**	**Plunge (βi)**
FZ3 FZ4 Intersection		34	35
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Failure	289	199	24

Table A.32 Conventional and Fuzzy SMR ratings of Slope 7 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 11 and Slope 7	P	│αj-αs│	10	0.85	│βj│	52	1.00	│βj-βs│	2	-6	-5.10	0.48	0.95	-56.64	-25.88	0
	T	│αj-αs-180│	190	0.15	1		1.00	│βj+βs│	106	0	0.00	0.14	1.00	-13.51	-1.95	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
11	216	126	52

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 7	226	136	54

Table A.33 Conventional and Fuzzy SMR ratings of Slope 7 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 11 and Slope 7	P	$\vert αj-αs \vert$	10	0.85	$\vert βj \vert$	52	1.00	$\vert βj-βs \vert$	9	-6	-5.10	0.48	0.95	-44.83	-20.48	0
	T	$\vert αj-αs-180 \vert$	190	0.15	1		1.00	$\vert βj+βs \vert$	95	0	0.00	0.14	1.00	-18.46	-2.66	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
11	216	126	52

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 7	226	136	43

Table A.34 Conventional and Fuzzy SMR ratings of Slope 7 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 11 and Slope 7	P	│αj-αs│	10	0.85	│βj│	52	1.00	│βj-βs│	20	0	0.00	0.48	0.95	-27.34	-12.49	0
	T	│αj-αs-180│	190	0.15	1		1.00	│βj+βs│	84	0	0.00	0.14	1.00	-19.04	-2.75	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
11	216	126	52

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 7	226	136	32

Table A.35 Conventional and Fuzzy SMR ratings of Slope 8 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 8 and Slope 8	P	$\lvert \alpha j-\alpha s \rvert$	12	0.7	$\lvert \beta j \rvert$	56	1.00	$\lvert \beta j-\beta s \rvert$	2	-6	-4.20	0.53	0.95	-56.64	-28.78	0
	T	$\lvert \alpha j-\alpha s-180 \rvert$	192	0.15	1		1.00	$\lvert \beta j+\beta s \rvert$	110	-6	-0.90	0.14	1.00	-11.61	-1.68	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
8	215	125	56
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**

Table A.36 Conventional and Fuzzy SMR ratings of Slope 8 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 8 and Slope 8	P	$\lvert \alpha j-\alpha s \rvert$	12	0.7	$\lvert \beta j \rvert$	56	1.00	$\lvert \beta j-\beta s \rvert$	13	0	0.00	0.53	0.95	-30.96	-15.73	0
	T	$\lvert \alpha j-\alpha s-180 \rvert$	192	0.15	1		1.00	$\lvert \beta j+\beta s \rvert$	99	0	0.00	0.14	1.00	-18.23	-2.63	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
8	215	125	56

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 8	227	137	43

Table A.37 Conventional and Fuzzy SMR ratings of Slope 8 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 8 and Slope 8	P	│αj-αs│	12	0.7	│βj│	56	1.00	│βj-βs│	20	0	0.00	0.53	0.95	-27.34	-13.89	0
	T	│αj-αs-180│	192	0.15	1		1.00	│βj+βs│	92	0	0.00	0.14	1.00	-18.62	-2.69	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
8	215	125	56

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 8	227	137	36

Table A.38 Conventional and Fuzzy SMR ratings of Slope 9 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 8 and Slope 9	P	│αj-αs│	14	0.7	│βj│	56	1.00	│βj-βs│	2	-6	-4.20	0.60	0.95	-56.64	-32.51	0
	T	│αj-αs-180│	194	0.15	1		1.00	│βj+βs│	110	-6	-0.90	0.14	1.00	-11.61	-1.68	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
8	220	130	56

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 9	234	144	54

Table A.39 Conventional and Fuzzy SMR ratings of Slope 9 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 8 and Slope 9	P	$\lvert\alpha j-\alpha s\rvert$	14	0.7	$\lvert\beta j\rvert$	56	1.00	$\lvert\beta j-\beta s\rvert$	13	0	0.00	0.60	0.95	-30.96	-17.77	0
	T	$\lvert\alpha j-\alpha s-180\rvert$	194	0.15	1		1.00	$\lvert\beta j+\beta s\rvert$	99	0	0.00	0.14	1.00	-18.23	-2.63	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
8	220	130	56
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 9	234	144	43

Table A.40 Conventional and Fuzzy SMR ratings of Slope 9 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 8 and Slope 9	P	│αj-αs│	14	0.7	│βj│	56	1.00	│βj-βs│	26	0	0.00	0.60	0.95	-10.35	-5.94	0
	T	│αj-αs-180│	194	0.15	1		1.00	│βj+βs│	86	0	0.00	0.14	1.00	-18.94	-2.73	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
8	220	130	56
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 9	234	144	30

Table A.41 Conventional and Fuzzy SMR ratings of Slope 10 of TKI Orhaneli Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 37																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 1 and slope	P	│αj-αs│	57	0.15	│βj│	58	1.00	│βj-βs│	4	-6	-0.90	0.94	0.95	-56.20	-50.10	0
	T	│αj-αs-180│	237	0.15	1		1.00	│βj+βs│	112	-6	-0.90	0.14	1.00	-11.64	-1.68	
Considering 2 and slope	P	│αj-αs│	107	0.15	│βj│	58	1.00	│βj-βs│	4	-6	-0.90	0.95	0.95	-56.20	-50.64	
	T	│αj-αs-180│	73	0.15	1		1.00	│βj+βs│	112	-6	-0.90	0.16	1.00	-11.64	-1.81	
Considering intersection of 1 and 2 and the slope	W	│αi-αs│	165	0.15	│βi│	57	1.00	│βi-βs│	3	-6	-0.95	0.94	0.95	-56.44	-51.26	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
1	202	112	58
2	6	276	58
Description		**Trend (αi)**	**Plunge (βi)**
1 2 Intersection		4	57
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 10	259	169	54

Table A.42 Conventional and Fuzzy SMR ratings of Slope 10 of TKI Orhaneli Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 24.2

Condition	Type		Value	F_1		Value	F_2		Value	F_3	Adjustment Factor ($F_1.F_2.F_3$)	Fuzzy F_1	Fuzzy F_2	Fuzzy F_3	Fuzzy Adjustment Factor ($F_1.F_2.F_3$)	F_4
Considering 1 and slope	P	│αj-αs│	57	0.15	│βj│	58	1.00	│βj-βs│	15	0	0.00	0.94	0.95	-27.00	-24.07	0
	T	│αj-αs-180│	237	0.15	1		1.00	│βj+βs│	101	0	0.00	0.14	1.00	-18.11	-2.61	
Considering 2 and slope	P	│αj-αs│	107	0.15	│βj│	58	1.00	│βj-βs│	15	0	0.00	0.95	0.95	-27.00	-24.33	
	T	│αj-αs-180│	73	0.15	1		1.00	│βj+βs│	101	0	0.00	0.16	1.00	-18.11	-2.82	
Considering intersection of 1 and 2 and the slope	W	│αi-αs│	165	0.15	│βi│	57	1.00	│βi-βs│	14	0	0.00	0.95	0.95	-28.80	-26.16	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
1	202	112	58
2	6	276	58
Description		**Trend (αi)**	**Plunge (βi)**
1 2 Intersection		4	57
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 10	259	169	43

Table A.43 Conventional and Fuzzy SMR ratings of Slope 10 of TKI Orhaneli Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering 1 and slope	P	│αj-αs│	57	0.15	│βj│	58	1.00	│βj-βs│	28	0	0.00	0.94	0.95	-10.42	-9.29	0
	T	│αj-αs-180│	237	0.15	1		1.00	│βj+βs│	88	0	0.00	0.14	1.00	-18.84	-2.72	
Considering 2 and slope	P	│αj-αs│	107	0.15	│βj│	58	1.00	│βj-βs│	28	0	0.00	0.95	0.95	-10.42	-9.39	
	T	│αj-αs-180│	73	0.15	1		1.00	│βj+βs│	88	0	0.00	0.16	1.00	-18.84	-2.94	
Considering intersection of 1 and 2 and the slope	W	│αi-αs│	165	0.15	│βi│	57	1.00	│βi-βs│	27	0	0.00	0.95	0.95	-10.38	-9.42	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
1	202	112	58
2	6	276	58
Description		**Trend (αi)**	**Plunge (βi)**
1 2 Intersection		4	57
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Slope 10	259	169	30

Table A.44 Conventional and Fuzzy SMR ratings of Can 5 of TKI Can Lignite Mine with the slope angle for CRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for CRMR = 34																	
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering Weak Layer and Can 5	P	│αj-αs│	0	1	│βj│	7	0.15	│βj-βs│	41	0	0	0.14	0.14	-11.43	-0.24	0
	T	│αj-αs-180│	180	0.15	1		1	│βj+βs│	55	0	0	0.14	1	-20.05	-2.89	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
Weak Layer	180	270	7
Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Can 5	180	270	48

Table A.45 Conventional and Fuzzy SMR ratings of Can 5 of TKI Can Lignite Mine with the slope angle for FRMR

SMR Evaluation by Determining Slope Angle from Modified Slope Performance Chart for FRMR = 20																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering Weak Layer and Can 5	P	│αj-αs│	0	1	│βj│	7	0.15	│βj-βs│	28	0	0	0.14	0.14	-10.42	-0.22	0
	T	│αj-αs-180│	180	0.15	1		1	│βj+βs│	42	0	0	0.14	1	-20.08	-2.90	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
Weak Layer	180	270	7

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Can 5	180	270	35

Table A.46 Conventional and Fuzzy SMR ratings of Can 5 of TKI Can Lignite Mine with the slope angle found from detailed stability analysis

SMR Evaluation by Determining Slope Angle from Analysis																
Condition	**Type**		**Value**	**F_1**		**Value**	**F_2**		**Value**	**F_3**	**Adjustment Factor ($F_1.F_2.F_3$)**	**Fuzzy F_1**	**Fuzzy F_2**	**Fuzzy F_3**	**Fuzzy Adjustment Factor ($F_1.F_2.F_3$)**	**F_4**
Considering Weak Layer and Can 5	P	│αj-αs│	0	1	│βj│	7	0.15	│βj-βs│	10	-6	-0.9	0.14	0.14	-44.58	-0.93	0
	T	│αj-αs-180│	180	0.15	1		1	│βj+βs│	24	0	0	0.14	1	-20.08	-2.90	

Discontinuity Name	**Dip Direction**	**Strike (αj)**	**Dip Amount (βj)**
Weak Layer	180	270	7

Slope	**Dip Direction**	**Strike (αs)**	**Dip Amount (βs)**
Can 5	180	270	17

Table A.47 Conventional and Fuzzy SMR scores of slopes of TKI Orhaneli Lignite Mine for slope design according to CRMR

SMR Scores Calculated by Slope Angles Which were Obtained from Slope Performance Chart for CRMR=37													
Slope	**Discontinuity**	**Failure Type**	**Conventional RMR**	**Fuzzy RMR**	**Conventional RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Conventional RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**
Slope 1	G10	P	37	24.2	36.24	**IVa**	-2.91	**Vb**	23.44	**IVb**	-15.71	**Vb**
Slope 1	G10	T	37	24.2	37.00	**IVa**	34.37	**IVa**	24.20	**IVb**	21.57	**IVb**
Slope 2	16	P	37	24.2	36.10	**IVa**	-14.19	**Vb**	23.30	**IVb**	-26.99	**Vb**
Slope 2	16	T	37	24.2	37.00	**IVa**	35.05	**IVa**	24.20	**IVb**	22.25	**IVb**
Slope 2	Fay 3	P	37	24.2	36.10	**IVa**	-14.48	**Vb**	23.30	**IVb**	-27.28	**Vb**
Slope 2	Fay 3	T	37	24.2	37.00	**IVa**	35.05	**IVa**	24.20	**IVb**	22.25	**IVb**
Slope 2	16, Fay3	W	37	24.2	37.00	**IVa**	13.34	**Va**	24.20	**IVb**	0.54	**Vb**
Slope 3	Fay 3	P	37	24.2	36.10	**IVa**	-3.20	**Vb**	23.30	**IVb**	-16.00	**Vb**
Slope 3	Fay 3	T	37	24.2	36.10	**IVa**	35.32	**IVa**	23.30	**IVb**	22.52	**IVb**
Slope 4	13	P	37	24.2	37.00	**IVa**	17.49	**Va**	24.20	**IVb**	4.69	**Vb**
Slope 4	13	T	37	24.2	33.25	**IVa**	36.38	**IVa**	20.45	**IVb**	23.58	**IVb**
Slope 5	12	P	37	24.2	37.00	**IVa**	24.52	**IVb**	24.20	**IVb**	11.72	**Va**
Slope 5	12	T	37	24.2	33.25	**IVa**	35.40	**IVa**	20.45	**IVb**	22.60	**IVb**
Slope 6	11	P	37	24.2	36.10	**IVa**	-13.61	**Vb**	23.30	**IVb**	-26.41	**Vb**
Slope 6	11	T	37	24.2	37.00	**IVa**	34.40	**IVa**	24.20	**IVb**	21.60	**IVb**
Slope 6	12	P	37	24.2	37.00	**IVa**	12.77	**Va**	24.20	**IVb**	-0.03	**Vb**

Table A.47 (cont'd)

SMR Scores Calculated by Slope Angles Which were Obtained from Slope Performance Chart for CRMR=37													
Slope	**Discontinuity**	**Failure Type**	**Conventional RMR**	**Fuzzy RMR**	**Conventional RMR + Conventional ($F_1.F_2.F_3$)+F_4**	**SMR Class**	**Conventional RMR + Fuzzy ($F_1.F_2.F_3$)+F_4**	**SMR Class**	**Fuzzy RMR + Conventional ($F_1.F_2.F_3$)+F_4**	**SMR Class**	**Fuzzy RMR + Fuzzy ($F_1.F_2.F_3$)+F_4**	**SMR Class**
Slope 6	12	T	37	24.2	36.10	**IVa**	35.32	**IVa**	23.30	**IVb**	22.52	**IVb**
Slope 6	11, 12	W	37	24.2	37.00	**IVa**	18.17	**Va**	24.20	**IVb**	5.37	**Vb**
Slope 7	11	P	37	24.2	31.90	**IVa**	11.12	**Va**	19.10	**Va**	-1.68	**Vb**
Slope 7	11	T	37	24.2	37.00	**IVa**	35.05	**IVa**	24.20	**IVb**	22.25	**IVb**
Slope 8	8	P	37	24.2	32.80	**IVa**	8.22	**Vb**	20.00	**Va**	-4.58	**Vb**
Slope 8	8	T	37	24.2	36.10	**IVa**	35.32	**IVa**	23.30	**IVb**	22.52	**IVb**
Slope 9	8	P	37	24.2	32.80	**IVa**	4.49	**Vb**	20.00	**Va**	-8.31	**Vb**
Slope 9	8	T	37	24.2	36.10	**IVa**	35.32	**IVa**	23.30	**IVb**	22.52	**IVb**
Slope 10	1	P	37	24.2	36.10	**IVa**	-13.10	**Vb**	23.30	**IVb**	-25.90	**Vb**
Slope 10	1	T	37	24.2	36.10	**IVa**	35.32	**IVa**	23.30	**IVb**	22.52	**IVb**
Slope 10	2	P	37	24.2	36.10	**IVa**	-13.64	**Vb**	23.30	**IVb**	-26.44	**Vb**
Slope 10	2	T	37	24.2	36.10	**IVa**	35.19	**IVa**	23.30	**IVb**	22.39	**IVb**
Slope 10	1,2	W	37	24.2	36.10	**IVa**	-13.84	**Vb**	23.30	**IVb**	-26.64	**Vb**

Table A.48 Conventional and Fuzzy SMR scores of slopes of TKI Orhaneli Lignite Mine for slope design according to FRMR

SMR Scores Calculated by Slope Angles Which were Obtained from Slope Performance Chart for FRMR=24.2												
Slope	**Discontinuity**	**Failure Type**	**Conventional RMR**	**Fuzzy RMR**	**Conventional RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Conventional RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**
Slope 1	G10	P	37	24.2	36.24	**IVa**	-13.43	**Vb**	23.44	**IVb**	-26.23	**Vb**
Slope 1	G10	T	37	24.2	37.00	**IVa**	34.28	**IVa**	24.20	**IVb**	21.48	**IVb**
Slope 2	16	P	37	24.2	36.10	**IVa**	-3.51	**Vb**	23.30	**IVb**	-16.31	**Vb**
Slope 2	16	T	37	24.2	37.00	**IVa**	34.34	**IVa**	24.20	**IVb**	21.54	**IVb**
Slope 2	Fay 3	P	37	24.2	36.10	**IVa**	-3.74	**Vb**	23.30	**IVb**	-16.54	**Vb**
Slope 2	Fay 3	T	37	24.2	37.00	**IVa**	34.34	**IVa**	24.20	**IVb**	21.54	**IVb**
Slope 2	16, Fay3	W	37	24.2	36.24	**IVa**	-9.36	**Vb**	23.44	**IVb**	-22.16	**Vb**
Slope 3	Fay 3	P	37	24.2	37.00	**IVa**	12.40	**Va**	24.20	**IVb**	-0.40	**Vb**
Slope 3	Fay 3	T	37	24.2	37.00	**IVa**	34.40	**IVa**	24.20	**IVb**	21.60	**IVb**
Slope 4	13	P	37	24.2	37.00	**IVa**	29.41	**IVb**	24.20	**IVb**	16.61	**Va**
Slope 4	13	T	37	24.2	36.10	**IVa**	35.32	**IVa**	23.30	**IVb**	22.52	**IVb**
Slope 5	12	P	37	24.2	37.00	**IVa**	32.52	**IVa**	24.20	**IVb**	19.72	**Va**
Slope 5	12	T	37	24.2	36.10	**IVa**	35.32	**IVa**	23.30	**IVb**	22.52	**IVb**
Slope 6	11	P	37	24.2	37.00	**IVa**	6.82	**Vb**	24.20	**IVb**	-5.98	**Vb**
Slope 6	11	T	37	24.2	37.00	**IVa**	34.31	**IVa**	24.20	**IVb**	21.51	**IVb**
Slope 6	12	P	37	24.2	37.00	**IVa**	27.67	**IVb**	24.20	**IVb**	14.87	**Va**

Table A.48 (cont'd)

SMR Scores Calculated by Slope Angles Which were Obtained from Slope Performance Chart for FRMR=24.2													
Slope	**Discontinuity**	**Failure Type**	**Conventional RMR**	**Fuzzy RMR**	**Conventional RMR + Conventional ($F_1.F_2.F_3$)+F_4**	**SMR Class**	**Conventional RMR + Fuzzy ($F_1.F_2.F_3$)+F_4**	**SMR Class**	**Fuzzy RMR + Conventional ($F_1.F_2.F_3$)+F_4**	**SMR Class**	**Fuzzy RMR + Fuzzy ($F_1.F_2.F_3$)+F_4**	**SMR Class**
Slope 6	12	T	37	24.2	37.00	**IVa**	35.27	**IVa**	24.20	**IVb**	22.47	**IVb**
Slope 6	11, 12	W	37	24.2	36.37	**IVa**	-1.97	**Vb**	23.57	**IVb**	-14.77	**Vb**
Slope 7	11	P	37	24.2	31.90	**IVa**	16.52	**Va**	19.10	**Va**	3.72	**Vb**
Slope 7	11	T	37	24.2	37.00	**IVa**	34.34	**IVa**	24.20	**IVb**	21.54	**IVb**
Slope 8	8	P	37	24.2	37.00	**IVa**	21.27	**IVb**	24.20	**IVb**	8.47	**Vb**
Slope 8	8	T	37	24.2	37.00	**IVa**	34.37	**IVa**	24.20	**IVb**	21.57	**IVb**
Slope 9	8	P	37	24.2	37.00	**IVa**	19.23	**Va**	24.20	**IVb**	6.43	**Vb**
Slope 9	8	T	37	24.2	37.00	**IVa**	34.37	**IVa**	24.20	**IVb**	21.57	**IVb**
Slope 10	1	P	37	24.2	37.00	**IVa**	12.93	**Va**	24.20	**IVb**	0.13	**Vb**
Slope 10	1	T	37	24.2	37.00	**IVa**	34.39	**IVa**	24.20	**IVb**	21.59	**IVb**
Slope 10	2	P	37	24.2	37.00	**IVa**	12.67	**Va**	24.20	**IVb**	-0.13	**Vb**
Slope 10	2	T	37	24.2	37.00	**IVa**	34.18	**IVa**	24.20	**IVb**	21.38	**IVb**
Slope 10	1,2	W	37	24.2	37.00	**IVa**	10.84	**Va**	24.20	**IVb**	-1.96	**Vb**

Table A.49 Conventional and Fuzzy SMR scores of slopes of TKI Orhaneli Lignite Mine for analytical slope design based on back analysis data

SMR Scores Calculated by Slope Angles Which were Obtained from Analysis												
Slope	**Discontinuity**	**Failure Type**	**Conventional RMR**	**Fuzzy RMR**	**Conventional RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Conventional RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**
Slope 1	G10	P	37	24.2	36.24	**IVa**	-2.91	**Vb**	23.44	**IVb**	-15.71	**Vb**
Slope 1	G10	T	37	24.2	37.00	**IVa**	34.23	**IVa**	24.20	**IVb**	21.43	**IVb**
Slope 2	16	P	37	24.2	37.00	**IVa**	12.30	**Va**	24.20	**IVb**	-0.50	**Vb**
Slope 2	16	T	37	24.2	37.00	**IVa**	34.25	**IVa**	24.20	**IVb**	21.45	**IVb**
Slope 2	Fay 3	P	37	24.2	37.00	**IVa**	12.16	**Va**	24.20	**IVb**	-0.64	**Vb**
Slope 2	Fay 3	T	37	24.2	37.00	**IVa**	34.25	**IVa**	24.20	**IVb**	21.45	**IVb**
Slope 2	16, Fay3	W	37	24.2	36.24	**IVa**	0.06	**Vb**	23.44	**IVb**	-12.74	**Vb**
Slope 3	Fay 3	P	37	24.2	37.00	**IVa**	23.45	**IVb**	24.20	**IVb**	10.65	**Va**
Slope 3	Fay 3	T	37	24.2	37.00	**IVa**	34.35	**IVa**	24.20	**IVb**	21.55	**IVb**
Slope 4	13	P	37	24.2	37.00	**IVa**	28.82	**IVb**	24.20	**IVb**	16.02	**Va**
Slope 4	13	T	37	24.2	36.10	**IVa**	35.32	**IVa**	23.30	**IVb**	22.52	**IVb**
Slope 5	12	P	37	24.2	37.00	**IVa**	32.97	**IVa**	24.20	**IVb**	20.17	**IVb**
Slope 5	12	T	37	24.2	37.00	**IVa**	34.33	**IVa**	24.20	**IVb**	21.53	**IVb**
Slope 6	11	P	37	24.2	37.00	**IVa**	27.71	**IVb**	24.20	**IVb**	14.91	**Va**
Slope 6	11	T	37	24.2	37.00	**IVa**	34.20	**IVa**	24.20	**IVb**	21.40	**IVb**
Slope 6	12	P	37	24.2	37.00	**IVa**	32.56	**IVa**	24.20	**IVb**	19.76	**Va**

Table A.49 (cont'd)

SMR Scores Calculated by Slope Angles Which were Obtained from Analysis												
Slope	**Discontinuity**	**Failure Type**	**Conventional RMR**	**Fuzzy RMR**	**Conventional RMR + Conventional ($F_1.F_2.F_3$)+F_4**	**SMR Class**	**Conventional RMR + Fuzzy ($F_1.F_2.F_3$)+F_4**	**SMR Class**	**Fuzzy RMR + Conventional ($F_1.F_2.F_3$)+F_4**	**SMR Class**	**Fuzzy RMR + Fuzzy ($F_1.F_2.F_3$)+F_4**	**SMR Class**
Slope 6	12	T	37	24.2	37.00	**IVa**	34.31	**IVa**	24.20	**IVb**	21.51	**IVb**
Slope 6	11, 12	W	37	24.2	37.00	**IVa**	27.58	**IVb**	24.20	**IVb**	14.78	**Va**
Slope 7	11	P	37	24.2	37.00	**IVa**	24.51	**IVb**	24.20	**IVb**	11.71	**Va**
Slope 7	11	T	37	24.2	37.00	**IVa**	34.25	**IVa**	24.20	**IVb**	21.45	**IVb**
Slope 8	8	P	37	24.2	37.00	**IVa**	23.11	**IVb**	24.20	**IVb**	10.31	**Va**
Slope 8	8	T	37	24.2	37.00	**IVa**	34.31	**IVa**	24.20	**IVb**	21.51	**IVb**
Slope 9	8	P	37	24.2	37.00	**IVa**	31.06	**IVa**	24.20	**IVb**	18.26	**Va**
Slope 9	8	T	37	24.2	37.00	**IVa**	34.27	**IVa**	24.20	**IVb**	21.47	**IVb**
Slope 10	1	P	37	24.2	37.00	**IVa**	27.71	**IVb**	24.20	**IVb**	14.91	**Va**
Slope 10	1	T	37	24.2	37.00	**IVa**	34.28	**IVa**	24.20	**IVb**	21.48	**IVb**
Slope 10	2	P	37	24.2	37.00	**IVa**	27.61	**IVb**	24.20	**IVb**	14.81	**Va**
Slope 10	2	T	37	24.2	37.00	**IVa**	34.06	**IVa**	24.20	**IVb**	21.26	**IVb**
Slope 10	1,2	W	37	24.2	37.00	**IVa**	27.58	**IVb**	24.20	**IVb**	14.78	**Va**

Table A.50 Conventional and Fuzzy SMR scores of slopes of TKI Can Lignite Mine for slope design according to FRMR

SMR Scores Calculated by Slope Angles Which were Obtained from Slope Performance Chart for FRMR=20													
Slope	**Discontinuity**	**Failure Type**	**Conventional RMR**	**Fuzzy RMR**	**Conventional RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Conventional RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**
Can 5	Weak Layer	P	34	20	34.00	**IVa**	34.00	**IVa**	20.00	**Va**	19.78	**Va**
Can 5	Weak Layer	T	34	20	34.00	**IVa**	34.00	**IVa**	20.00	**Va**	17.10	**Va**

Table A.51 Conventional and Fuzzy SMR scores of slopes of TKI Can Lignite Mine for analytical slope design based on back analysis data

SMR Scores Calculated by Slope Angles Which were Obtained from Analysis												
Slope	**Discontinuity**	**Failure Type**	**Conventional RMR**	**Fuzzy RMR**	**Conventional RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Conventional RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Conventional $(F_1.F_2.F_3)+F_4$**	**SMR Class**	**Fuzzy RMR + Fuzzy $(F_1.F_2.F_3)+F_4$**	**SMR Class**
Can 5	Weak Layer	P	34	20	33.10	**IVa**	33.07	**IVa**	19.10	**Va**	19.07	**Va**
Can 5	Weak Layer	T	34	20	34.00	**IVa**	31.10	**IVa**	20.00	**Va**	17.10	**Va**