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A Visualization Approach for Predicting Loosening Loads in Rock Tunnels

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Abstract

The purpose of this work is to apply Geographic Information System (GIS) to analyze joint sets and to predict loosening loads (blocks and wedges) in tunnel openings.

Moreover, the overall intent is to integrate GIS techniques in the design and construction of underground openings. To date, there has been no applications of GIS in organizing and analyzing data for predicting loosening loads in tunnels and underground caverns.

The process of determining loads in tunnels is basically use of ground reaction curves, rock classification systems and application of geologic methods to predict ground behavior. These processes require an extended amount of time particularly when several rock engineering parameters such as rock type, rock quality, geologic features, weathering and etc. are included in the analysis of multiple tunnel alignments. The goal in this study is to develop a process in which Python, ArcGIS, Excel and AutoCAD are used to firstly, identify prominent joint sets and secondly, to predict critical rock blocks and wedges responsible for loosening loads in tunnels.

For this study, a geology plan view containing 100 arbitrarily oriented joint surfaces was developed and used as a basic data set. In order to computerize the process, two major tasks were completed. First, major joint sets were identified in the arbitrary geologic map using ArcGIS, Python and Excel programs. Once the sets were identified, a hypothetical tunnel opening was superimposed on one group of joint sets such that tunnel alignment was oriented sub-parallel with the strike of the group of joint sets. The hypothetical tunnel cross-section was developed in AutoCAD and along with the joint set data were utilized to predict the geometry of the rock blocks and the loosening loads in the arch and sidewall of the opening.

Based on the results of this study, it is concluded that GIS methodology improved the efficiency to process joint orientation data and use this information to predict tunnel support requirements. The real contribution in this study is the improved efficiency for analyzing joint orientation data either in geologic maps or from field measurements in predicting rock loads in tunnels. Multiple scenarios of joint set orientations and selection of tunnel alignments can efficiently analyzed using the techniques developed in this

study. However, this study was just a very initial step in improving the tunnel design process by using GIS.

1. Introduction

Design and construction of tunnels is highly dependent on understanding of rock properties and ground behavior. For selecting proper support system in a tunnel, predicting ground behavior is critical in addition to rock quality. Since tunnel design is studied under rock engineering, almost all conducted researches in this area deal with calculations in rock mechanics, such as stress-strain relations or rock classifications, such as Rock Quality Designation (RQD) or Rock Mass Rating (RMR). RQD is an index to determine the quality of rock mass. It is a modified core recovery percentage in which recovered length of core is divided by length of the core logger. It does not count uncovered core to downgrade the quality designation of rock (Deer 1988). However, these methods are not considered in this study. An important aspect of rock engineering is mechanism of rock failure, which has not been worked on much. This mechanism is critical in predicting loosening loads. For this purpose, geologic features and structures, such as joints and faults should be considered. This method was developed in the 1970's by Ed Cording and James Mahar and has been applied to hundreds of underground projects across the world. Some of those projects are as following:

- Dupont Circle Station, Washington DC metro system
- Roslyn Station, Washington DC
- Airport Station, South Korea
- Hollands Tunnel, Sweden
- Escondida Water Supply Project, Antofagasta, Chile

This process is easy to understand and has been done by hand, but the downside is that it is time consuming and takes much effort to accomplish the intended purposes, as well as not providing the opportunity of comparing different scenarios in a short time. Also it limits the ability of the engineer to consider different parameters at the same time and analyze the effect of each individual parameter on the design. In this study, "Loosening Conditions" are considered and this work applied Geographic Information System (GIS) in analyzing data to predict loosening behavior and loading conditions in tunnels based on geologic features presented in a geologic map, so that the deficiencies with the traditional method could be remediated. Since GIS is a system of storing and analyzing

big data bases, it provides the ability to consider different properties in the analysis stage in a short time.

It should be considered that GIS is a tool and the purpose of a tool is to supplement the existing knowledge, not to be interpreted as a replacement for it and the work in this study is the very first step and ground breaking stage of using GIS in underground construction. By using this system, the time needed for identifying joint sets and analyzing different conditions was significantly reduced. For this purpose, a code was written in python that will help the engineer with identifying major joint sets needed to predict ground behavior and design primary supporting system in rock tunnels based on criteria defined in the next chapters. After defining critical joint sets, AutoCAD was used to demonstrate blocks and wedges.

GIS application will be more evident by accomplishing future work ideas proposed at the end of current study. In the larger picture, future applications of GIS and the other tools used in this study will improve our ability to refine predictions of loosening loads by taking into account the myriad of geotechnical parameters such as shear strength in the design and construction of underground openings. This can become a very powerful, time and cost saving tool for consulting firms to analyze and propose multiple alignment for tunnels in different phases of projects, such as bidding stage in a very short time and more precise manner in underground construction.

1.1 Engineering Geology Study

Geotechnical Investigation is the phase of studying and collecting data about rock and soil properties, such as plasticity, unconfined compression strength and geologic features, such as joints. It plays an important role in all civil engineering projects since it provides engineers with critical information for designing, choosing a proper site for the project, predicting ground behavior, construction means and methods as well as putting together cost and estimate.

In nature, rock masses have mechanical defects and breaks in them. These defects could be related to the intact properties of rock mass, such as intact strength. Rock masses fractures can be closely or widely spaced. These fractures can be defined into two categories: joints and faults.

Terzaghi defined joints as cracks or fractures in rock along which displacement is not observed. They can be open or closed, meaning there can be a space in between sides of the crack. Spacing of joints determines block size in a rock mass. Faults are large extent fractures along which adjoining rock mass has displaced.

The very first step in geotechnical investigations is to collect and summarize geotechnical and geologic data. It helps the engineer with identifying and predicting problems that might be encountered in the construction phase. When exploring for rock tunnels, the effect of geologic features on the ground behavior and supporting system should be assessed, not just described. In rocks, there are some specific geologic structures causing same stability problems such as falling blocks from the top, sliding blocks into the openings and side walls instability that need to be supported. Primary features that control ground behavior in rock tunnels are joints, shears and shear zones (Cording, Deere 1974). During the exploration stage, such features should be searched for. Geotechnical Investigation can include use of geologic maps and field mapping, collecting samples for laboratory tests, and doing field tests, such as penetration test. Geographic Information System (GIS) is ideally suited to summarize and analyze data

since this system is capable of storing huge amounts of information and provide the opportunity to consider multiple fields of data in analysis and design at the same time. The scope of this study is to use GIS in identifying joint sets and predict loosening behavior in tunnels. The ultimate goal in design of rock tunnels is to predict loading conditions and ground behavior around tunnel opening and use them for designing support system.

This study concentrates on predicting loosening conditions in rock tunnels. For this purpose we need to identify critical engineering geologic parameters. These feature for the current study are orientation and frequency of joints in rocks, then categorize them into sets in order to predict rock blocks and wedges dimensions and determine different modes of failure in a tunnel opening, such as falling blocks from the arch, toppling blocks, and sliding blocks. This goal has been accomplished by integrating programming in GIS with AutoCAD and Excel programs.

1.2 Research Goals

The goal was to decrease analysis time and improve the accuracy and efficiency in designing tunnels for loosening ground by applying GIS software and programing. For this purpose two objectives needed to be completed. These objectives were as following:

Objective 1: Identify joint sets from the developed geologic map based on the strike, dip direction and dip amount of joints.

Objective 2: Use the identified joint sets to develop cross sections of tunnel, showing formed blocks and wedges to estimate loosening loads and behavior in a tunnel opening.

It was concluded that using Python as programing language along with Excel, ArcGIS and AutoCAD have great contribution in design process and efficiency and will provide the engineer the opportunity of comparing different conditions in the design with less effort and much higher accuracy.

1.3 Thesis Sequence

The thesis is organized as follows. Chapter 1 discusses the theme of the thesis. Chapter 2 discusses the literature review, geology background in geotechnical engineering, and GIS applications in civil engineering. Chapter 3 presents the details of the methodology for predicting ground behavior and data gathering. Chapter 4 focuses on the results of the study. Chapter 5 presents the conclusion and future work.

2. LITERATURE REVIEW

2.1 Prediction of Loosening Loads around Rock Tunnel Openings

There are different failure conditions that can happen in a tunnel construction, such as loosening conditions, squeezing condition, overstressed condition, flowing ground and etc. In this study loosening conditions are considered. As far as loosening conditions are concerned, most of the previous works are based on Finite Element analysis or rock classification systems, but not based on cracks and fractures in rocks. Cording and Mahar conducted a study on the effect of natural geologic discontinuities on behavior of rocks in tunnels from 1971 to 1974. They studied 9 case histories and the result of their work was published in Rapid Excavation and Tunneling Conference (1974). The study described effect of geologic features such as joints, shears and shear zones on formation and movement of rock wedges in tunnels in Washington D. C. and New York City. The tunnels were driven through foliated metamorphic rocks. Structural history in both areas were similar, which caused similarities in properties of major joint sets and shear zones in rocks. In both locations, same planes of weakness were observed. Foliation was poorly to well developed and was striking in North-South direction, dipping east or west. Encountered rocks in tunnels were primary schist and gneiss of mica-quartz and mica-feldspar-quartz composition. The RQD values of 50% to 100% were generally observed which indicated fair to excellent rock quality.

Observations in that study were made in different tunnels with different dimensions in that geologic formation. Variation in properties such as opening, filling, spacing, and weathering of features in those tunnels were accounted by Deere and Mahar for significant difference in rock wedges requiring support.

The most significant features encountered in the tunnels were joints, shears and shear zones. Also the conditions that these features caused the most serious difficulties were

identified which were dependent on the range of strike of joints and the intersection of the features with each other.

Well-developed joints were observed in almost all metamorphic rocks in those tunnels. They occurred in at least three or four major sets (Fig 2.1). From this figure it is apparent that joints repeated in a pattern, and formed same joint sets. For example joint sets 2 in Manhattan and joint set 2 in Van Cortland. They are striking same direction and dipping same direction with almost same dip angles. Here the significance of analyzing joints strike and dip and categorizing them into sets could be realized. It is a very hard task when we are dealing with a great amount of data, so a systematic approach for analyzing the data could be really helpful for the engineer by saving time and effort for analysis.

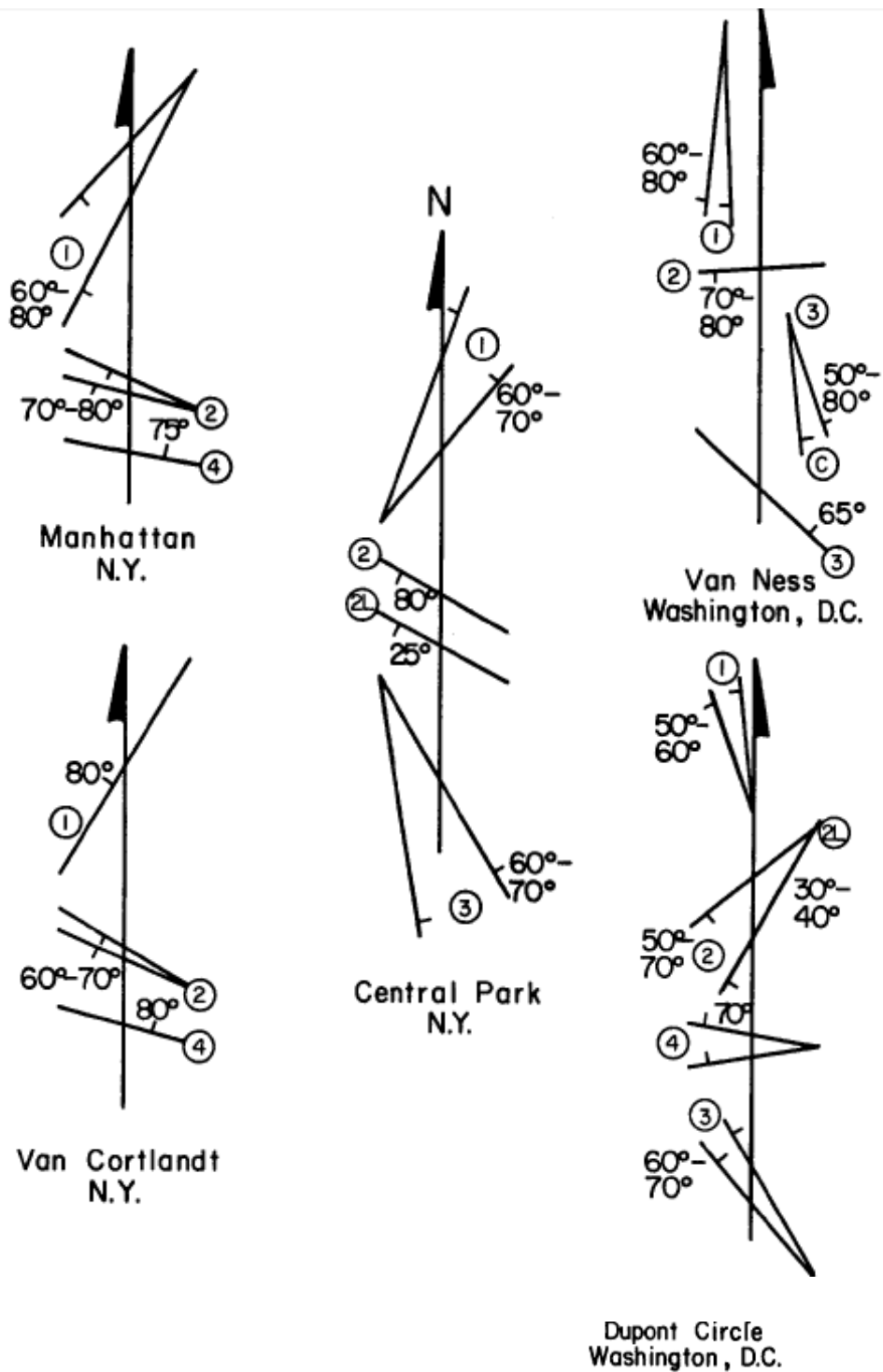


Figure 2.1 Major joint sets in Washington D.C and New York tunnels. Reprinted from “The Effect of Natural Discontinuities on Behavior of Rock in Tunnels” by E.C, J.M, 1972, RETC, Volume 1, page 109.

In another study, Cording and Deere concentrated on field measurement and observation in rock tunnel construction. The observations included visual inspections, geologic mapping, and correlation of geology with support conditions, such as buckling as well as loads on support system and movement of rock wedges. The purpose of the study was to provide information dealing with interaction of rock movements and support conditions to develop more efficient design and construction methods. There were measuring instrumentations such as strain gages and extensometers used in the project. They were concentrated in special sections where typical geologic and construction conditions were present. This approach was used to understand the performance of tunnels and the design assumptions for supporting systems. In that study, design considerations and description of instrumentation program for shallow chambers were discussed. They recommended to consider actual geometry of joints around opening and determine wedges presenting potential stability problem for evaluating design loads. Figure 2.2 shows the effect of joint orientation on crown stability. The blocks formed on the crown were a result of different joint sets intersecting each other. Block sizes were dependent on the angle at which joints intersected in cross section, which actually was dip angle of each joint set.

In that study they also discussed about friction between joints and friction angles which are beyond scope of current study.

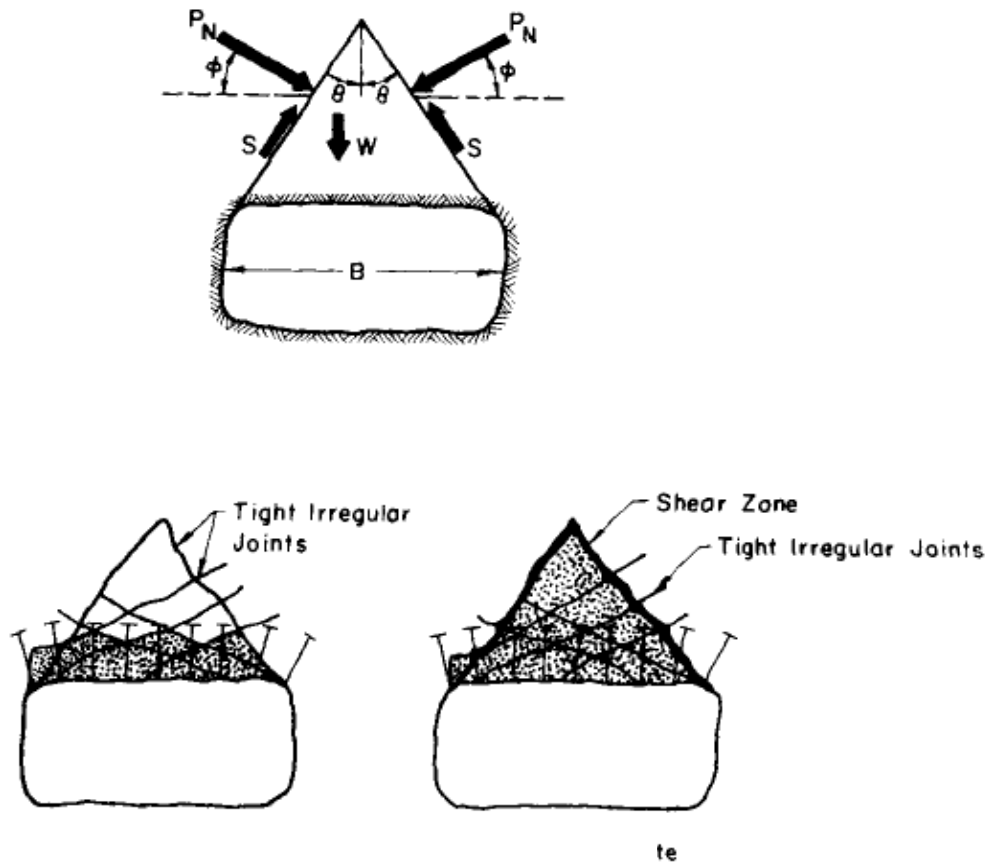


Figure 2.2 Effect of joint orientation on crown stability. Reprinted from “Rock Tunnel Supports and Field Measurements” by E.C, D.D, 1972, RETC, Volume 1, page 606.

The above studies were done based on considering geologic features for failure mechanism of rocks. There has been many works on analyzing failure using Finite Element methods. Following are two studies that concentrated on distribution of pressure along joints and failure process of rock in jointed rocks using FE methods. Since these studies are beyond the scope of current research, only the results have been implied. For more information, reader is suggested to read full papers.

In a study with the title of ‘Modeling Failure of jointed rock slope with two main joint sets using a novel DEM bond contact model’ (Jiang et al 2015) failure process and mechanism of jointed rock slopes was investigated. A novel bond contact model with Distinct Element Method (DEM) was applied. The bond contact model was validated by series of direct shear tests on jointed models. DEM slope models were generated. It was concluded that novel bond contact model used in DEM code could tackle fundamental problems of jointed rock slope failure. Also it could help with better understanding of slope failure mechanism.

Moorak Son and Jaehyuan Park (2014) conducted a research with the title of ‘Physical and numerical tests of excavation wall in jointed rock masses’. The goal was to examine distribution and magnitude of earth pressure of open cuts in jointed rocks on support systems. For this purpose, concrete blocks with man-made joints representing jointed rock mass were used. A physical model test was carried out. The model test was simulated numerically. The results of numerical tests were compared with Peck’s empirical earth pressure for soil grounds and it was concluded that earth pressure in rock masses could be very different from that in soil ground.

There are several packages used for tunnel design, such as C-Tunnel or DIANA. They use Finite Element analysis for determining stresses around the opening by creating meshes. These packages do not consider ground behavior in their analysis, which is very critical in the design and construction stage. Also the loading condition they consider is a uniform. In reality, uniform loading does not occur and in most of conditions non uniform loading happens. This has a significant effect on support systems design since non uniform loads create moments. Figure 2.3 illustrates an analysis done by DIANA. This model was taken from a video on YouTube. It shows meshing that is used for a FE analysis.

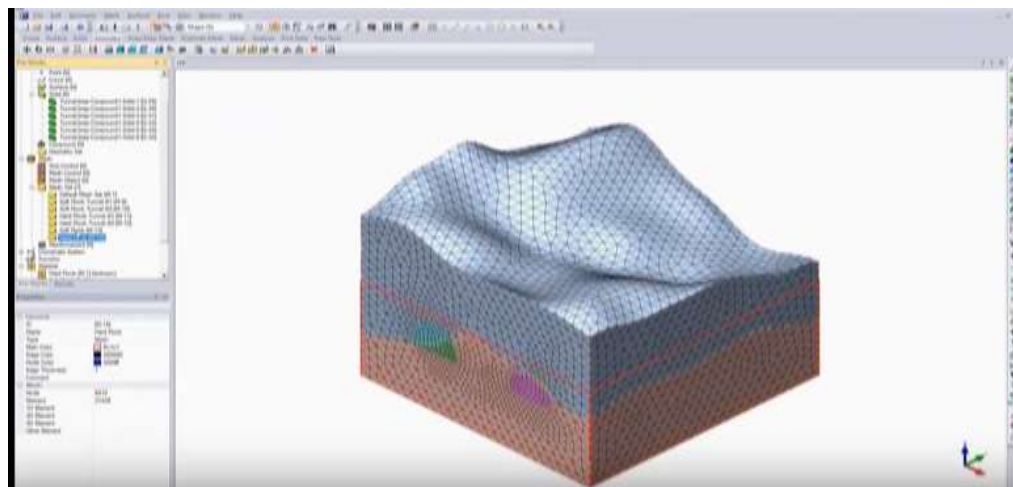
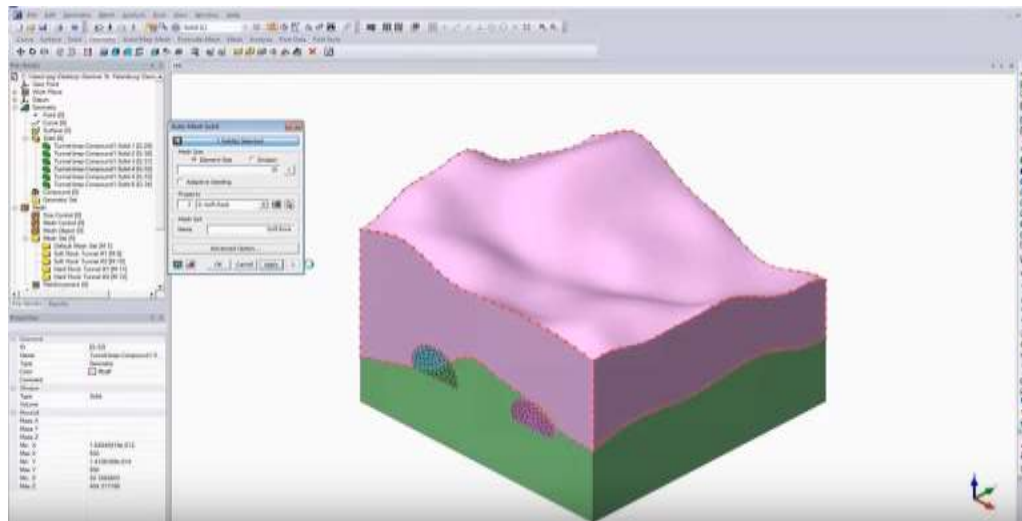


Figure 2.3 Finite Element analysis by DIANA Reprinted from YouTube, by TNO DIANA BV, 2013 from <https://www.youtube.com/watch?v=0Eo3obdbn4>.

2.2 GIS Applications

GIS (Geographic Information System) is a computer based system to store and manage data bases. It is a very powerful tool since it provides opportunity of collecting, storing, analyzing and updating data. Data collection can be done through variety of sources and formats such as digitized and scanned data, text files and spatial data forms. GIS software packages, such as ArcGIS is capable of digitizing paper maps. Using this feature, user can assign information, such as coordinates to the elements of map. Also ArcGIS is capable of reading in satellite images that contain variety information, such as elevation.

This system has become a very powerful tool since it provides a means of geographic presentation of data, combines data from different sources, and displays spatial relationships and has the ability to interface coordinate systems.

GIS has been proliferated in civil engineering as a tool in recent years. It has been recognized as a beneficial technology in most of civil engineering fields. GIS initially was not developed as a tool for civil engineering modeling, otherwise engineers would not work on fitting various models in GIS (Miles & Ho 1999).

GIS has applications in different fields of civil engineering such as transportation, environmental, water resources and geotechnics. It has been used in transportation engineering planning and maintenance. As far as maintenance is concerned, GIS can be used to prepare a systematic maintenance approach for existing and new pavements. In a study done by Kmetz (2011), it was used first to rate conditions of roads in a city and then to implement a plan that will enhance the overall life cycle of road. In water resources, there has been applications for modeling Solid Waste Water (Chang et al 1997), Sediment Transport (Mashriqui & Cruise 1997), Storm Water Pollution (Wong et al. 1997). In geotechnical engineering, it has been used to study liquefaction (Luna and Frost 1998) and seismic slope stability (Ho & Miles 1997). Details about these researches are not related to the scope of current study. As far as tunnel engineering is concerned, there has been almost no application in tunnel design and construction.

There has been considerable researches in using GIS to study lineaments mapping of lineaments, geothermal energy transport or deposit concentration prediction, which is applicable in mining engineering and etc. In underground construction design, we are not concerned about how geologic maps are created, but use them for designing purposes. Since these studies are beyond the scope of current research, just results of one publication are mentioned here. For more information reader is suggested to read the publications in those areas.

A study with title of “Mapping of Lineaments for Groundwater Targeting and Sustainable Water Resource Management in Hard Rock Hydrogeological Environment Using RS-GIS” was done in 2013 (Prabu, P. & Rajagopalan, B.). The research focused on applying GIS and Remote Sensing methodology for regional groundwater potential evaluation. Figure 2.4 and 2.5 illustrate the result of their work. They used rose diagram to present distribution of joints in the map. There is no information about how they categorized joints and how rose diagram was plotted. The application of rose diagram in this study and current study are different. Rose diagram is introduced in chapter 3.

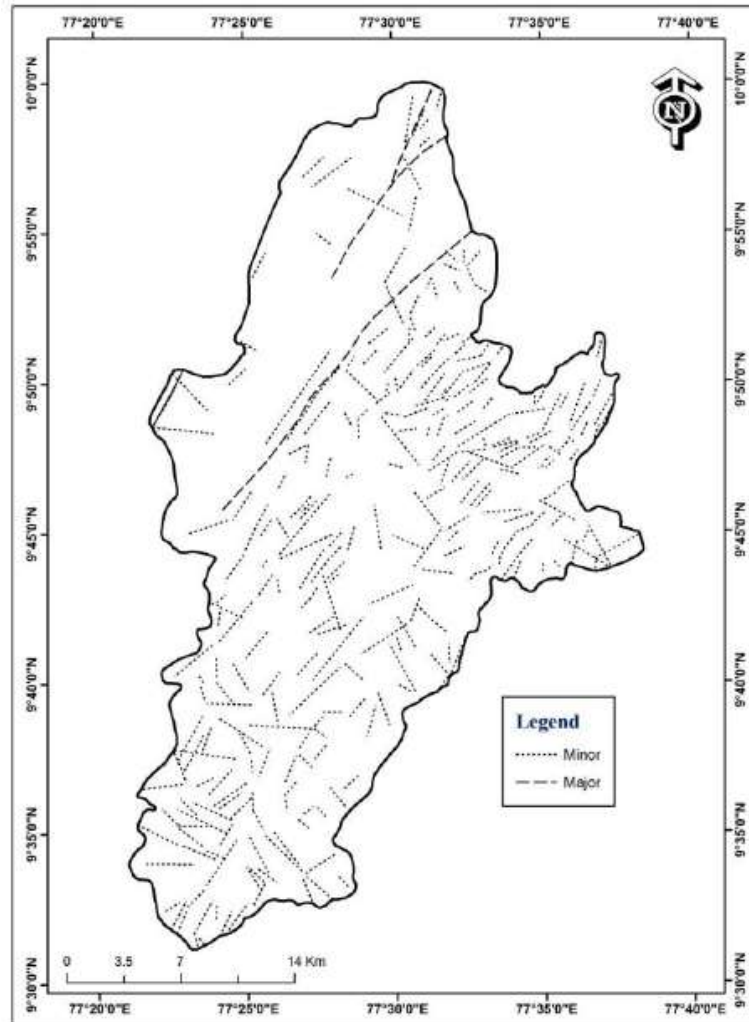


Figure 2.4 Lineament map. Reprinted from “Mapping of Lineaments for Groundwater Targeting and Sustainable Water Resource Management in Hard Rock Hydrogeological Environment Using RS-GIS” by P.P, B.R, 2013, INTECH, Chapter 10, page 239.

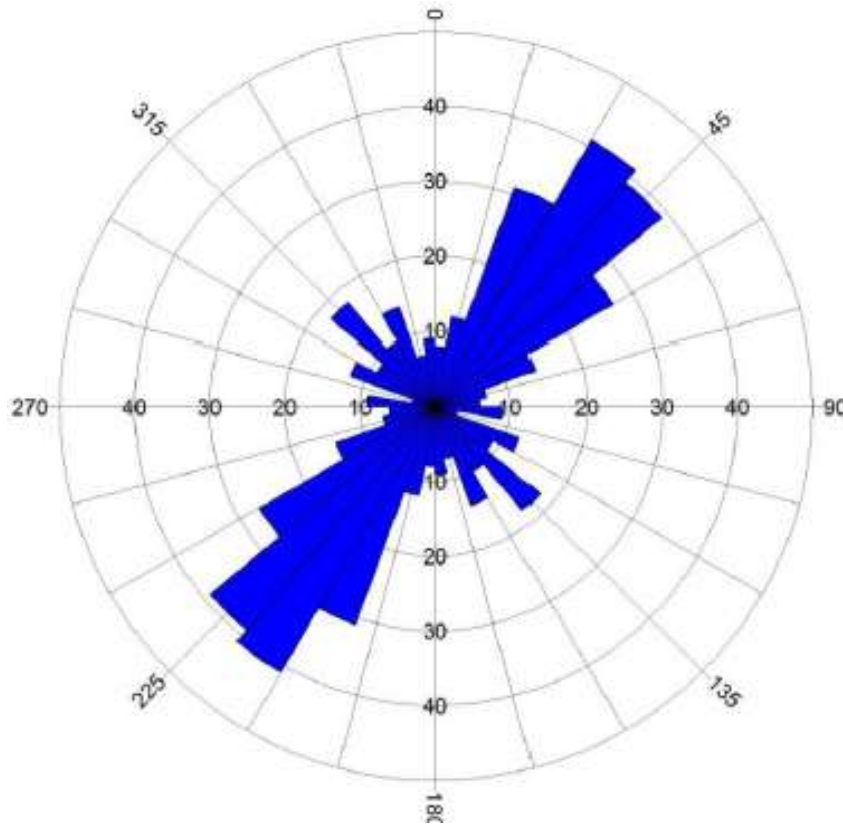


Figure 2.5 Lineament rose plot. Reprinted from “Mapping of Lineaments for Groundwater Targeting and Sustainable Water Resource Management in Hard Rock Hydrogeological Environment Using RS-GIS” by P.P, B.R, 2013, INTECH, Chapter 10, page 241.

In order to manage, display and disseminate spatial information, GIS utilizes different software programs such as ArcGIS, Vulcan, Leapfrog and etc. ‘ArcGIS’ is the industry standard GIS software used by most of civil engineering consulting firms. It assimilates information, and provides large set of geo-processing procedures such as map digitizing, queries and map overlay. It is capable of supporting multiple data formats, such as images, text and tables.

Queries are used in almost every analysis. This is preparatory step of extracting certain features prior to performing another function (<http://support.esri.com/>). Some common applications of queries are as following:

- Selecting features of interest/significance: Searching a table to which a feature meets certain criteria. For example, determining the number of rock tunnels in Washington DC area that encountered large loosening loads.
- Exploring spatial patterns: Determines whether rock tunnels with significant loosening loads are spaced or clustered in the same area of Washington DC.
- Isolating features for additional analysis: Select largest tunnels and determine the number of these tunnels closest to hydroelectric power plants.
- Exploring spatial relationship: Where tunnels cross unstable shale units mapped at the ground surface.

There are some disadvantages of using ArcGIS such as not being able to create 3D models. Leapfrog is another package that uses GIS and is capable of creating 3D models, but for the purpose of designing for loosening conditions, just a 3D model is not satisfactory. The engineer needs to analyze the data and determine the most adverse loading conditions to come up with design requirements for support systems. Figure 2.6 is an illustration of a 3D model created by leapfrog.
(<http://www.leapfrog3d.com/products/leapfrog-geo/videos>)

Vulcan is also capable of creating 3D models. Application of Vulcan is in mining industry. It provides models and information for mining operation and products, not stability of loosening loads.

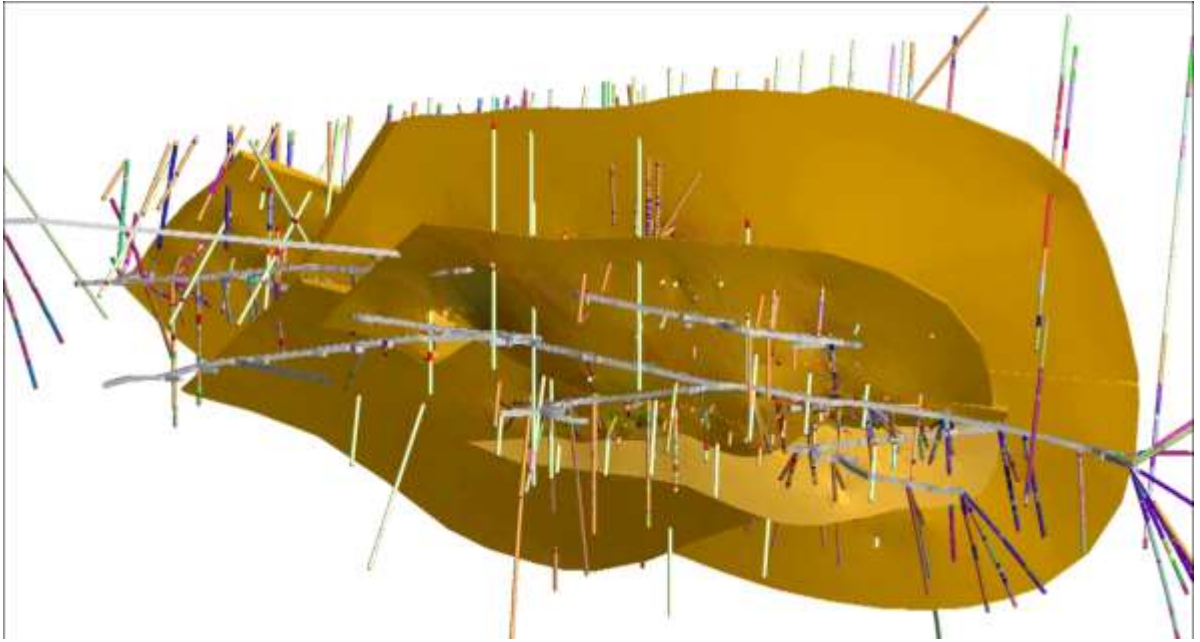


Figure 2.6 3D model created by leapfrog Reprinted
from <http://www.leapfrog3d.com/products/leapfrog-geo/videos>

3. Methodology

3.1 Introduction

The methodology used for predicting loosening loads is based on identifying joint sets and superimposing them to identify rock blocks and wedges. A joint set consists of joints that strike subparallel with each, dipping same direction and have almost same dip angle (see section 3.3). Joints that are striking within 20° from each other are considered sub parallel (see section 3.2.1). In order to identify joint sets, first joints should be organized based on their strike. Joints that strike sub parallel with each other and dip in the same direction are categorized as a set, then subdivided to low dipping and high dipping sets based on dip angle (see section 3.3). Dip is an acute angle that joint makes with horizontal plane. Strike and dip are always perpendicular to each other in a geologic map. In this study these processes were done by a code that was written in python. After determining joint sets, results were used to create cross section showing loosening loads (see section 4.4).

In this study, an arbitrary joint diagram was developed. The overall pattern was more complex than found in most tunnel settings in order to include different condition that might be encountered in the field. Joints were placed in four quadrant. The intension was to develop the code so that it would be independent of quadrants and origin location. Individual orientations were constructed arbitrarily and no specific strike and dip was entered into the diagram. As far as strike was concerned, the intention was to replicate typical joint patterns that are observed in nature. This includes having some of joints parallel, sub parallel, and intersecting each other.

In total, 100 joints were placed in plan view (see Figure 3.1). For each individual joint, an ID number, starting coordinates, ending coordinates, dip direction and dip angle were assigned. Dip amount and direction were assigned arbitrarily and are not shown on figure 1. It makes the figure too much crowded.

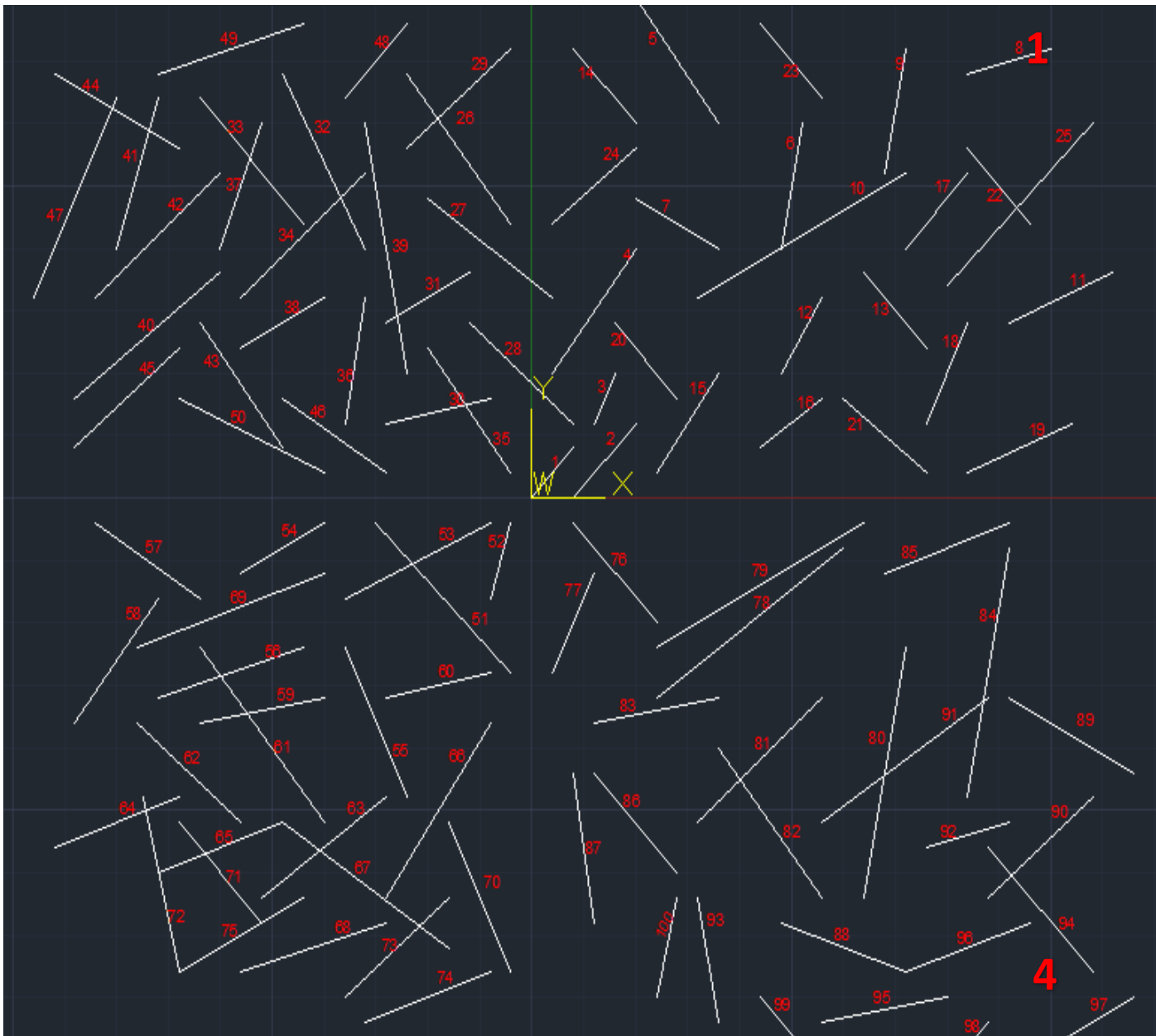
2**1****3****4**

FIGURE 3.1 Arbitrary developed geology map used in study

3.2 Data Collection Procedures

Geologic features play an important role in determining loading conditions on an opening. The ultimate goal of geologic study is to identify “joint sets”.

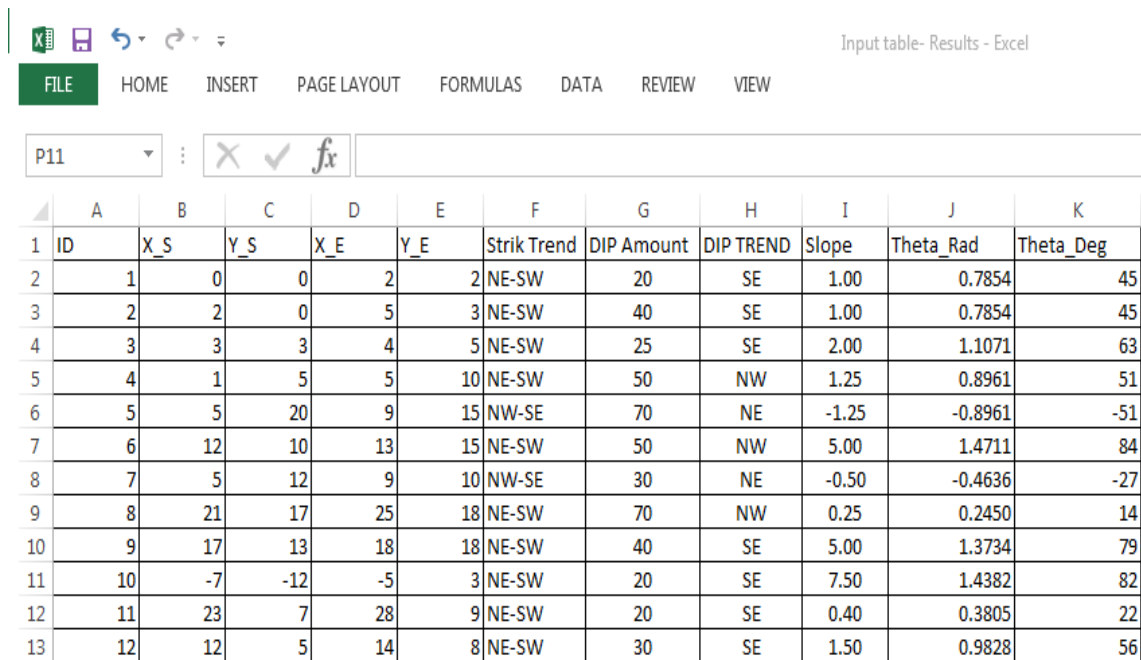
For this study, the arbitrary geologic map was first developed on a piece of engineering paper. Then coordinates of beginning and ending point of joints were entered to an Excel spreadsheet as well as dip direction and dip angle (See table 3.1). Using starting and ending point coordinates, strike was calculated. Since joints are same as lines in plan view, strike was calculated using equation of slope for a line (columns I, J and K in table 3.1). This table was entered in ArcGIS and digital geologic map was created (see figure 4.1). ArcGIS is capable of creating maps and storing multiple fields of data, so it provides the opportunity of running queries on the map. The column of ‘strike trend’ was not used in coding in python, it was provided to check results of code.

Usually joints that are most frequent in a 20° interval, are categorized into a joint set (Mahar et al 1972). Each set striking in a direction (NE-SW or NW-SE) can be categorized into maximum of 4 sets based on their dip trend (NW or SE for joints striking NE-SW and NE or SW for joints striking NW-SE) and their dip amount (low angle for joints with dip angle of less than 45° degrees and high angle for joints with dip angle of greater than 45°). The information about strike, dip direction and dip amount are stored in a table called ‘Attribute Table’ in ArcGIS. The code extracted the columns related to each field and stored them into lists. Then using the explained criteria, it categorized them into sets. First a shapefile was created using ArcGIS. Shapefile is an Esri vector data storage format for compiling location, shape and attributes of geographic features [www.esri.com]. It stores information as a set of related files. Shapefiles are readable by python using arcpy library.

In order to create the shapefile, ‘XYToLine’ from ‘Data Management’ toolbox in ArcGIS was used. This tool creates line features based on values in a start x-coordinate field, start y-coordinate field, end x-coordinate field and end y-coordinate field of a table.

Since joints in a geologic map are scattered in different directions and locations, they need to be organized in order to identify dominant directions and joint sets. Plotting rose diagrams in an efficient way to organize joints and provides ability to identify sets based on frequency of joints falling into same strike bands. A rose diagram is a circular histogram displaying frequency and directional data for each category. They are used to plot orientation of joints and their frequency in structural geology (see section 3.3.1)

Table 3.1 Excel spreadsheet data set



	A	B	C	D	E	F	G	H	I	J	K
1	ID	X_S	Y_S	X_E	Y_E	Strik Trend	DIP Amount	DIP TREND	Slope	Theta_Rad	Theta_Deg
2	1	0	0	2	2	NE-SW	20	SE	1.00	0.7854	45
3	2	2	0	5	3	NE-SW	40	SE	1.00	0.7854	45
4	3	3	3	4	5	NE-SW	25	SE	2.00	1.1071	63
5	4	1	5	5	10	NE-SW	50	NW	1.25	0.8961	51
6	5	5	20	9	15	NW-SE	70	NE	-1.25	-0.8961	-51
7	6	12	10	13	15	NE-SW	50	NW	5.00	1.4711	84
8	7	5	12	9	10	NW-SE	30	NE	-0.50	-0.4636	-27
9	8	21	17	25	18	NE-SW	70	NW	0.25	0.2450	14
10	9	17	13	18	18	NE-SW	40	SE	5.00	1.3734	79
11	10	-7	-12	-5	3	NE-SW	20	SE	7.50	1.4382	82
12	11	23	7	28	9	NE-SW	20	SE	0.40	0.3805	22
13	12	12	5	14	8	NE-SW	30	SE	1.50	0.9828	56

Terms and calculation processes are illustrated in Figures 3.2 to 3.5. Each figure demonstrates calculation in each quadrant.

- Figure Quadrant
- 3.2 I
- 3.3 II
- 3.4 III
- 3.5 IV

3.2.1 EXCEL SPREADSHEET

Using starting and ending X and Y coordinates, the strike direction of the joint was established by calculating theta angle in degrees between the joint and the positive x-axis. This is a three step process (See Tables 3.2 to 3.5). Joints were represented as lines in the x-y plane. The slope of a line is calculated using the following equation (Table 3.2):

- $m = (y_2 - y_1) / (x_2 - x_1)$

By taking inverse tangent of slope, the angle (theta) of a line is calculated in radians.

Finally, Theta_Rad is converted to degrees

- $\text{Theta_Degrees} = \tan^{-1}(\text{Slope}) * 180 / 3.1415$

Procedure for all four quadrants was the same. Joints have positive and negative slopes.

They are chosen from different quadrants to show that location of joints does not affect the procedure.

QUADRANT I

Table 3.2 Excel spreadsheet for joint 1 in quadrant 1

Convert to degrees

	A	B	C	D	E	F	G	H	I	J	K
1	ID	X_S	Y_S	X_E	Y_E	Strike Trend	DIP Amount	DIP Trend	Slope	Theta_Rad	Theta_Deg
2	1	0	0	2	2	NE-SW	20	SE	1	0.7853982	45

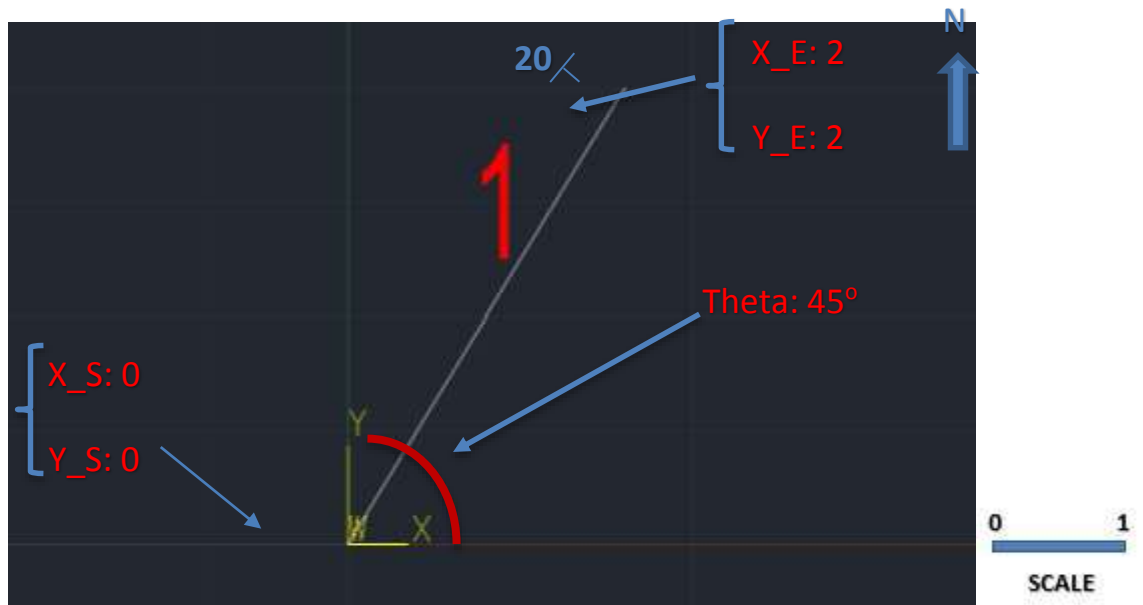


Figure 3.2 Illustration of joint 1 properties in quadrant I

QUADRANT II

Table 3.3 Excel spreadsheet for joint 35 in quadrant 2

ID	X_S	Y_S	X_E	Y_E	Strike Trend	DIP Amount	DIP Trend	Slope	Theta_Rad	Theta_Deg
35	-5	6	-1	1	NW-SE	80	SW	-1.25	-0.896055	-51.3401917



Figure 3.3 Illustration of joint 35 properties in quadrant II

QUADRANT III

Table 3.4 Excel spreadsheet for joint 52 in quadrant 3

ID	X_S	Y_S	X_E	Y_E	Strik Trend	DIP Amount	DIP TREND	Slope	Theta_Rad	Theta_Deg
52	-2	-4	-1	-1	NE-SW	18	NW	3.00	1.2490	72

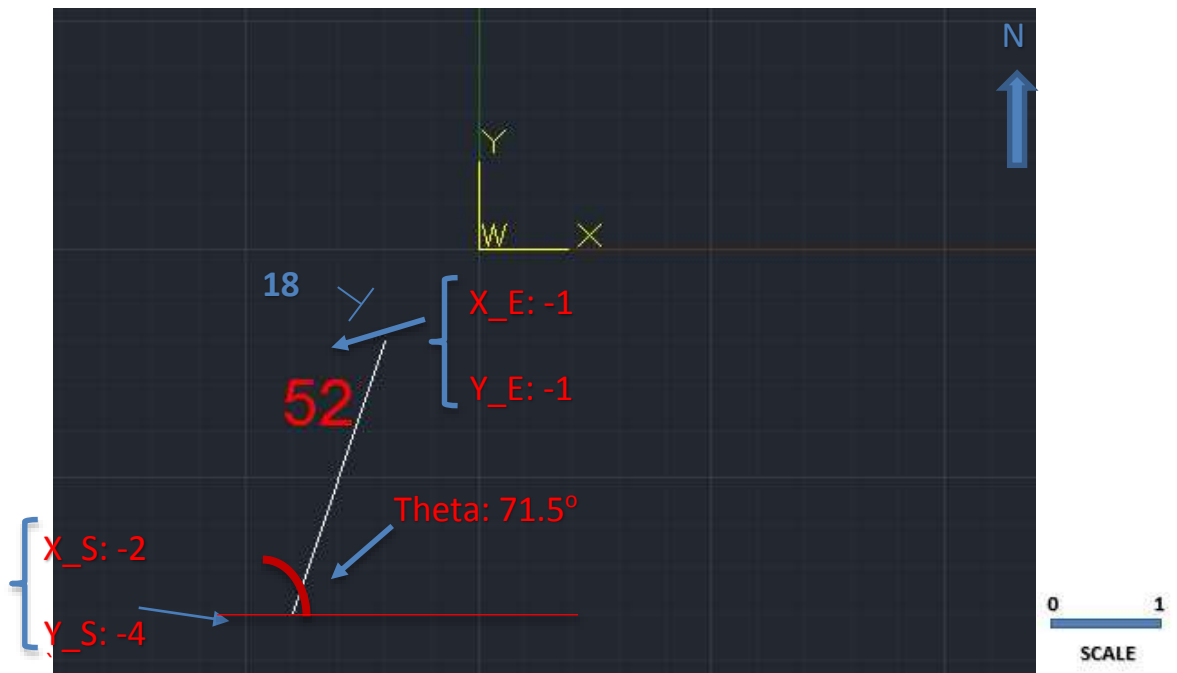


Figure 3.4 Illustration of joint 52 properties in quadrant III

QUADRANT IV

Table 3.5 Excel spreadsheet for joint 76 in quadrant 4

ID	X_S	Y_S	X_E	Y_E	Strike Trend	DIP Amount	DIP Trend	Slope	Theta_Rad	Theta_Deg
76	2	-1	6	-5	NW-SE	30	SW	-1	-0.785398	-45

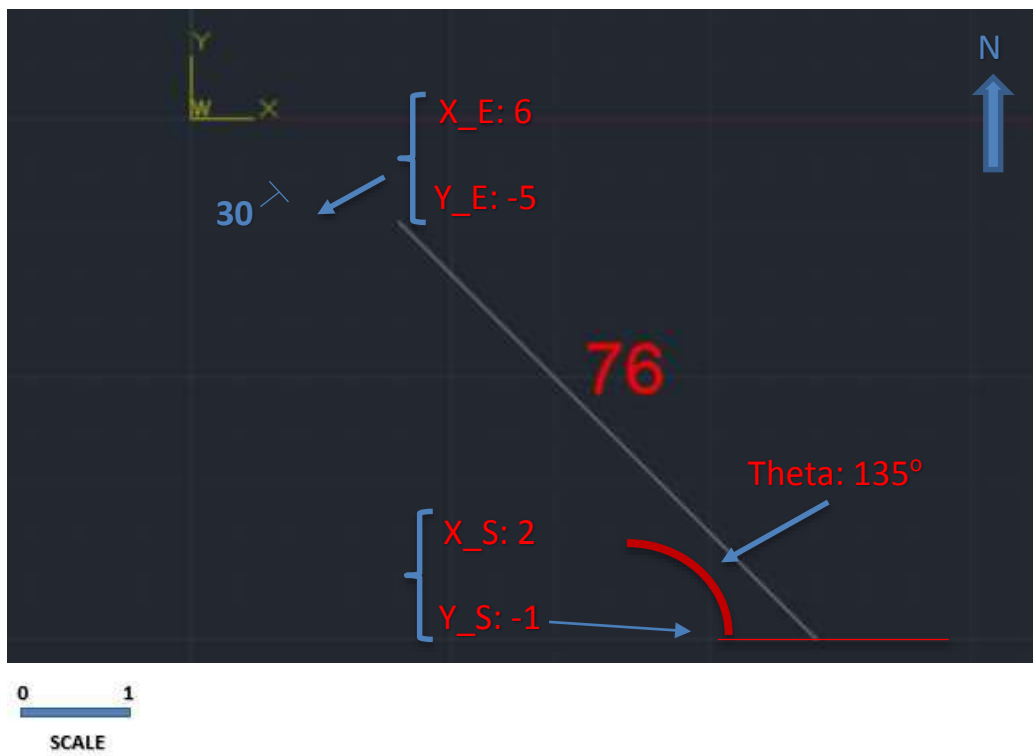


Figure 3.5 Illustration of joint 76 properties in quadrant IV

3.3 CODING PROCEDURES IN PYTHON

Plotting a rose diagram is a useful way to visualize joints in an organized manner. In this study, part of code iterated through information provided in the previous chapter and developed needed data to plot a rose diagram in Excel.

From the spreadsheet developed in section 3.2, python read the following information:

- ID
- Theta
- Dip Amount
- Dip Trend

Then, python changed negative theta angles to positive by adding 180° to negative theta angles (See Figure 3.6).

Using positive theta angle has some advantages. It made writing code for calculating strike azimuth of joints easier, there was no need to use quadrants in follow-on steps.

Also follow-on process were independent of origin location.

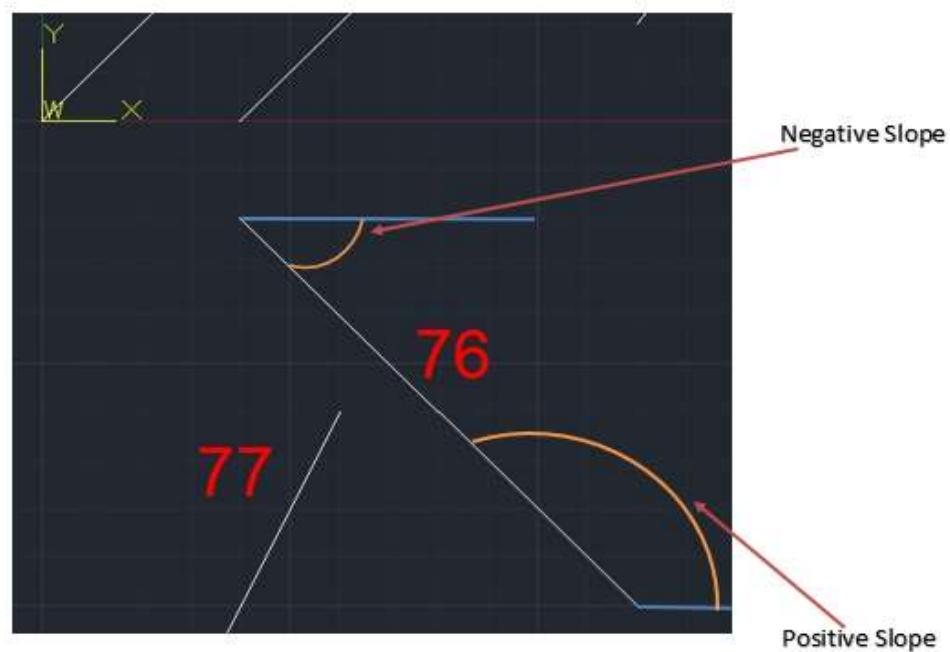


Figure 3.6 Conversion of negative theta angle to positive value

3.3.1 DETERMINING JOINT SETS

Joint sets were determined in 3 steps. Steps are explained in this section.

STEP 1

First step is calculating 'Strike Azimuth'. Strike azimuth is the angle between the joint trace and positive north direction. It makes analysis independent of strike direction. In order to calculate strike azimuth only positive theta angles are needed. All positive angles were between 0 and 180°. Joints that have strike azimuth of 180 to 270° are in the same direction as joints that have strike azimuth of 0 to 90°. Joints that have strike azimuth of 90 to 180° are in the same direction as joints that had strike azimuth of 270 to 360°. Calculated strike azimuths were between 0 to 90° or 270 to 360°.

This is the reason python did not need 'Strike direction' column from the Excel spread sheet. Also by using strike azimuth, analysis was independent of origin and quadrant location. In other word, the location of joint does not affect set designation. Following is the piece of code written in python to calculate strike azimuth:

```
#Calculating Azimuth
```

```
for i in range(0, len(Slope)) :
```

```
    if 0 < Slope[i] <90 :
```

```
        Azimuth.append( 90 - Slope[i])
```

```
    elif 90 < Slope[i] < 180 :
```

```
        Azimuth.append( 360-(Slope[i]-90))
```


Step 2

In this step, calculated azimuth strikes from previous step were categorized into 5° bands by the code. Total of 36 bands were formed, 18 bands in the upper right quadrant of the rose diagram, and 18 bands in the upper left quadrant of the rose diagram. Since azimuth strike values were either between 0 to 90° or 270 to 360° , only the upper hemisphere of the rose diagram was filled.

Python exported bands information as an Excel file. The file included 3 columns: bands, frequency of joints within that band and average strike azimuth of joints within that band. (See Table 4.2 in chapter 4).

Step 3

Rose diagrams visualize compass distribution of strike data independent of geographic location. The length of the radius in rose diagram is proportional to frequency of joint orientations in an interval. Figure 3.7 shows the rose diagram for joints in figure 3.1. The diagram was plotted in Excel by inserting a donut diagram.

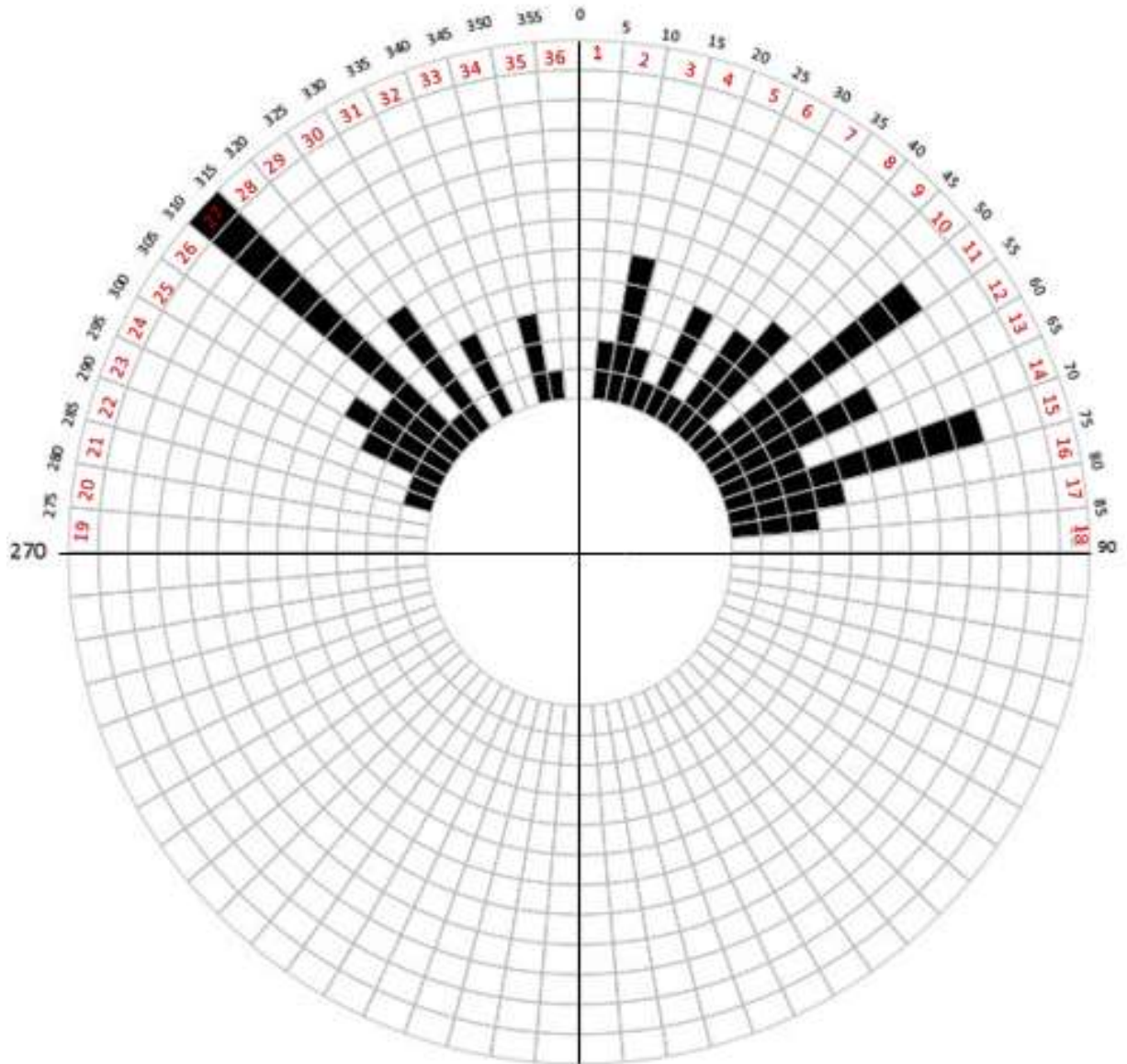


Figure 3.7 Rose diagram of strike for joints in figure 3.1

From rose diagram, dominant joint directions were estimated by user. Usually joints that fall into a set are within 10 degrees from the average strike value chosen as the strike of set (Mahar et al 1972). The process of determining dominant strike directions may be done by writing a code, but visualizing the condition of joints can help engineer in coming up with proper design, such as choosing proper alignment.

After user identified dominant strike directions, joints were categorized to final sets using python. Code asked user to enter the beginning and ending band of dominant strike direction. User only needed to enter the digit after 'I' from Table 4.2. For example, for joints between I4 and I6, enter 4 and 6 when indicated by code.

Python found all joints that fell within these limits and developed lists containing following information:

- ID of joints
- Dip angle
- Dip trend
- Strike azimuth

Using these lists, python calculated average azimuth strike of joints and range of azimuth strike (maximum strike azimuth – minimum strike azimuth) of joints falling within given limits. (See section 4.3). Range of strike helps the designer in determining block size.

Then it split joints based on their dip direction. For example, joints striking NE-SW were split to NW or SE dipping. Each dipping direction was then subdivided based on dip angle. If dip angle was less than 45° , joints were designated as low dipping while greater than 45° was high dipping. Python calculated frequency, average of dip amount and average of azimuth strike for all of joints falling in each set. Then numbers were assigned to the joint sets to separate them from each other. For example, joint set 1L represented 'joint set number 1 with low dipping joints, or joint set 2H represented 'joint set number 2 with high dipping joints'.

Python exported this output as an Excel file. For each dominant strike direction, a separate excel file was exported. The file contained following information. These information can help the engineer in choosing proper alignment and ground behavior (see section 4.3):

- Number of joints in each dominant strike direction
- Strike azimuth average of joints within dominant strike direction

- Range of strike azimuth of joints within dominant strike direction
- Maximum azimuth strike of joints within dominant strike direction
- Minimum azimuth strike of joints within dominant strike direction
- Information on dip for joints within dominant strike direction
- SE, NW, SW or NE trend
- Frequency of each dip trend
- Frequency of low angle joints for each set (Less than 45°)
- Minimum low angle dip amount in each set
- Maximum low angle dip amount in each set
- Range of low angle dipping joints in each set
- Frequency of high angle joints for each set (greater than 45°)
- Minimum high angle dip amount in each set
- Maximum high angle dip amount in each set
- Range of high angle dipping joints in each set

These tables are presented in chapter 4.

3.4 USE OF AUTOCAD IN PREDICTING LOOSENING LOADS AND BLOCKS IN TUNNEL OPENING

Using information developed from previous steps along with AutoCAD, models of tunnel cross section for predicting block size and ground behavior were constructed.

Tunnel geometry was plotted in AutoCAD, followed by plotting each joint set on the opening using dip angles. Offset of opening was plotted in order to determine depth of load zone. Offset distance varies between $1/3$ to $1/2$ width of opening, depending on depth of tunnel (Mahar, Cording 1974).

Large over breaks and fall outs may occur when joints intersect in the walls and arch of tunnel (Mahar et al 1972). After defining the loading zone, joints were each placed in the following locations:

- Tangent to arch to consider falling blocks from arch
- Intersection with tunnel invert to consider sliding and toppling blocks from side into opening

The distance between joint sets should be divided based on spacing between joints measured from field investigations, because spacing controls the distance between joints (Mahar, Cording 1974). In this study, spacing was not considered since the focus was on orientation. The distance between joints was divided to $1/3$ of width of opening for this study. By using joints pattern, loosening load blocks and wedges were developed.

Apparent orientation was not considered, since it usually does not make a big difference in size of block that can affect design of support systems.

Intersecting joints formed rock blocks (See Fig. 4.6 to 4.9). Rock blocks within the loading zone should be supported. Rock blocks outside loaded zone are stable where support on the tunnel perimeter is adequate (Mahar, Cording 1974).

Nature of rock block movement is dependent on inclination and nature of rock block geometry. Based on these criteria, three different loosening conditions are expected:

1. Falling Blocks: Direct gravity fall of rock blocks from arch into the opening. Rock anchors are required to hold blocks in place. Rock anchor will act in tension.
2. Sliding Condition: Rock blocks slide into opening from sides. This condition happens as result of inclined blocks orienting towards opening. This requires wall support or rock anchor. Rock anchor will act in shear and tension.
3. Toppling Condition: Rock blocks topple into opening. Toppling happen as a result of center of gravity of block being located towards opening. This requires rock anchors to hold blocks in place. Rock anchor will act in shear and tension.

As far as frequency of occurrence is concerned, falling blocks from the top are the most common loosening loads. Then sliding conditions are next and occur in the side walls. Toppling conditions are the least common loosening behavior. Based on all cross sections, critical conditions could be identified. This includes conditions that cause the most extreme loads and moments around opening and in the arch. The required support system should be designed by structural engineer.

In this study, tunnel alignment was plotted subparallel with joint sets 1 and 2 in order to consider the most adverse conditions, since these joint sets run parallel with the alignment. In this condition, support systems are required along tunnel alignment, as oppose if joint sets go through the alignment, we are only dealing with loosening loads in a short section of tunnel. Then tunnel cross sections were constructed. In the cross sections, approximate perimeter of expected rock loading conditions was plotted. After defining load zone, planes of joint set combinations were plotted on tunnel cross section. For joints with strike azimuths in set Nos 1 and 2, four different tunnel cross sections were developed:

- Low dip on Low dip

- High dip on High dip
- Low dip on High dip
- High dip on low dip

These cross sections were used to identify rock blocks and loading conditions.

Orientation of geologic structures and their direction determine types of over break and fallouts in tunnels (Mahar et al 1972). Based on joint sets orientation in the tunnel opening fall out blocks, sliding blocks, and toppling blocks were identified (see section 4.4).

4. RESULTS OF STUDY

4.1 Introduction

This chapter presents results of this study. A total of 14 joint sets were identified from Figure 3.1. Using the criteria explained in chapter 3, cross sections were constructed. They are illustrated in figures 4.4 through 4.7.

Tables 4.1 through 4.5 illustrate summary of joint sets information.

4.2 Joint Data Results Exported from Python

Table 4.1 shows input data read by python. Columns A through E, and G through I were input data developed from Fig 3.1 and tabulated in Excel (See Table 4.1). Python used these columns to calculate values in columns L and M. Columns L and M were not output data but rather used to help determine joint sets.

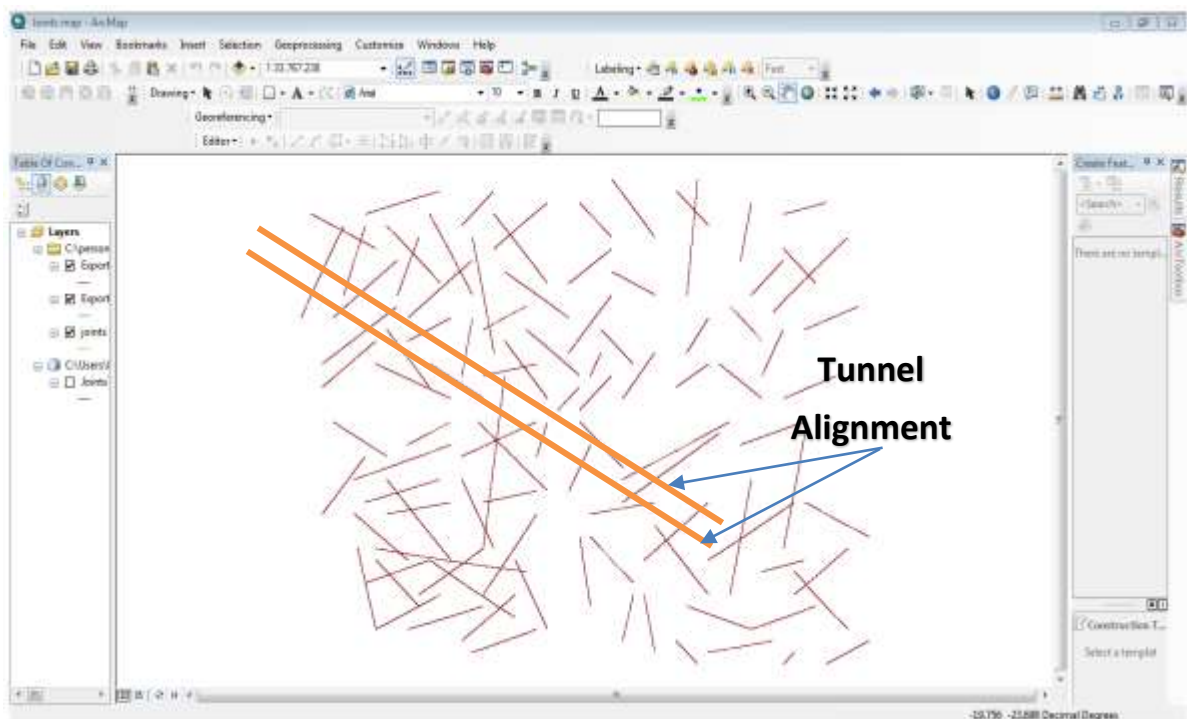


FIGURE 4.1 Joint set orientation map including proposed tunnel alignment used in study in ArcGIS

Table 4.1 Input data and results calculated using Python

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	A	B	C	D	E	F	G	H	I	J	K	L	M
1	ID	X_S	Y_S	X_E	Y_E	Strik Trend	DIP Amount	DIP TREND	Slope	Theta_Rad	Theta_Deg	Strike Azimuth	Strik Trend
2	1	0	0	2	2	NE-SW	20	SE	1.00	0.7854	45	45	NE-SW
3	2	2	0	5	3	NE-SW	40	SE	1.00	0.7854	45	45	NE-SW
4	3	3	3	4	5	NE-SW	25	SE	2.00	1.1071	63	26.57	NE-SW
5	4	1	5	5	10	NE-SW	50	NW	1.25	0.8961	51	38.7	NE-SW
6	5	5	20	9	15	NW-SE	70	NE	-1.25	-0.8961	-51	321.34	NW-SE
7	6	12	10	13	15	NE-SW	50	NW	5.00	1.4711	84	5.71	NE-SW
8	7	5	12	9	10	NW-SE	30	NE	-0.50	-0.4636	-27	296.57	NW-SE
9	8	21	17	25	18	NE-SW	70	NW	0.25	0.2450	14	75.96	NE-SW
10	9	17	13	18	18	NE-SW	40	SE	5.00	1.3734	79	11.31	NE-SW
11	10	-7	-12	-5	3	NE-SW	20	SE	7.50	1.4382	82	7.59	NE-SW
12	11	23	7	28	9	NE-SW	20	SE	0.40	0.3805	22	68.2	NE-SW
13	12	12	5	14	8	NE-SW	30	SE	1.50	0.9828	56	33.69	NE-SW
14	13	16	9	19	6	NW-SE	50	NE	-1.00	-0.7854	-45	315	NW-SE
15	14	2	18	5	15	NW-SE	60	NE	-1.00	-0.7854	-45	315	NW-SE
16	15	6	1	9	5	NE-SW	80	SE	1.33	0.9273	53	36.87	NE-SW
17	16	11	2	14	4	NE-SW	70	NW	0.67	0.5880	34	56.31	NE-SW
18	17	18	10	21	13	NE-SW	25	NW	1.00	0.7854	45	45	NE-SW
19	18	19	3	21	7	NE-SW	40	SE	2.00	1.1071	63	26.57	NE-SW
20	19	21	1	26	3	NE-SW	70	SE	0.40	0.3805	22	68.2	NE-SW
21	20	4	7	7	4	NW-SE	50	NE	-1.00	-0.7854	-45	315	NW-SE
22	21	15	4	19	1	NW-SE	40	NE	-0.75	-0.6435	-37	306.87	NW-SE
23	22	21	14	24	11	NW-SE	30	NE	-1.00	-0.7854	-45	315	NW-SE
24	23	11	19	14	16	NW-SE	20	NE	-1.00	-0.7854	-45	315	NW-SE
25	24	1	11	5	14	NE-SW	60	NW	0.75	0.6435	37	53.13	NE-SW
26	25	20	8.5	27	15	NE-SW	50	NW	0.93	0.7484	43	47.12	NE-SW
27	26	-6	17	-1	11	NW-SE	10	NE	-1.20	-0.8761	-50	320.19	NW-SE
28	27	-5	12	1	8	NW-SE	80	SW	-0.67	-0.5880	-34	303.69	NW-SE
29	28	-3	7	2	3	NW-SE	40	SW	-0.80	-0.6747	-39	308.66	NW-SE
30	29	-6	14	-1	18	NE-SW	35	NW	0.80	0.6747	39	51.34	NE-SW
31	30	-7	3	-2	4	NE-SW	25	SE	0.20	0.1974	11	78.69	NE-SW
32	31	-7	7	-3	9	NE-SW	40	NW	0.50	0.4636	27	63.43	NE-SW
33	32	-12	17	-8	10	NW-SE	70	NW	-1.75	-1.0517	-60	330.26	NW-SE
34	33	-16	16	-11	11	NW-SE	40	NE	-1.00	-0.7854	-45	315	NW-SE
35	34	-14	8	-8	13	NE-SW	80	SE	0.83	0.6947	40	50.19	NE-SW
36	35	-5	6	-1	1	NW-SE	80	SW	-1.25	-0.8961	-51	321.92	NW-SE
37	36	-9	3	-8	8	NE-SW	30	SE	5.00	1.3734	79	11.31	NE-SW
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READY													

Table 4.2 Summary of joint frequency in 5° bands used to determine joint sets in rose diagram

Interval	Frequency	Average strike azimuth in band
I1	0	0
I2	2	7
I3	5	12
I4	2	18
I5	1	22
I6	4	27
I7	1	34
I8	4	37
I9	5	45
I10	1	47
I11	9	52
I12	4	57
I13	6	63
I14	3	68
I15	9	72
I16	4	77
I17	3	81
I18	0	0
I19	0	0
I20	0	0
I21	0	0
I22	1	288
I23	1	293
I24	3	297
I25	4	302
I26	3	308
I27	12	315
I28	1	319
I29	5	321
I30	0	0
I31	3	332
I32	0	0
I33	0	0
I34	3	348
I35	1	351
I36	0	0

In order to determine joint sets, frequency of joints in 15 to 20° intervals was used. Intervals in which most joints are clustered form joint sets. There is no minimum number of joints for selecting a joint sets.

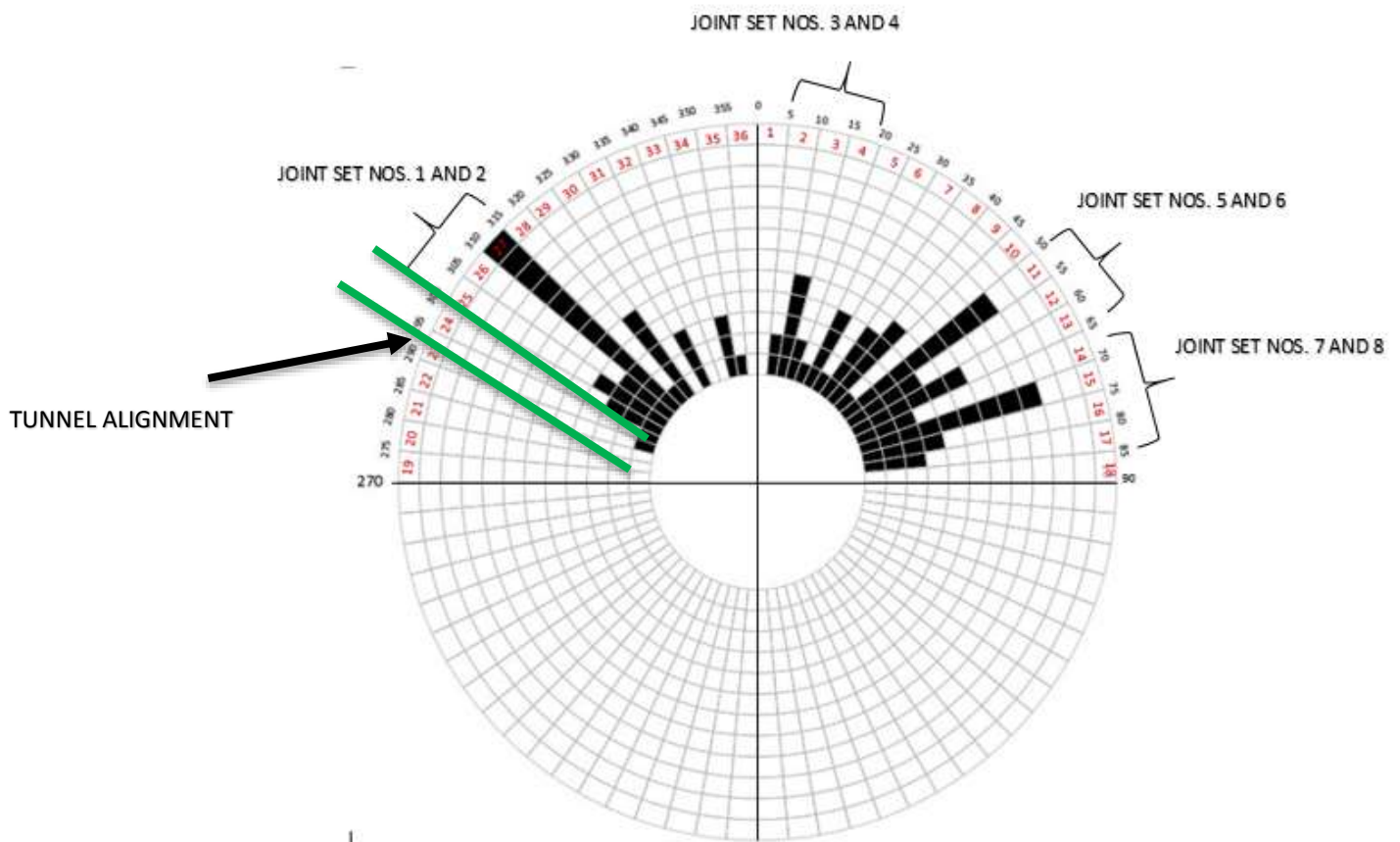


FIGURE 4.2 Upper hemisphere rose diagram of joint strike from Fig. 4.1

4.3 Joint Set Summary

Table 4.3 shows summary of identified joint sets. Average strike azimuth is the sum of the azimuths in each individual joint set divided by number of joints in the set. Azimuth strike range is the difference between maximum and minimum azimuth strikes within each joint set.

Dip amount range is the difference between maximum and minimum dip amount in each of low and high angle joint set designation.

Table 4.3 Summary of joint sets identified in figure 3.1

Set	Azimuth Strike Range	Dip Direction	Dip Amount Range
1L	N 45-51 W	NE	13-40
1H	N 45-58 W	NE	48-70
2L	N 45-59 W	SW	10-43
2H	N 45-59 W	SW	53-80
3L	N 8-18 E	SE	10-40
4H	N 6-14 E	NW	50-65
5L	N 51-63 E	SE	20-28
5H	N 50-56 E	SE	48-80
6L	N 50-63 E	NW	10-40
6H	N 50-56 E	NW	60-82
7L	N 68-79 E	SE	10-41
7H	N 68-76 E	SE	50-83
8L	N 67-81 E	NW	21-40
8H	N 72-81 E	NW	50-82

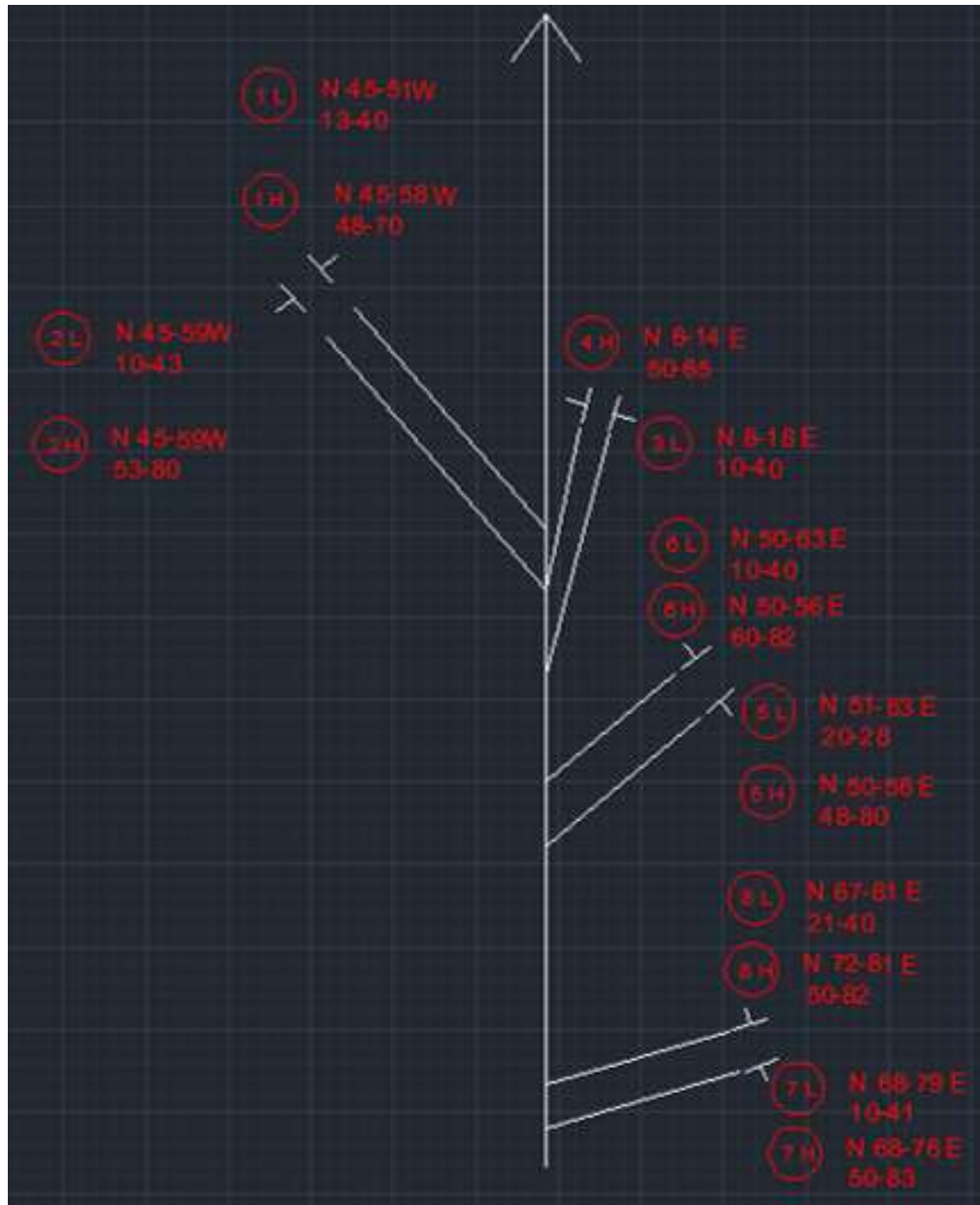


Figure 4.3 Summary of all joint set orientations in arbitrary joint map (Fig. 3.1)

Table 4.4 provides details on the total number of joints within same joint set strike and average strike azimuth of joints within same joint set strike.

Table 4.4 Frequencies and attitudes of dominant joint set strikes.

Joints with Strike N 45-59 W Dip SW AND NE (joint set 1 and 2)

Number of Joints	19
Strike Azimuth Average	311
Strike Azimuth Range	14
Maximum Strike Azimuth	315
Minimum Strike Azimuth	301

Joints with Strike N 6-18 E Dip SE AND NW (joint sets 3 and 4)

Number of Joints	9
Strike Azimuth Average	12
Strike Azimuth Range	13
Maximum Strike Azimuth	18
Minimum Strike Azimuth	6

Joints with Strike N 50-63 E Dip SE AND NW (joint sets 5 and 6)

Number of Joints	19
Strike Azimuth Average	56
Strike Azimuth Range	13
Maximum Strike Azimuth	63
Minimum Strike Azimuth	50

Joints with Strike N 67-81E Dip SE AND NW (joint sets 7 and 8)

Number of Joints	19
Strike Azimuth Average	74
Strike Azimuth Range	14
Maximum Strike Azimuth	81
Minimum Strike Azimuth	67

Tables 4.8 to 4.18 provide orientation data on all individual joint sets in Fig. 3.1. These tables include detailed summary of each joint set orientation and frequency. They separate joints with same strike trend and same dip direction into high and low angle joints. They were developed using python.

Table 4.5 Joint Set 1L: Strike N 45-59 W Dip 13 to 40° NE

Maximum Strike Azimuth of NE Low Angle Joints	315
Minimum Strike Azimuth of NE Low Angle Joints	301
Range Strike Azimuth of NE Low Angle Joints	14
Frequency of NE Low Angle Joints	7
Average Dip of NE Low Angle Joints	24
Minimum NE Low Dip Angle Joints	13
Maximum NE Low Dip Angle Joints	40
Range of Dip of NE Low Angle Joints	27

Table 4.6 Joint Set 1H: Strike N 45-59 W Dip 48 to 70° NE

Maximum Strike Azimuth of NE High Angle Joints	315
Minimum Strike Azimuth of NE High Angle Joints	301
Range of Strike Azimuth of NE High Angle Joints	14
Frequency of NE High Angle Joints	5
Average Dip of NE High Angle Joints	55
Minimum Dip of NE High Angle Joints	48
Maximum Dip of NE High Angle Joints	70
Range of Dip of NE High Angle Joints	22

Table 4.7 Joint Set 2L: Strike N 45-51 W Dip 10 to 43° SW

Maximum Strike Azimuth of SW Low Angle Joints	315
Minimum Strike Azimuth of SW Low Angle Joints	309
Range Strike Azimuth of SW Low Angle Joints	6
Frequency of SW Low Angle Joints	4
Average Dip of SW Low Angle Joints	30
Minimum Dip of SW Low Angle Joints	10
Maximum Dip of SW Low Angle Joints	43
Range of Dip of SW Low Angle Joints	33

Table 4.8 Joint Set 2H: Strike N 45-58 W Dip 53 to 80° SW

Maximum Strike Azimuth of SW High Angle Joints	315
Minimum Strike Azimuth of SW High Angle Joints	302
Range of Strike Azimuth of SW High Angle Joints	13
Frequency of SW High Angle Joints	3
Average Dip of SW High Angle Joints	67
Minimum Dip of SW High Angle Joints	53
Maximum Dip of SW High Angle Joints	80
Range of Dip of SW High Angle Joints	27

Table 4.9 Joint Set 3L: Strike 8-18 E Dip 10 to 40° SE

Maximum Strike Azimuth of SE Low Angle Joints	18
Minimum Strike Azimuth of SE Low Angle Joints	8
Range Strike Azimuth of SE Low Angle Joints	11
Frequency of SE Low Angle Joints	5
Average Dip of SE Low Angle Joints	25
Minimum Dip of SE Low Angle Joints	10
Maximum Dip of SE Low Angle Joints	40
Range of Dip of SE Low Angle Joints	30

Table 4.10 Joint Set 4H: Strike N 6-14 E Dip 50 to 65° NW

Maximum Strike Azimuth of NW High Angle Joints	14
Minimum Strike Azimuth of NW High Angle Joints	6
Range of Strike Azimuth of NW High Angle Joints	8
Frequency of NW High Angle Joints	2
Average Dip of NW High Angle Joints	57
Minimum Dip of NW High Angle Joints	50
Maximum Dip of NW High Angle Joints	65
Range of Dip of NW High Angle Joints	15

4.11 Joint Set 5L: Strike N 51-63 E, Dip 20 to 28° SE

Maximum Strike Azimuth of SE Low Angle Joints	63
Minimum Strike Azimuth of SE Low Angle Joints	51
Range Strike Azimuth of SE Low Angle Joints	12
Frequency of SE Low Angle Joints	3
Average Dip of SE Low Angle Joints	25
Minimum Dip of SE Low Angle Joints	20
Maximum Dip of SE Low Angle Joints	28
Range of Dip of SE Low Angle Joints	8

Table 4.12 Joint Set 5H: Strike N 50-56 E, Dip 48 to 80° SE

Maximum Strike Azimuth of SE High Angle Joints	56
Minimum Strike Azimuth of SE High Angle Joints	50
Range of Strike Azimuth of SE High Angle Joints	6
Frequency of SE High Angle Joints	2
Average Dip of SE High Angle Joints	64
Minimum Dip of SE High Angle Joints	48
Maximum Dip of SE High Angle Joints	80
Range of Dip of SE High Angle Joints	32

Table 4.13 Joint Set 6L: Strike N 50-63 E, Dip 10 to 40° NW

Maximum Strike Azimuth of NW Low Angle Joints	63
Minimum Strike Azimuth of NW Low Angle Joints	50
Range Strike Azimuth of NW Low Angle Joints	13
Frequency of NW Low Angle Joints	10
Average Dip of NW Low Angle Joints	27
Minimum NW Low Dip Angle Joints	10
Maximum NW Low Dip Angle Joints	40
Range of Dip of NW Low Angle Joints	30

Table 4.14 Joint Set 6H: Strike N 50-56 W, Dip 60 to 82° NW

Maximum Strike Azimuth of NW High Angle Joints	56
Minimum Strike Azimuth of NW High Angle Joints	50
Range of Strike Azimuth of NW High Angle Joints	6
Frequency of NW High Angle Joints	4
Average Dip of NW High Angle Joints	73
Minimum Dip of NW High Angle Joints	60
Maximum Dip of NW High Angle Joints	82
Range of Dip of NW High Angle Joints	22

Table 4.15 Joint Set 7L: Strike N 68-79E, Dip 10 to 41° SE

Maximum Strike Azimuth of SE Low Angle Joints	79
Minimum Strike Azimuth of SE Low Angle Joints	68
Range Strike Azimuth of SE Low Angle Joints	11
Frequency of SE Low Angle Joints	7
Average Dip of SE Low Angle Joints	26
Minimum Dip of SE Low Angle Joints	10
Maximum Dip of SE Low Angle Joints	41
Range of Dip of SE Low Angle Joints	31

Table 4.16 Joint Set 7H: Strike N 68-76 E, Dip 50 to 83° SE

Maximum Strike Azimuth of SE High Angle Joints	76
Minimum Strike Azimuth of SE High Angle Joints	68
Range of Strike Azimuth of SE High Angle Joints	8
Frequency of SE High Angle Joints	4
Average Dip of SE High Angle Joints	68
Minimum Dip of SE High Angle Joints	50
Maximum Dip of SE High Angle Joints	83
Range of Dip of SE High Angle Joints	33

Table 4.17 Joint Set 8L: Strike N 67-81 W, Dip 21 to 40° NW

Maximum Strike Azimuth of NW Low Angle Joints	81
Minimum Strike Azimuth of NW Low Angle Joints	67
Range Strike Azimuth of NW Low Angle Joints	14
Frequency of NW Low Angle Joints	3
Average Dip of NW Low Angle Joints	31
Minimum NW Low Dip Angle Joints	21
Maximum NW Low Dip Angle Joints	40
Range of Dip of NW Low Angle Joints	19

Table 4.18 Joint Set 8H: Strike N 72-81 W, Dip 50 to 82° NW

Maximum Strike Azimuth of NW High Angle Joints	81
Minimum Strike Azimuth of NW High Angle Joints	72
Range of Strike Azimuth of NW High Angle Joints	9
Frequency of NW High Angle Joints	5
Average Dip of NW High Angle Joints	67
Minimum Dip of NW High Angle Joints	50
Maximum Dip of NW High Angle Joints	82
Range of Dip of NW High Angle Joints	32

4.4 Loosening Behavior in Hypothetical Tunnel Intersected By Joints in Sets 1 And 2

This section illustrates cross section of tunnel alignment superimposed by joint sets 1 and 2. Total of 4 cross sections were constructed in AutoCAD. These cross sections help to identify loosening loads. Fall out blocks, sliding blocks, and toppling blocks are shown in figures 4.4 to 4.7.

In figure 4.4, block number 1 is expected to fall into opening from the crown due to gravity. Blocks 2 and 3 are expected rotate into opening, since their center of gravity is located towards opening. They create toppling condition. Blocks that are located below blocks 2 and 3 are expected to slide into opening. These blocks have fairly homogenous geometry and are inclined towards opening. Gravity will pull them into opening along joints 1L and 2L. Loosening conditions if figure 4.5 to 4.7 are determined using same criteria.

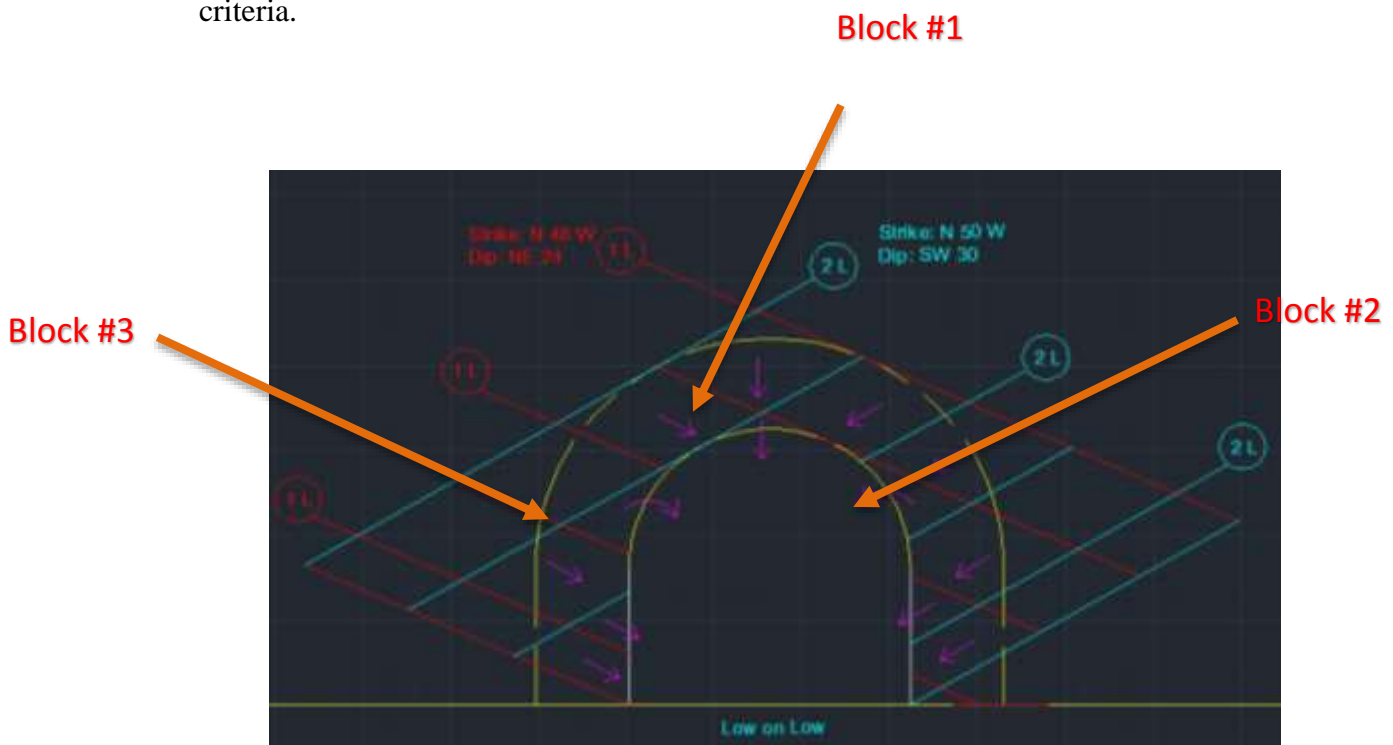


Figure 4.4 Tunnel cross section superimposed by joint sets 1L and 2L

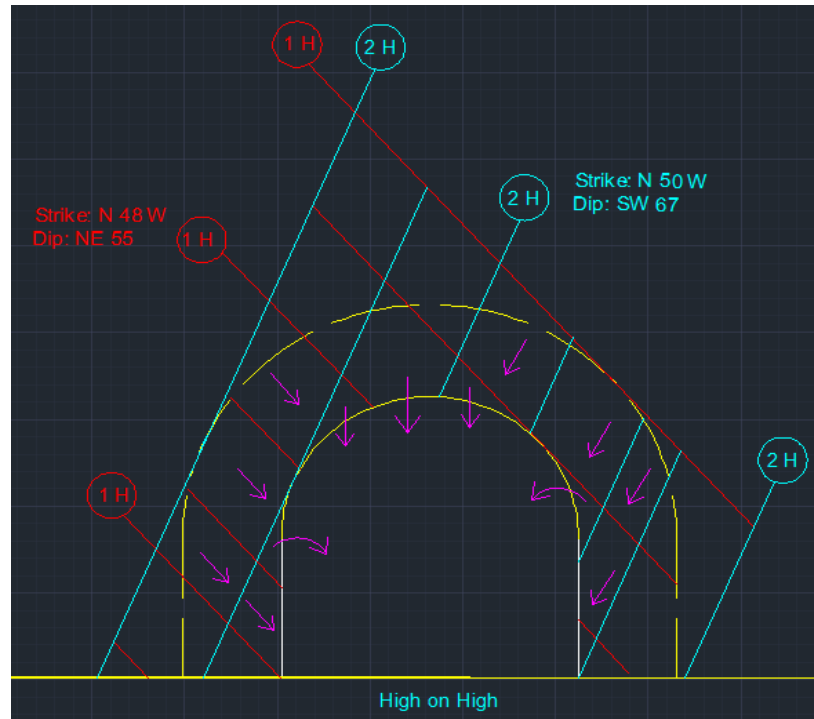


Figure 4.5 Tunnel cross section superimposed by joint sets 1H and 2H

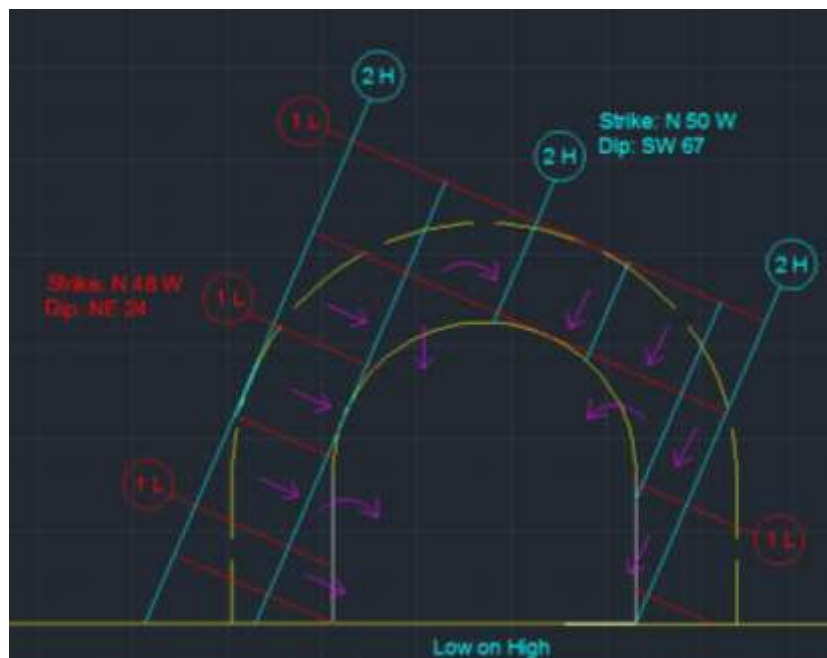


Figure 4.6 Tunnel cross section superimposed by joint sets 1L and 2H

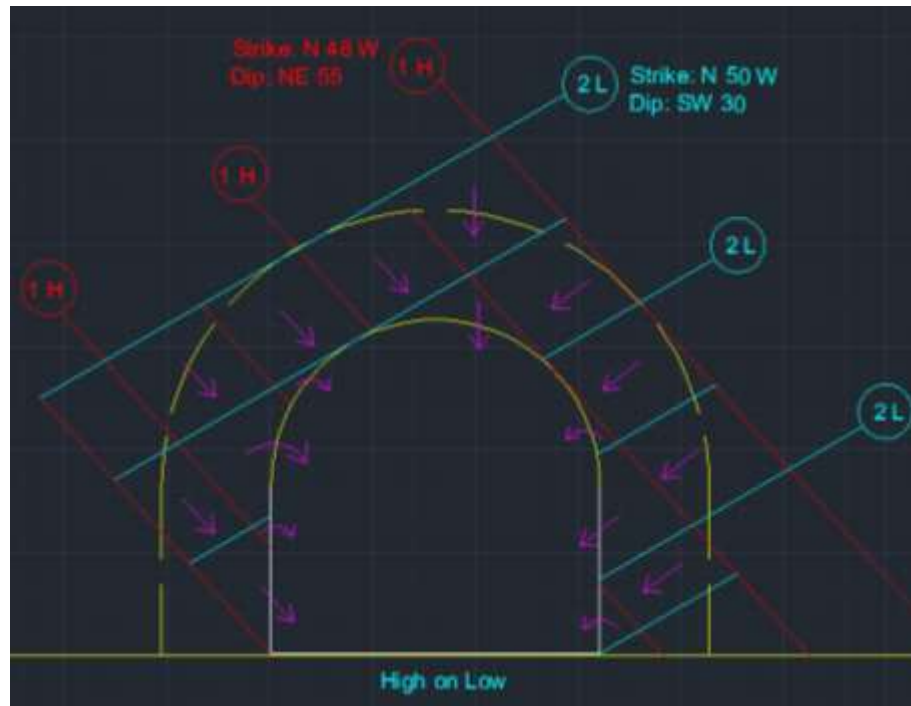


FIGURE 4.7 Tunnel cross section superimposed by joint sets 1H and 2L

5. CONCLUSION AND FUTURE WORK

There could be improvements in both the GIS and AutoCAD part of the study.

Followings are areas that could be worked on in future and improve the current work.

5.1 GIS IMPROVEMENT

There could be improvements for collecting and analyzing data instead of entering them by hand. ArcGIS is capable of digitizing paper maps. Using this feature, user can digitize available geologic maps and read in coordinate information of joints into the program, so there will be no need to enter the information into a spreadsheet by hand. ArcGIS can store information in an Attribute Table. It is a table, like an Excel spreadsheet in ArcGIS environment. Also additional fields could be added to the attribute table, so they would be considered in the analysis and produce more accurate and realistic result, such as:

- Joint spacing
- Joint continuity
- Joint opening
- Joint filling
- Rock type
- Rate of advance in different rock types

The python code could also be improved. In this study apparent dip was not used. It is possible to add some lines to the code to calculate apparent dip based. In most cases, the apparent dip does not have a significant effect on the loading condition, but calculating that can reassure the designer about this fact. Using the rate of advance from the attribute table and length of alignment, code can give an estimate of time needed to complete the project.

5.2 AutoCAD Improvement

AutoCAD is capable of creating 3D models. Using this feature it is possible to locate centroid of blocks which can be useful in design of supporting systems. Also, loads from blocks could be calculated by calculating area and volume of each block.

5.3 Conclusion

The purpose of this study was to apply Geographic Information System (GIS) into geotechnical engineering and identify possibility of using this system to analyze, process and provide necessary information for plotting cross sections, rather than doing them by hand. It was concluded that this method is an improvement over conventional approach. There was a significant increase in speed of data analysis. The whole process of categorizing joints into sets took less than couple of minutes, while doing that by hand will take hours to days. It increased efficiency and accuracy by providing ability to accommodate different information at the same time, also provided needed information to plot different cross sections and joint sets orientations. It helps the designer to identify loosening behaviors such as toppling and sliding conditions and provide needed information such as load zone and depth to come up with the proper and adequate supporting system design. This study also revealed that this system is suitable for parametric study, since it is capable of considering different information, such as spacing, filling in joints, continuity and etc. at the same time. The current methodology only considered strike and dip angle of joints to categorize joints into sets.

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