ASCE METROPOLITAN SECTION

STRUCTURAL GEOLOGY AND ITS INFLUENCE ON THE KINEMATICS OF ROCK STABILITY:

A Critical Foundation Consideration in Urban Environments

"Foundation Challenges in Urban Environments" Presented by
ASCE Metropolitan Section / Geo-Institute Chapter
May 16, 2013 • New York City

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HOFSTRA UNIVERSITY

Learning Objectives

Upon completion of this presentation, the participant should be able to:

- *Briefly describe field investigation data collection methods*
- *Identify the rock mass strength parameters required for further analysis*
- *Identify the three principal modes of rock mass failure evaluated through kinematic analysis (planar sliding, wedge sliding and toppling)*

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Field Investigation Objectives and Data Collection Methods

The stability of rock excavations is typically governed by the structural geology of the rock in which the slope is excavated.

Naturally occurring breaks such as bedding planes, joints, and faults may be collectively termed "discontinuities" – preferential planes of weakness through the stronger, intact rock mass.

Stability failure tends to occur preferentially along these surfaces.

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Field Investigation Objectives and Data Collection Methods

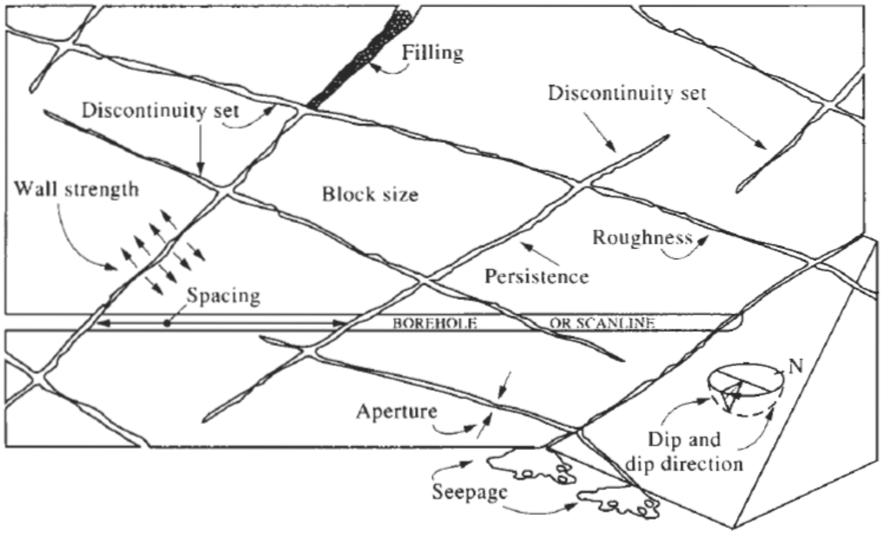
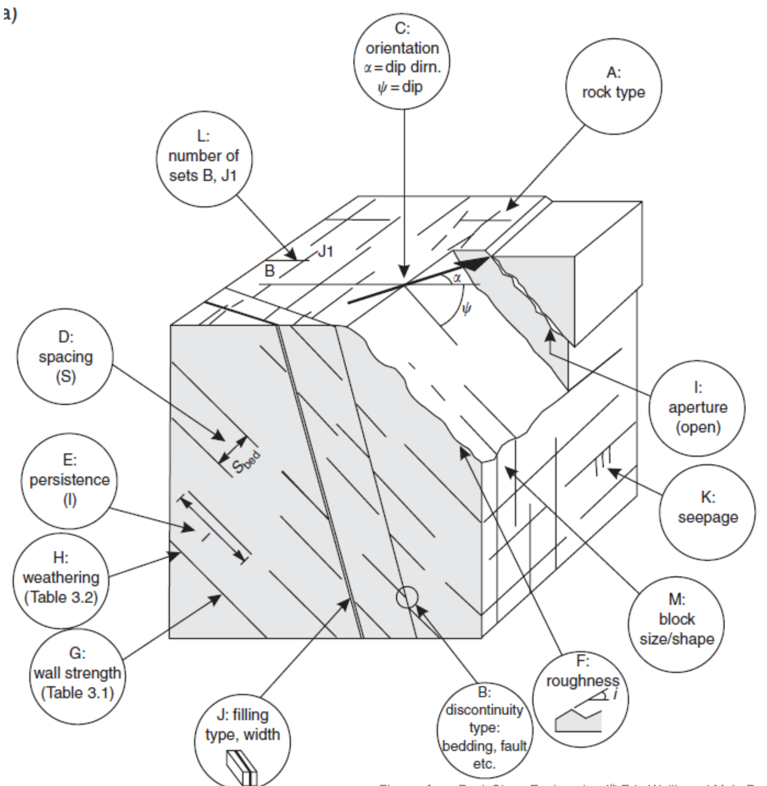


Figure 7.3 Schematic of the primary geometrical properties of discontinuities in rock (from Hudson, 1989).

Figure from *Engineering Rock Mechanics An Introduction to the Principles*, Hudson and Harrison, pg. 116.

The most common discontinuities are joints and bedding planes – other important discontinuities are planes of cleavage and schistosity.

Characteristics of discontinuities in rock masses.



Figures from *Rock Slope Engineering* 4th Ed., Wyllie and Mah, Pg. 55

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Field Investigation Objectives and Data Collection Methods

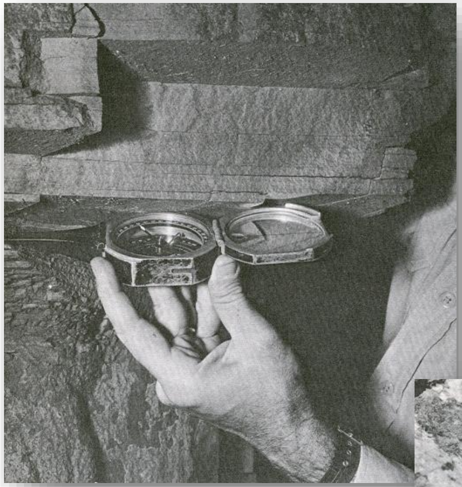


Figure from *Structural Geology*, 3rd Ed., Billings, Plate 1. pg. 36

Measuring Strike

Measuring Dip

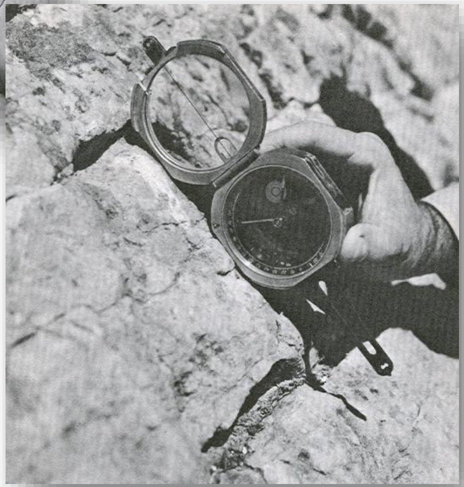


Figure from *Structural Geology*, 3rd Ed., Billings, Plate 2. pg. 38

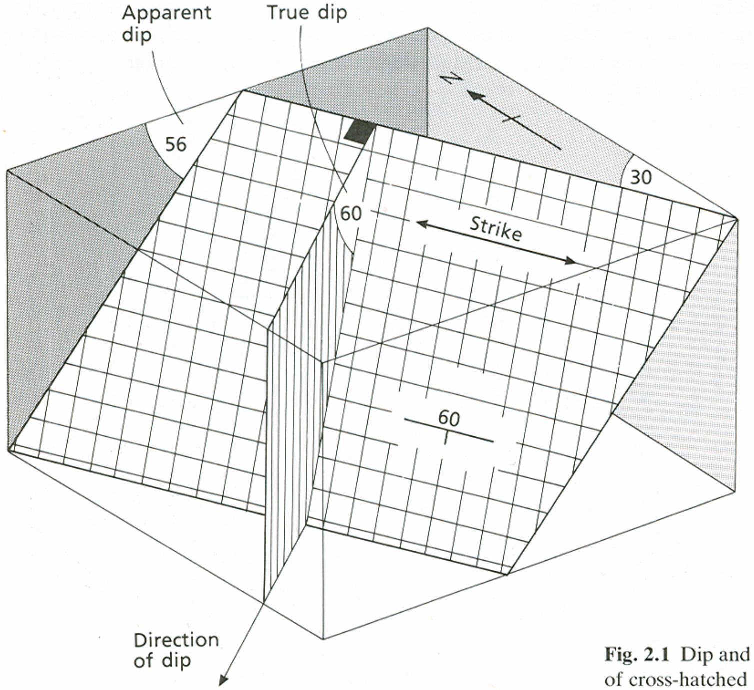


Fig. 2.1 Dip and strike: orientation of cross-hatched plane can be expressed as follows: strike 330°, dip 60°W, or dip 60° towards 240°.

Figure from *Engineering Geology*, 1st Ed., Bell, pg. 28

Field Investigation Objectives and Data Collection Methods

A Schmidt rebound hammer may be used to determine an approximate measurement of surface hardness for the intact rock mass for correlation to other rock mass properties.

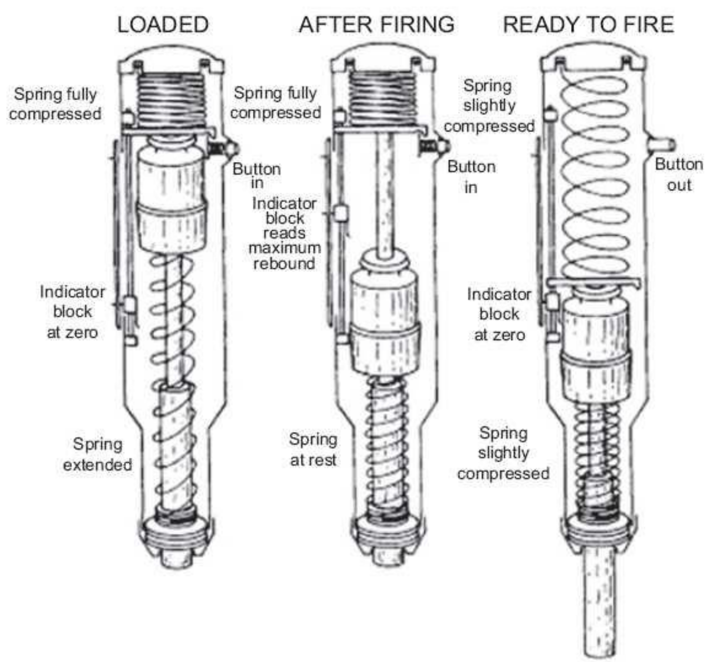
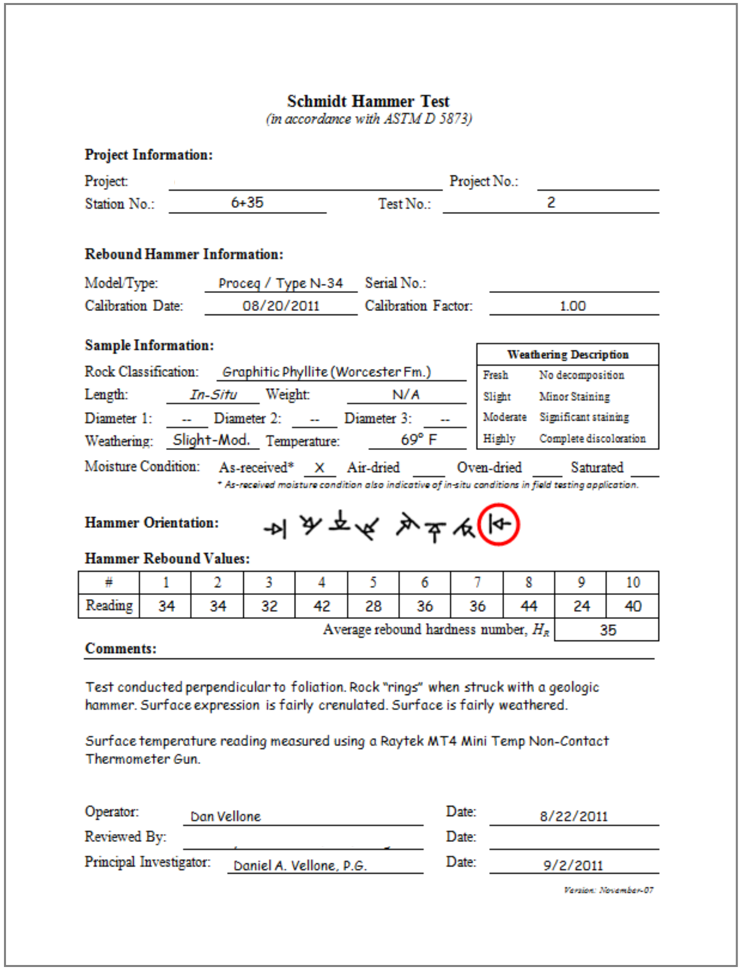


Figure from Basu and Aydin (2004) and Aydin (2009)



Schmidt Hammer Test
(in accordance with ASTM D 5873)

Project Information:

Project: ______ Project No.: ______
Station No.: 6+35 Test No.: 2

Rebound Hammer Information:

Model/Type: Proceq / Type N-34 Serial No.: ______
Calibration Date: 08/20/2011 Calibration Factor: 1.00

Sample Information:

Rock Classification: Graphitic Phyllite (Worcester Fm.)
Length: *In-Situ* Weight: N/A
Diameter 1: -- Diameter 2: -- Diameter 3: --
Weathering: Slight-Mod. Temperature: 69° F

Weathering Description	
Fresh	No decomposition
Slight	Minor Staining
Moderate	Significant staining
Highly	Complete discoloration

Moisture Condition: As-received* X Air-dried ___ Oven-dried ___ Saturated ___
** As-received moisture condition also indicative of in-situ conditions in field testing application.*

Hammer Orientation:

Hammer Rebound Values:

#	1	2	3	4	5	6	7	8	9	10
Reading	34	34	32	42	28	36	36	44	24	40
								Average rebound hardness number, H_R		35

Comments:

Test conducted perpendicular to foliation. Rock "rings" when struck with a geologic hammer. Surface expression is fairly crenulated. Surface is fairly weathered.

Surface temperature reading measured using a Raytek MT4 Mini Temp Non-Contact Thermometer Gun.

Operator: Dan Vellone Date: 8/22/2011
Reviewed By: ______ Date: ______
Principal Investigator: Daniel A. Vellone, P.G. Date: 9/2/2011

Version: November-07

Field Investigation Objectives and Data Collection Methods

The degree and intensity of the field investigation is directly related to the complexity of the project

Geological data must be used in support of engineering design

The analysis is only as good as the data collected

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NYC, NY

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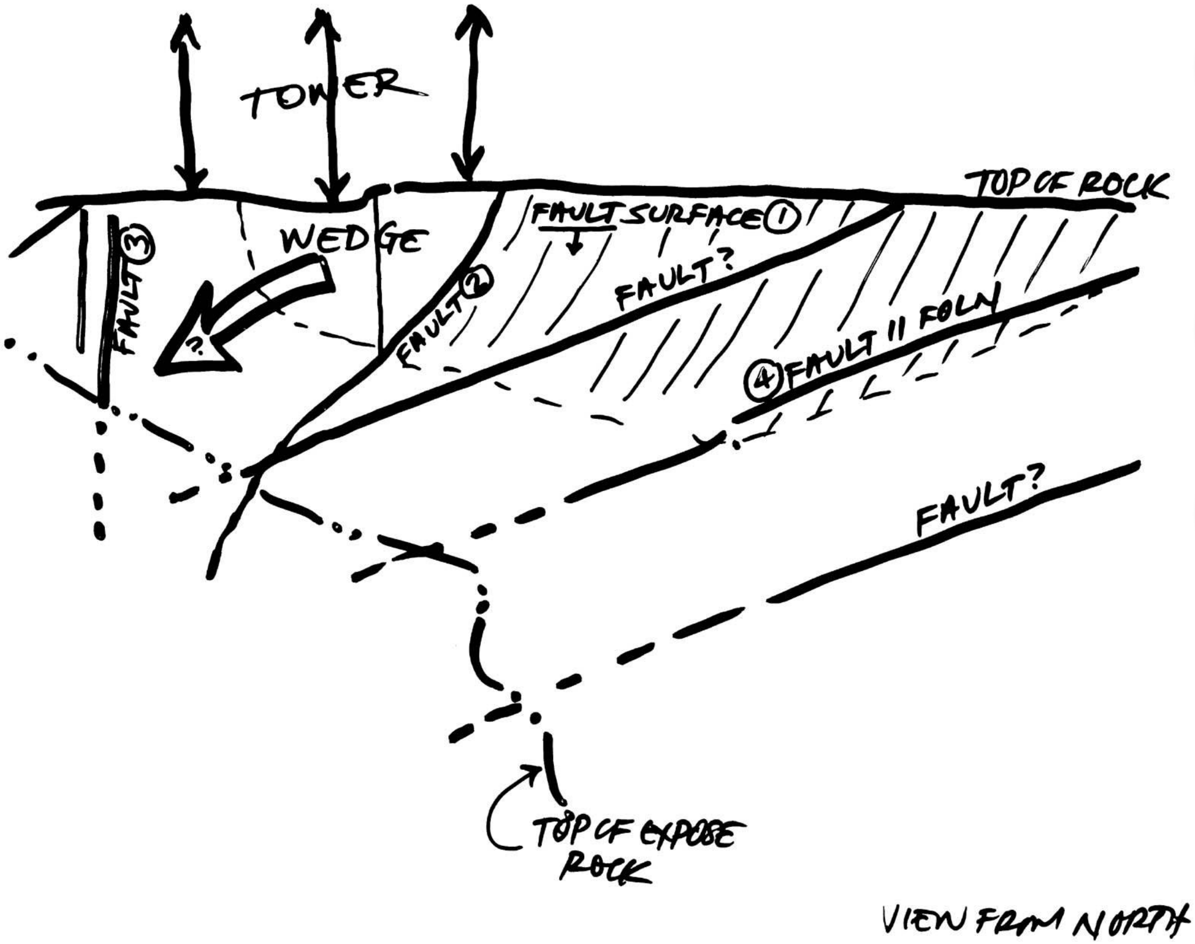

1. *N40E, 75SE*
   Dip-slip Slicks
   55 into S50E
2. *N67W, 55SW*
   Cuts Fault #1
3. *N23E, 65SE*
4. *N80E, 22SE*
   Arched, variable

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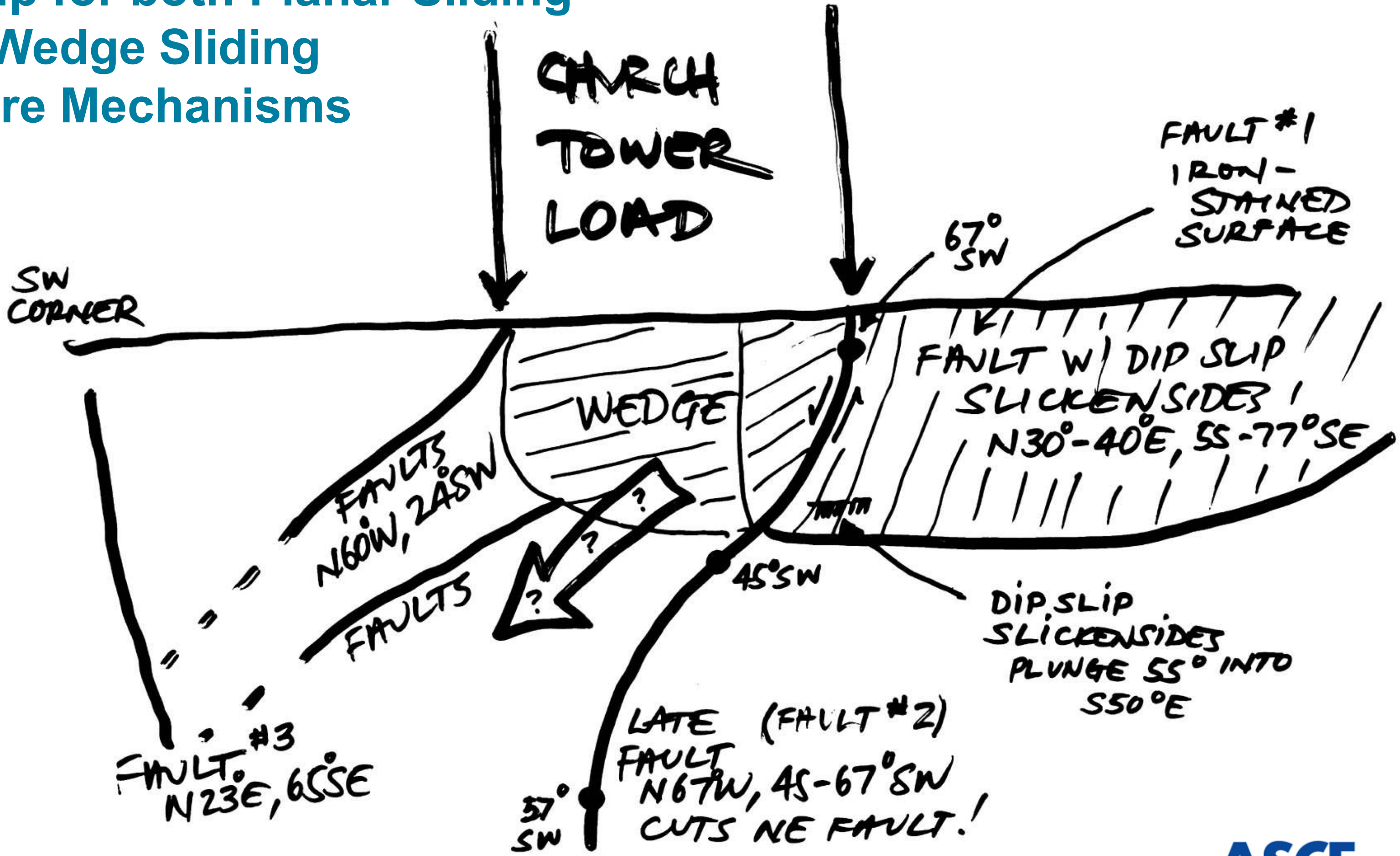
Set-up for both Planar Sliding and Wedge Sliding Failure Mechanisms



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NW-trending Faults Project Across Site

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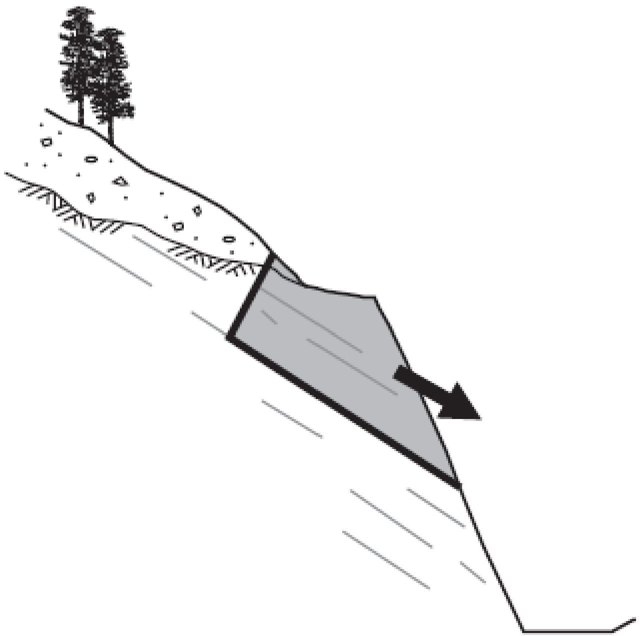
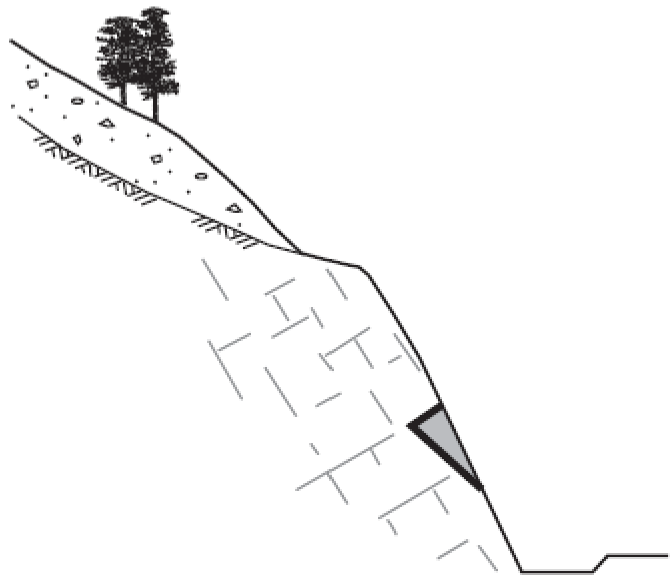
Rock Stability Failure Mechanisms

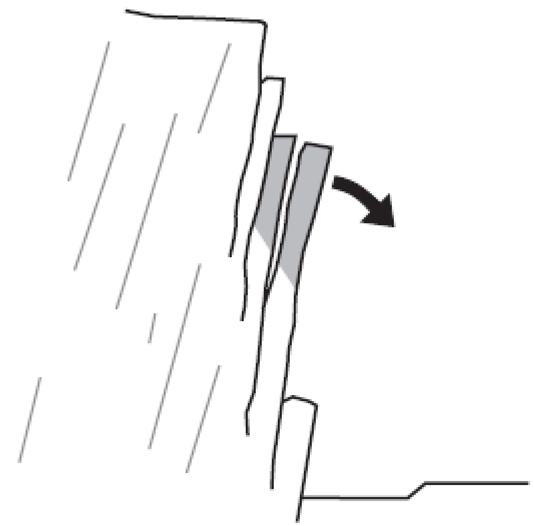
Cross Sectional View Through Typical Slope Profiles



Planar Sliding Failure



Wedge Sliding Failure



Toppling Failure

Figures from *Rock Slope Engineering* 4th Ed., Wyllie and Mah

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Kinematic Analysis of Rock Stability

- In order to optimize the design of excavation support methods it is necessary to consider how the rock mass will first respond to the excavation without considering support.
- These structural geological features that influence rock cut stability often occur in three dimensions with a degree of natural scatter.

Kinematic Analysis of Rock Stability

	Isometric View	*Equal Area Stereonets*	
Planar Sliding Failure			*Persistent joints dipping out of the slope face and striking parallel to the face*
Wedge Sliding Failure			*Two intersecting discontinuities forming tetrahedral blocks*
Toppling Failure			*Discontinuities dipping steeply into the face*

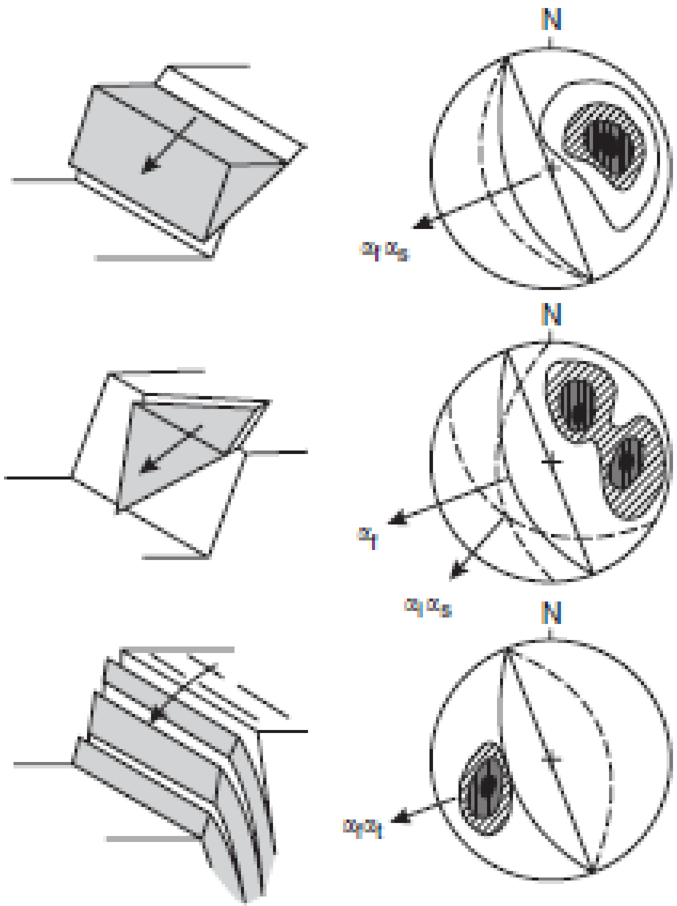

Figure from *Rock Slope Engineering* 4th Ed., Wyllie and Mah, pg. 36

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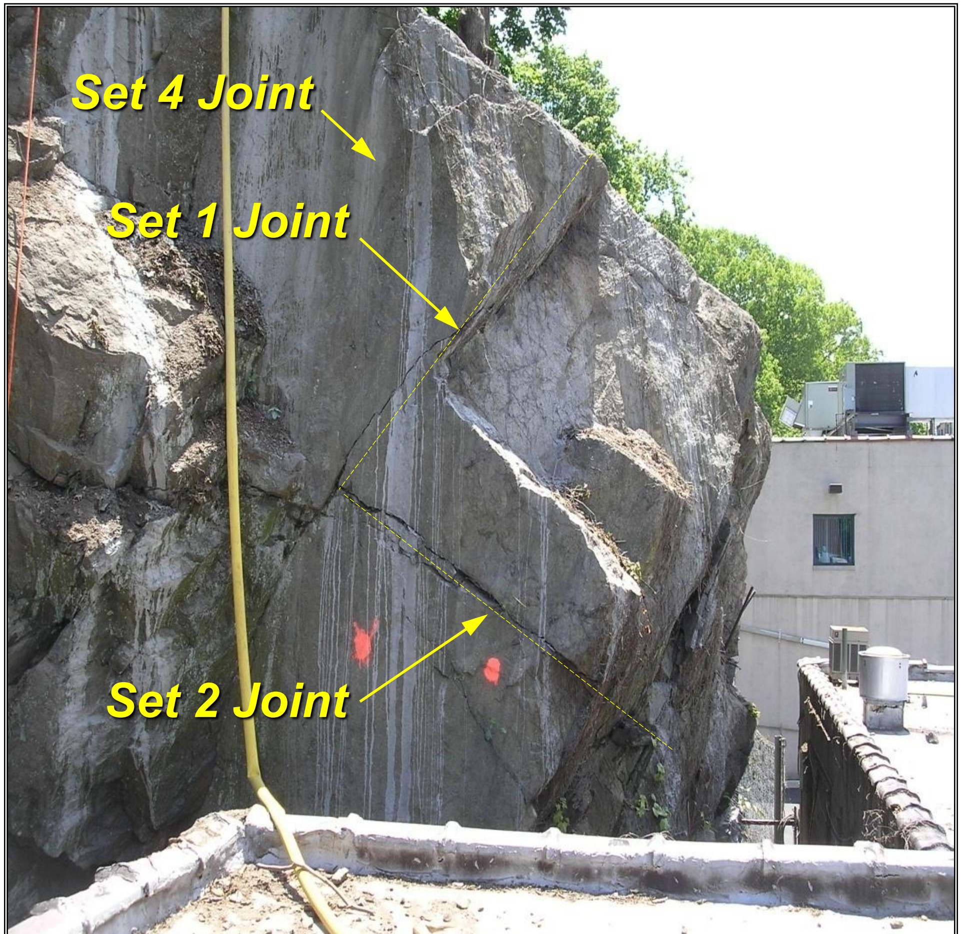
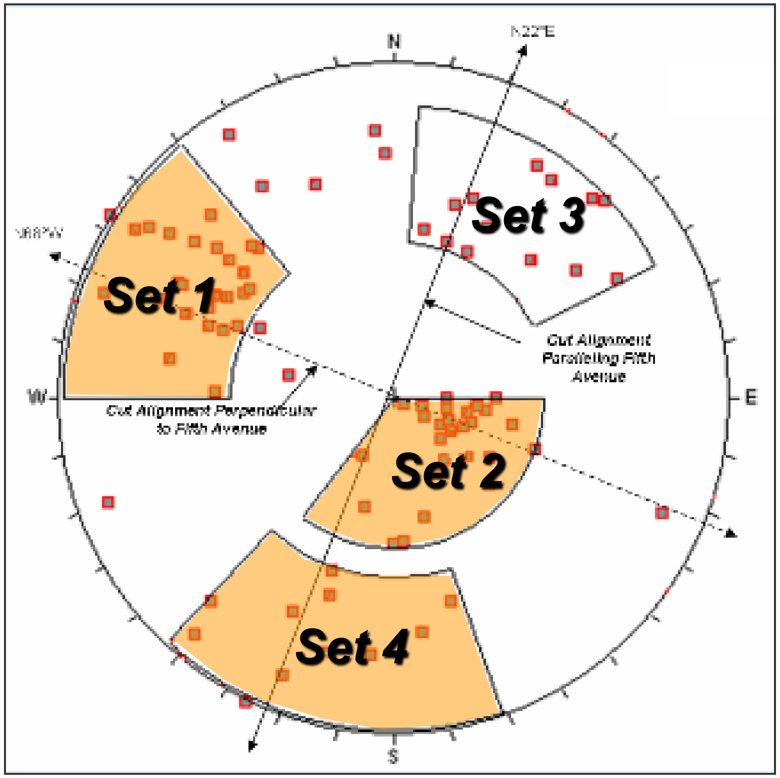
Planar Forming Geometry



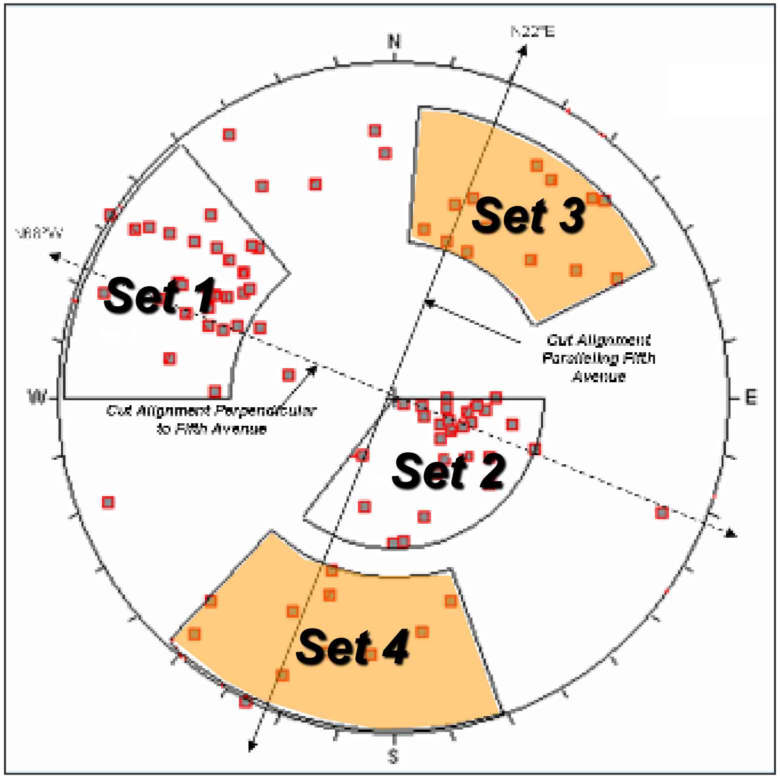
Fifth Avenue, Pelham, NY



Poles

Equal Angle
Lower Hemisphere
87 Poles
87 Entries

Wedge Forming Geometry



Poles

Equal Angle
Lower Hemisphere
87 Poles
87 Entries

Fifth Avenue, Pelham, NY

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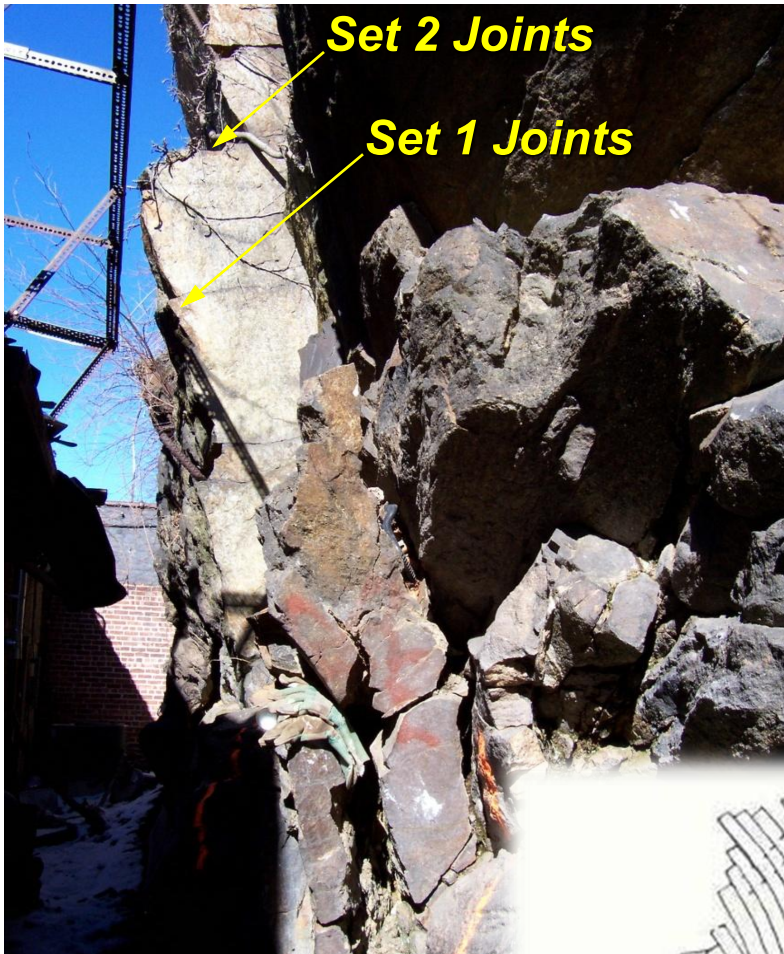
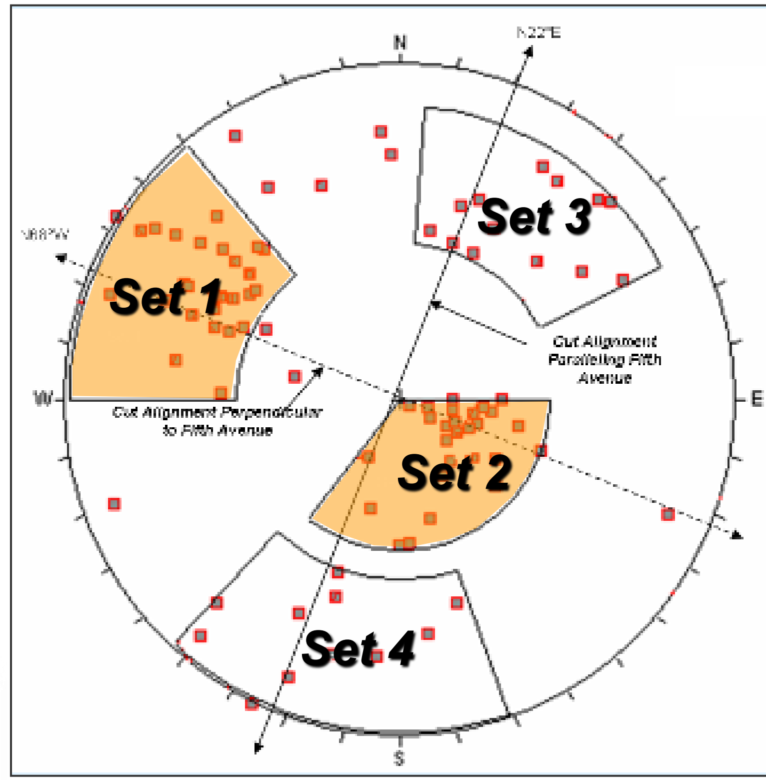
Toppling Forming Geometry





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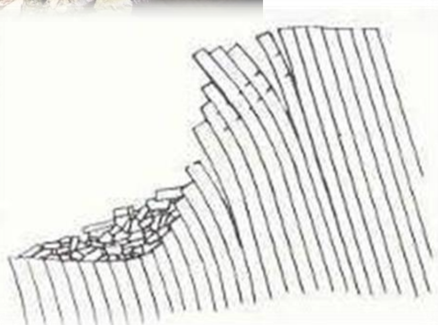


Fifth Avenue, Pelham, NY

Laboratory Determination of Rock Strength

Example strength test Specimen

The orientation of weakness planes (typically known as s-planes) can influence the direction of breakage.

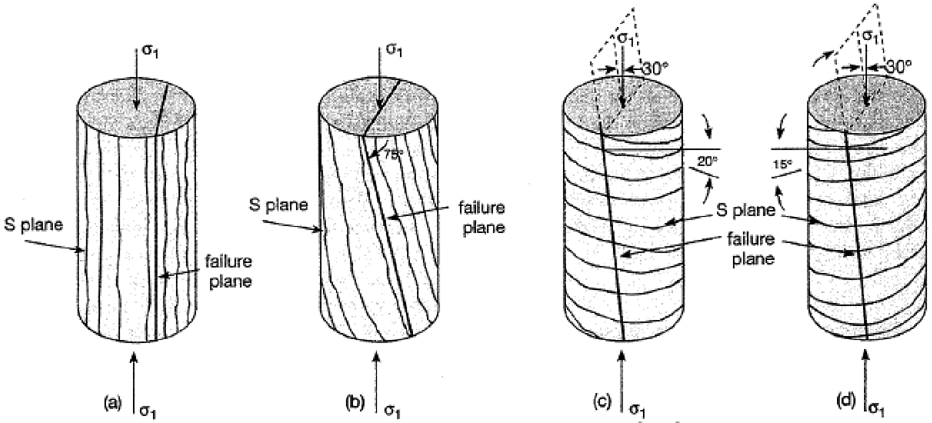


FIGURE 10.27 Dependence of failure plane location on orientation of *s* planes in test specimens.

Figure from *Geology Applied to Engineering*, West, pg. 214.

In sedimentary rocks this consists of prominent bedding structures. In metamorphic rocks – foliation or schistocity. In extrusive igneous rocks this may consist of flow banding.

Laboratory Determination of Rock Strength

Initial rock core preparation of phyllite sample prior to testing.

After strength testing failure.

Discontinuity failure along foliation plane.

Boring ID	Sample ID	Depth, ft	Bulk Density, lb/ft^3	Compressive Strength, psi	Failure Type	In conformance with ASTM D 4543
PA-1	C-4	37.20-37.57	178	10,502	2	YES

Notes: Density determined on core samples by measuring dimensions and weight and then calculating.

All specimens tested at the approximate as-received moisture content and at standard laboratory temperature.

Failure Type: 1 = Intact Material Failure; 2 = Discontinuity Failure (See attached photographs)

Rock Mass Strength Parameters

The Hoek-Brown failure criterion may be used to determine rock mass strength characteristics.

Hoek-Brown Classification

intact uniaxial compressive strength = 10502 psi

GSI = 50   mi = 7   Disturbance factor = 0.7

Hoek-Brown Criterion

mb = 0.449   s = 0.0007   a = 0.506

Mohr-Coulomb Fit

cohesion = 43.988 psi   friction angle = 51.10 deg

Rock Mass Parameters

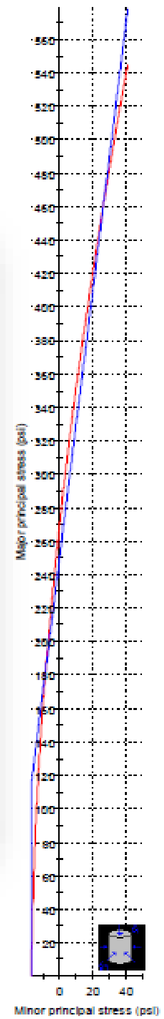
tensile strength = -16.681 psi

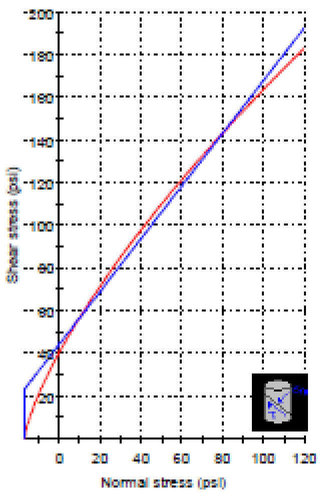
uniaxial compressive strength = 268.966 psi

global strength = 930.723 psi

modulus of deformation = 802213.33 psi

Software: RocScience *RocData*, ver. 3.0





Kinematic Analysis of Rock Stability

In order to use the data to evaluate the stability of the rock cut, it is necessary to analyze the data using stereographic projection to identify discontinuity sets, and examine their influence on excavation stability.

- The stereographic projection method allows the three-dimensional orientation data to be represented and analyzed in two dimensions.

- The analysis consideres kinematically possible structurally controlled failures within the rock mass, as opposed to non-structurally controlled failures in which some or all of the failure surface passes through intact rock.

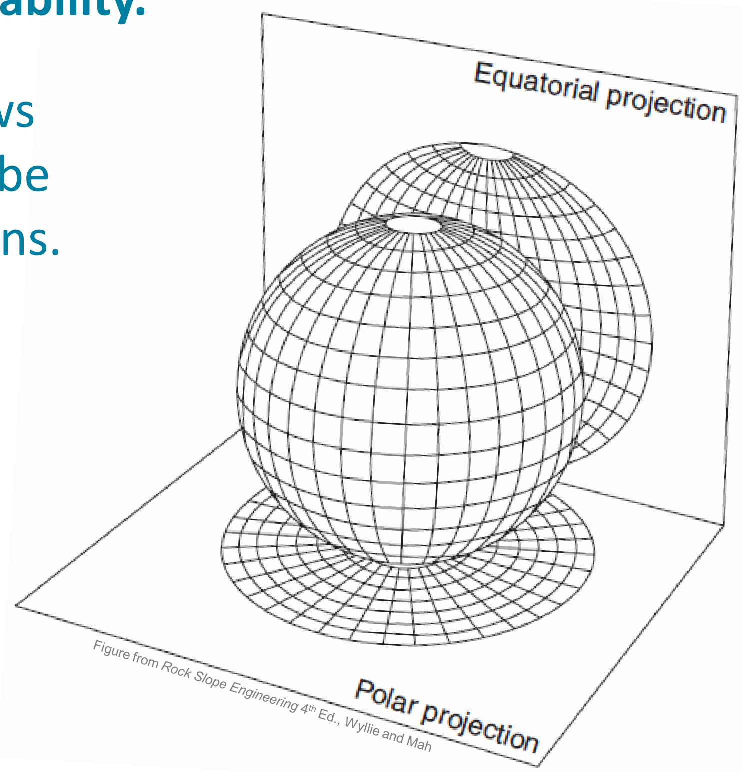


Figure from Rock Slope Engineering 4th Ed., Wyllie and Mah

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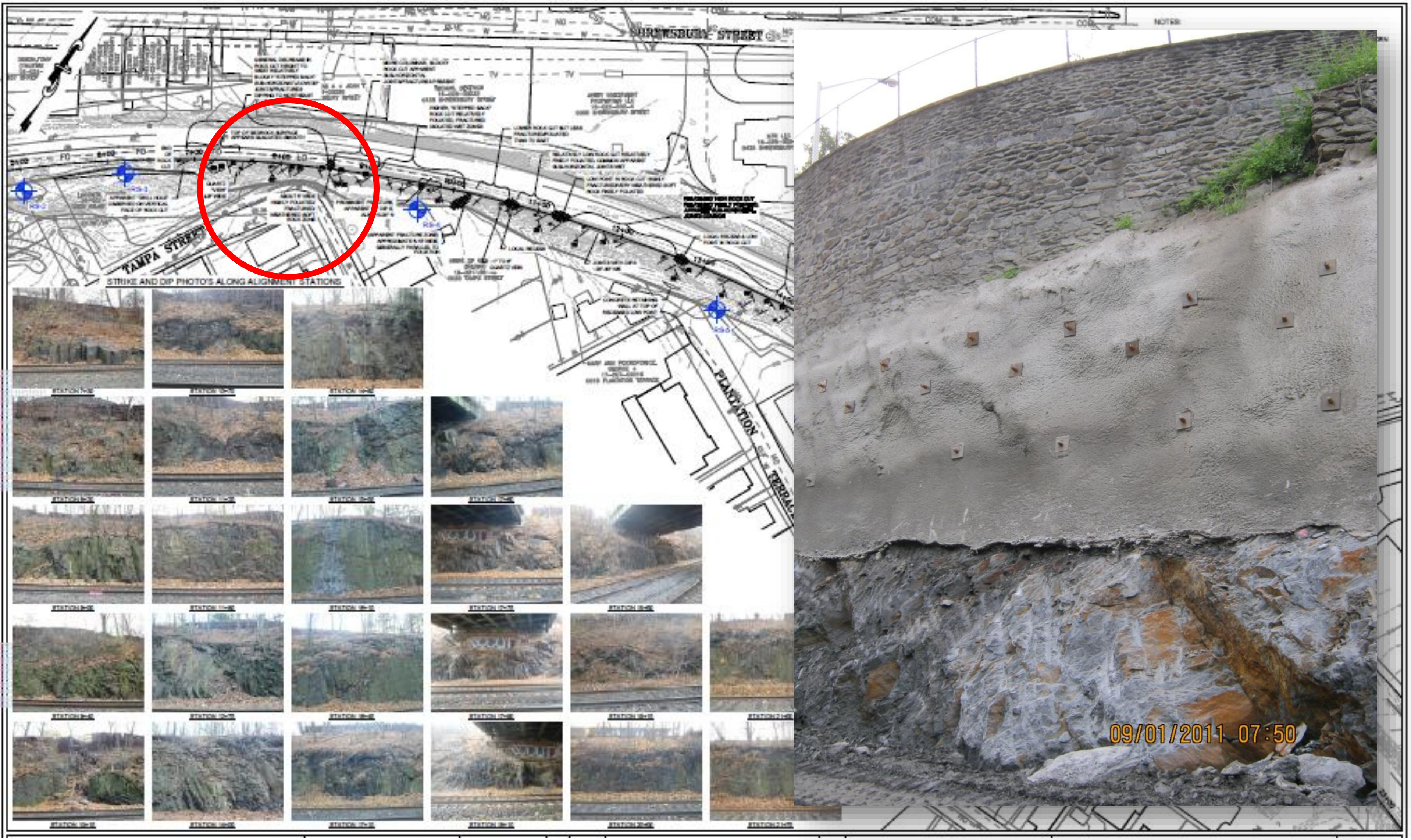
Raw Data from Field Mapping Program

Structural geology mapping data

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Number	Dip	Dip Direction	Quantity	Azimuth	Strike	Dip	Feature	Aperature	Infilling	Weathering	CUT	Station	Mapped By	Formation	Rock Classification
1	90	300	1	30	N30E	VERT	FOLIATION				South	6+00	D.A. Vellone	Worcester Phyllite	Siliceous Phyllite
2	82	306	1	36	N36E	82N	FOLIATION			Weathered	South	6+28	D.A. Vellone	Worcester Phyllite	Siliceous Phyllite
3	84	298	1	28	N28E	84N	FOLIATION			Weathered	South	6+30	D.A. Vellone	Worcester Phyllite	Siliceous Phyllite
4	70	48	1	318	N318W	70E	JOINT				South	6+28	D.A. Vellone	[illegible]	Siliceous Phyllite
5	67	46	1	316	N316W	67E	JOINT				South	6+32	[illegible]	[illegible]	Siliceous Phyllite
6	90	297	1	27	N27E	VERT	FOLIATION				South	6+35	[illegible]	[illegible]	Siliceous Phyllite
7	86	302	1	32	N32E	86N	FOLIATION			Weathered	South	[illegible]	[illegible]	[illegible]	Siliceous Phyllite
8	88	298	1	28	N28E	88N	FOLIATION			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Siliceous Phyllite
9	82	297	1	27	N27E	82NW	FOLIATION				[illegible]	6+67	[illegible]	[illegible]	
10	24	209	1	299	N299W	24S	JOINT				[illegible]	[illegible]	[illegible]	Worcester Phyllite	
11	72	302	1	32	N32E	72N	FOLIATION			[illegible]	[illegible]	[illegible]	[illegible]	Worcester Phyllite	Graphitic Phyllite
12	86	305	1	35	N35E	86N	FOLIATION			[illegible]	[illegible]	[illegible]	D.A. Vellone	Worcester Phyllite	Graphitic Phyllite
13	85	295	1	25	N25E	85N	FOLIATION		[illegible]	[illegible]	[illegible]	7+75	D.A. Vellone	Worcester Phyllite	Graphitic Phyllite
14	85	[illegible]	[illegible]	[illegible]	[illegible]	85N	FOLIATION		[illegible]	[illegible]	[illegible]	7+75	D.A. Vellone	Worcester Phyllite	Graphitic Phyllite
15	87	295	[illegible]	[illegible]	[illegible]	87N	[illegible]			Slight	South	7+93	D.A. Vellone	Worcester Phyllite	Siliceous Phyllite
16	87	296	1	26	N26E	[illegible]	[illegible]			Slight	South	8+00	D.A. Vellone	Worcester Phyllite	Siliceous Phyllite
17	18	29	2	299	[illegible]	[illegible]	JOINT				South	8+00	D.A. Vellone	Worcester Phyllite	
18	83	305	1	35	[illegible]	[illegible]	[illegible]	[illegible]			South	8+55	D.A. Vellone	Worcester Phyllite	Graphitic Phyllite
19	88	[illegible]	1	[illegible]	N299W	[illegible]	[illegible]			Slight	South	8+67	D.A. Vellone	Worcester Phyllite	
20	89	[illegible]	1	[illegible]	N53E	89N	[illegible]			Weathered	South	9+59	D.A. Vellone	Worcester Phyllite	
21	77	236	2	[illegible]	[illegible]	77W	[illegible]			Slight	South	9+82	D.A. Vellone	Worcester Phyllite	
22	90	[illegible]	2	[illegible]	[illegible]	90W	[illegible]			Slight	South	9+91	D.A. Vellone	Worcester Phyllite	
23	86	[illegible]	[illegible]	[illegible]	N310W	86W	JOINT				South	9+99	D.A. Vellone	Worcester Phyllite	
24	87	299	[illegible]	[illegible]	N29E	87N	FOLIATION				South	10+08	D.A. Vellone	Worcester Phyllite	Graphitic Phyllite
25	78	[illegible]	1	49	N49E	78N	FOLIATION			Weathered	South	10+38	D.A. Vellone	Worcester Phyllite	Graphitic Phyllite
26	84	[illegible]	1	286	N286W	84N	JOINT				South	10+83	D.A. Vellone	Worcester Phyllite	
27	85	302	1	32	N32E	85N	FOLIATION				South	11+10	D.A. Vellone	Worcester Phyllite	Graphitic Phyllite
28	56	190	1	280	N280W	56S	JOINT				South	11+30	D.A. Vellone	Worcester Phyllite	
29	73	30	1	300	N300W	73NE	JOINT				South	11+55	D.A. Vellone	Worcester Phyllite	
30	42	180	1	270	N270W	42S	JOINT				South	11+55	D.A. Vellone	Worcester Phyllite	

Railroad cut at Plantation Street, Worcester, MA

Compilation of Mapping Data



Railroad cut at Plantation Street, Worcester, MA

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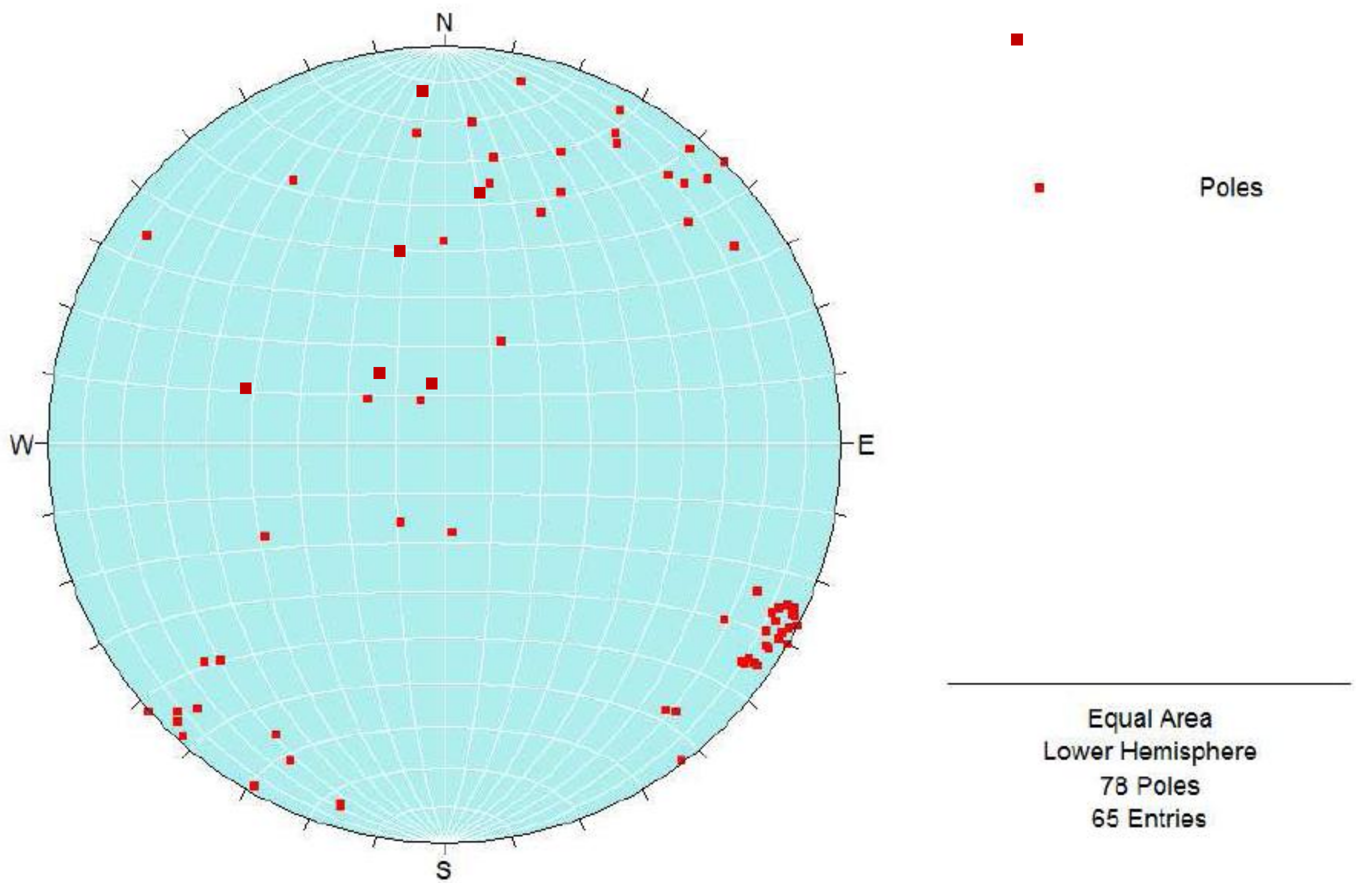
Raw Data from Field Mapping

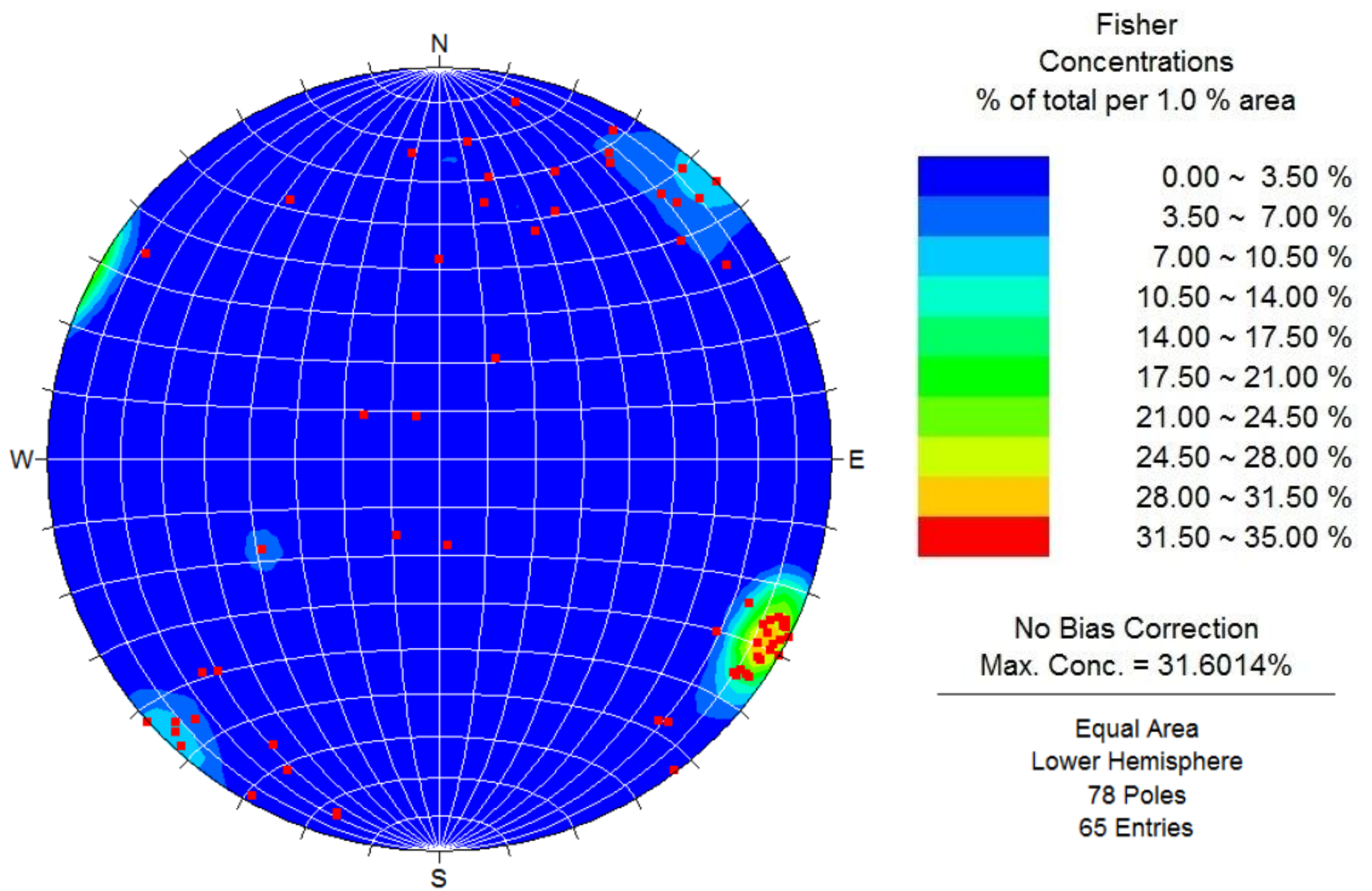
All natural discontinuities have a certain amount of variation in their orientations that result in scatter of the pole plots using stereographic analysis.



Software: RocScience *Dips*, ver. 5.1

Fischer Concentration Plot

By contouring the plot, the most highly concentrated areas of poles can be more readily identified.



Software: RocScience *Dips*, ver. 5.1

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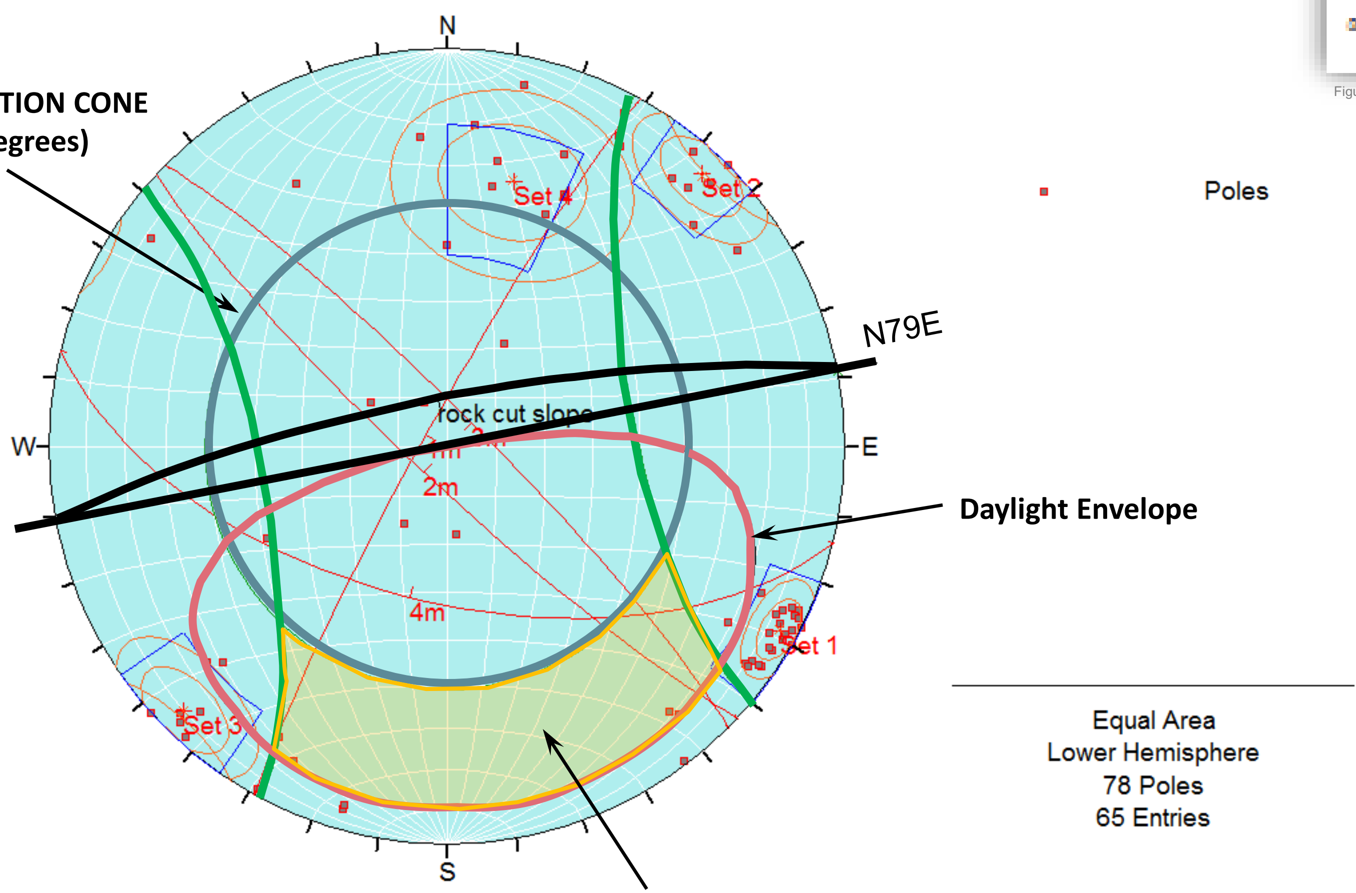
Planar Sliding Failure Analysis



POLE FRICTION CONE (51 degrees)

Daylight Envelope

PLANAR SLIDING ZONE

80 degree rock cut slope face angle shown

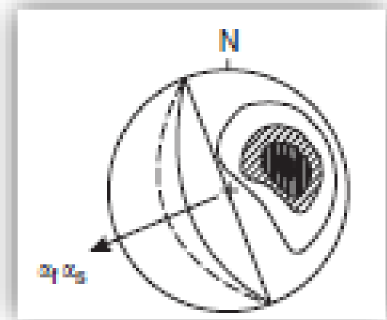


Figure from *Rock Slope Engineering* 4th Ed., Wyllie and Mah

Software: RocScience *Dips*, ver. 5.1

Wedge Sliding Failure Analysis

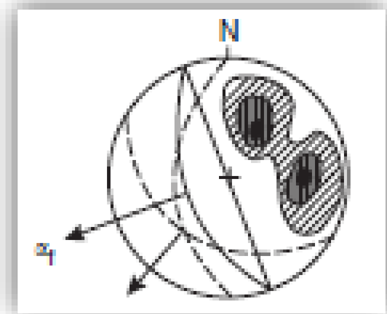
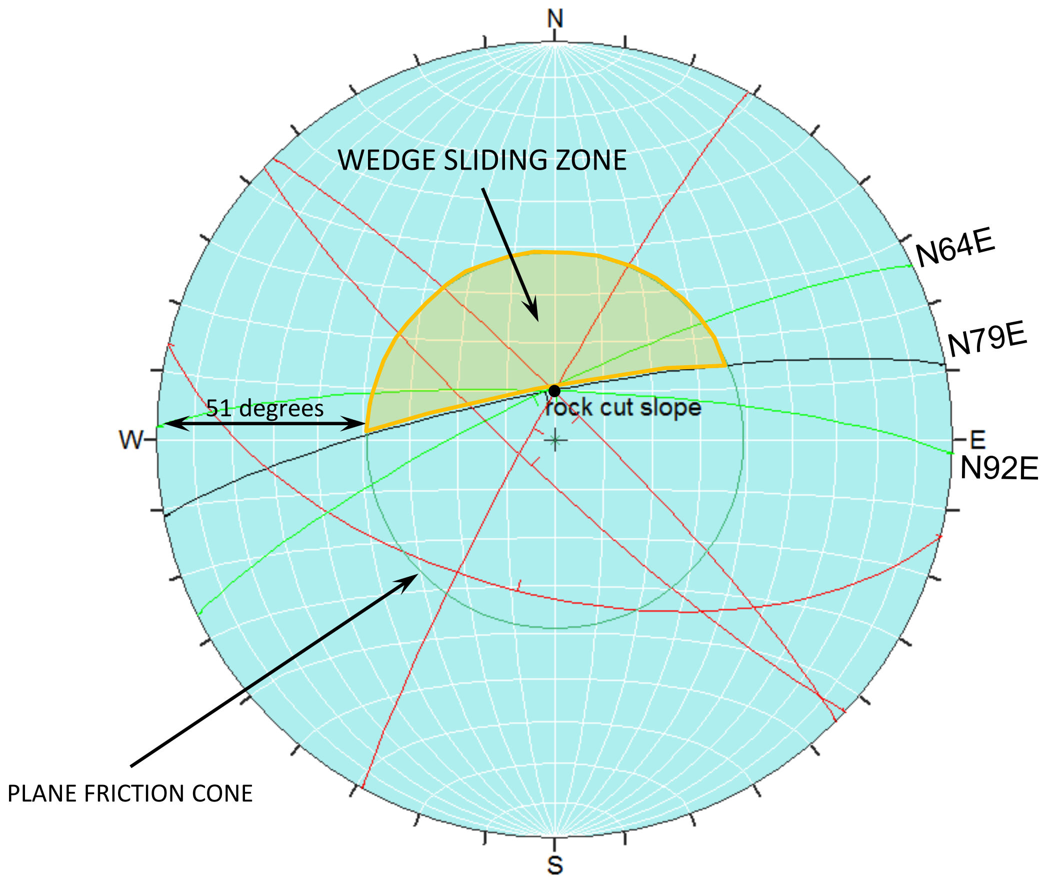


Figure from *Rock Slope Engineering* 4th Ed., Wyllie and Mah



Orientations

ID		Dip / Direction
4		80 / 349
5		80 / 002
6		80 / 334
1	w	85 / 299
2	w	83 / 223
3	w	83 / 045
4	w	58 / 194

Equal Area
Lower Hemisphere
78 Poles
65 Entries

80 degree rock cut slope face angle shown
Variability in rock cut slope alignment shown

Software: RocScience *Dips*, ver. 5.1

Wedge Sliding Failure Analysis

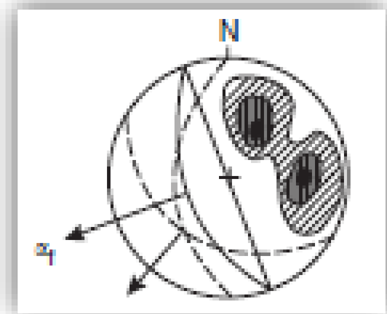
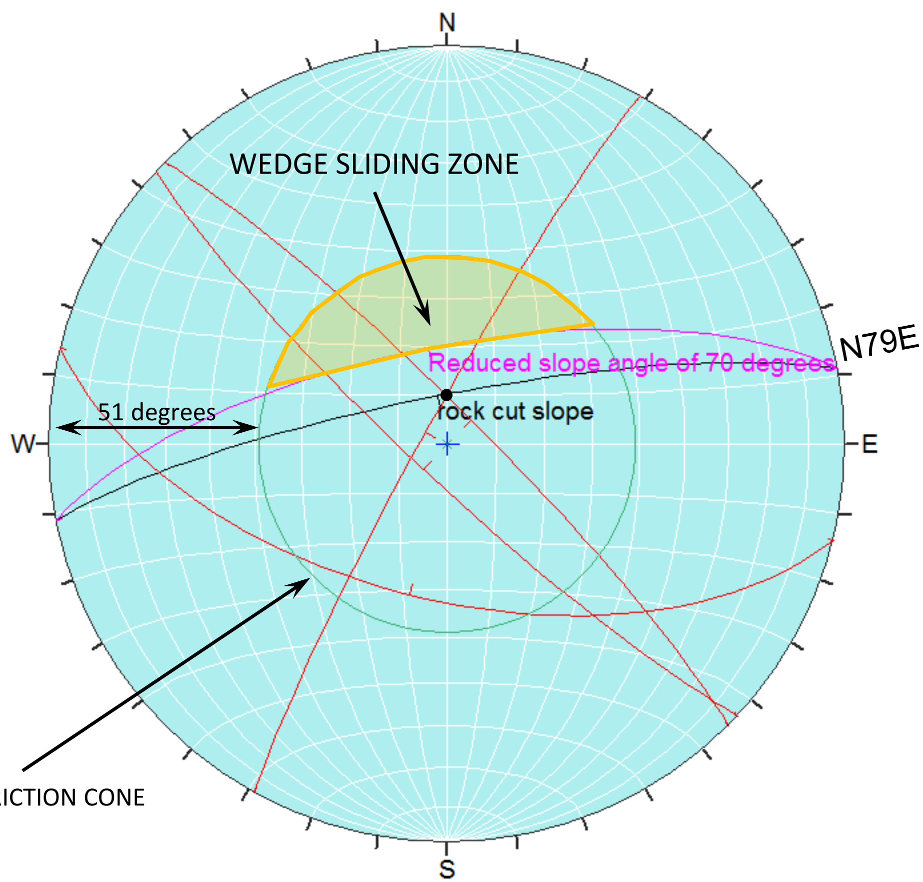


Figure from *Rock Slope Engineering* 4th Ed., Wyllie and Mah



Orientations

ID		Dip / Direction
4		80 / 349
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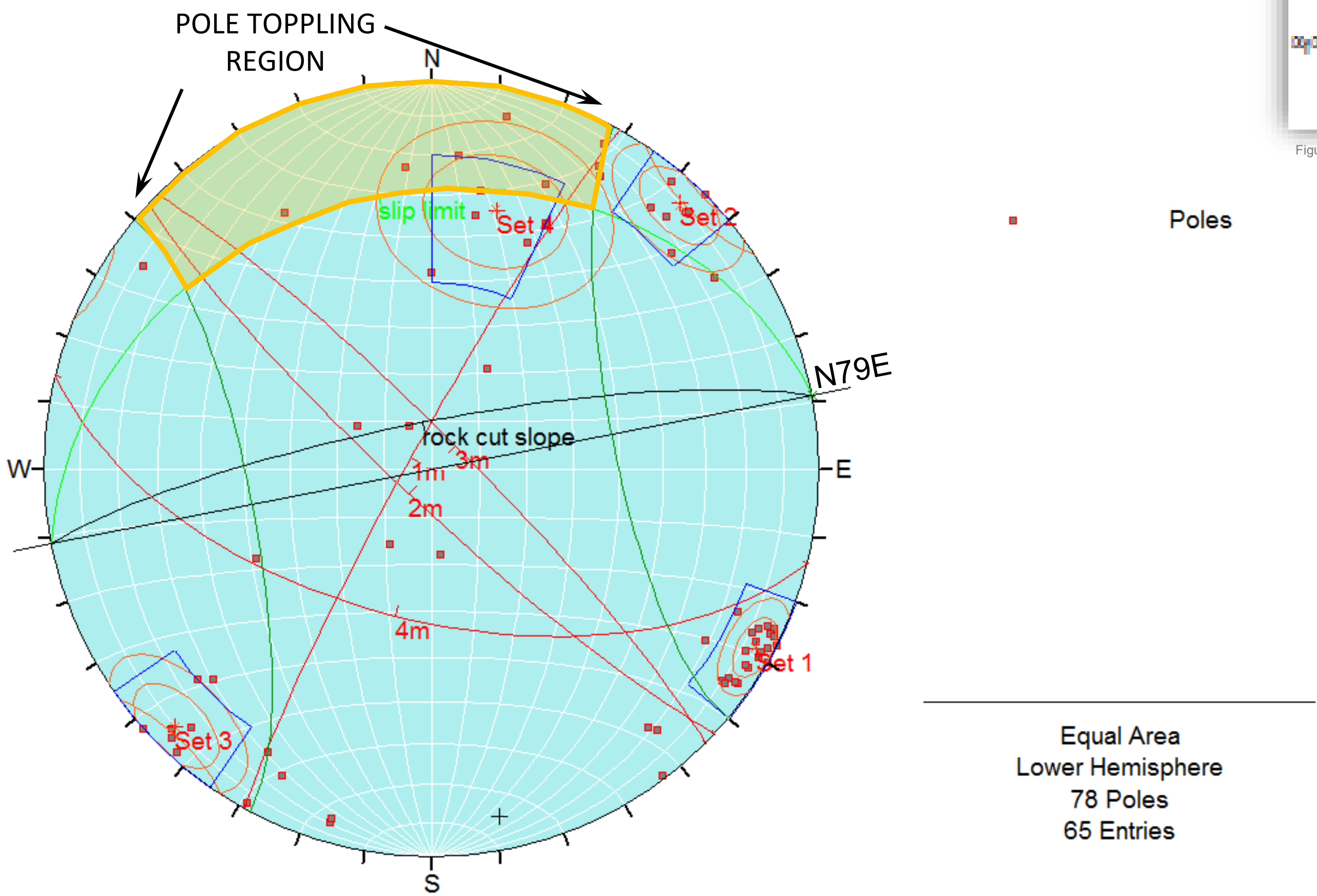
Equal Area
Lower Hemisphere
78 Poles
65 Entries

80 degree rock cut slope face angle shown
Variability in rock cut slope face angle shown

Software: RocScience *Dips*, ver. 5.1

Toppling Failure Analysis



80 degree rock cut slope face angle shown

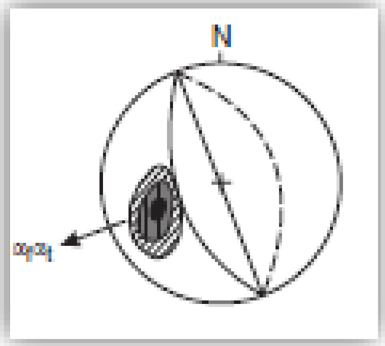
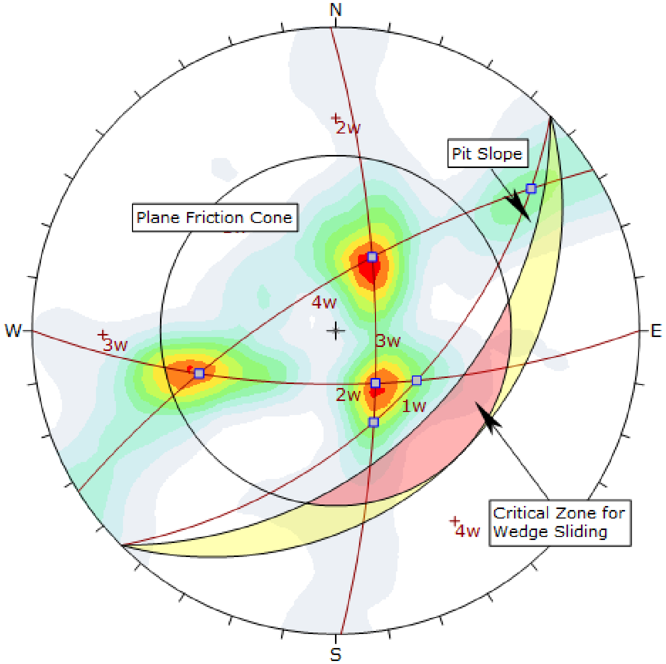


Figure from *Rock Slope Engineering* 4th Ed., Wyllie and Mah

Software: RocScience *Dips*, ver. 5.1

A word of caution...

RocScience Dips version 6.0 was released 2012. A major new upgrade to the program is the kinematic analysis toolkit for rock stability analysis.



Symbol	Feature
(red square)	Critical Intersection
(blue square)	Intersection

Color	Density Concentrations
	0.00 - 0.50
	0.50 - 1.00
	1.00 - 1.50
	1.50 - 2.00
	2.00 - 2.50
	2.50 - 3.00
	3.00 - 3.50
	3.50 - 4.00
	4.00 - 4.50
	4.50 - 5.00
Maximum Density	4.71%
Contour Data	Intersections
Contour Distribution	Fisher
Counting Circle Size	1.0%

Kinematic Analysis	Wedge Sliding		
Slope Dip	45		
Slope Dip Direction	135		
Friction Angle	30°		
	Critical	Total	%
Wedge Sliding	0	6	0.00%

	Color	Dip	Dip Direction	Label
User Planes				
1		45	135	pit slope
Mean Set Planes				
1w		56	135	
2w		70	180	
3w		75	89	
4w		73	328	

Simply input the slope orientation and friction angle, choose the failure mode, and a template is overlaid on the stereonet, highlighting the critical zone

Wedge sliding stability analysis using mean joint set planes

ASCE METROPOLITAN SECTION Geo-Institute Chapter

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METROPOLITAN SECTION

STRUCTURAL GEOLOGY AND ITS INFLUENCE ON THE KINEMATICS OF ROCK STABILITY:

A Critical Foundation Consideration in Urban Environments

Thank You

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USDA NRCS
United States Department of Agriculture
Natural Resources Conservation Service

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