ROCK SLOPES: POLE COUNTING OR ALL-WEDGE ANALYSIS?

ALVARO J. GONZALEZ G.[1]

[1]*Associate Professor- National University of Colombia*
(ajgon@cable.net.co; ajgonzalezga@unal.edu.co)

Abstract

The usual way to carry out rock slope stability analyses is: (a) to make a rock mass discontinuity pole counting to identify the predominant directions of rock discontinuities; (b) with strength data for the discontinuities, to carry on plane, wedge and toppling failure analyses for the slopes involved. Although pole counting analyses are very useful and they always should be done, they do not insure that the actual failure plane or planes are identified, i.e. the plane in a predominant direction is not necessarily the weakest plane. To try to overcome this difficulty, the Author has developed a simple DOS based FORTRAN program: ALLWEDGE (50kB), which identifies all kinematically possible wedges for a rock slope and analyzes them with Mohr-Coulomb strength parameters (c´ and ϕ´) for the discontinuities and the Hoek and Bray (1977) complete method of wedge analysis without a tension crack. The program allows to process up to 400 discontinuities (theoretically 79,800 wedges for each slope) and 30 slopes, common rock unit weight, slope water conditions and earthquake horizontal and vertical accelerations. It also allows to include for each slope: external forces, maximum width (which limits wedge height) and to list only the wedges with a factor of safety less than a predetermined value. It also can calculate the stabilizing tension and its direction to reach a predetermined factor of safety. Output files could be very large. An example is presented for both the traditional method and the all-wedge method and conclusions are derived.

Keywords: rock slope; wedge failure; poles; slope stability

1. Usual procedure for rock slope stability analyses and difficulties

The usual procedure to carry out rock slope stability analyses is:

(a) to make a rock mass discontinuity pole counting to identify the predominant directions of rock discontinuities.

(b) with strength data for the discontinuities, to carry on plane, wedge and toppling failure analyses for the slopes involved.

Although pole counting analyses are very useful and they always should be done, they do not insure that the actual failure plane or planes are identified, i.e. the plane in a predominant direction is not necesarily the weakest plane.

The Author has analyzed actual wedge and plane rock slope failures in which the actual failure planes were not the ones with the predominant direction, due to the fact that either the discontinuity field survey was not as complete as required or that the critical discontinuities were not easily detected in these field surveys.

2. Proposed procedure for rock slope wedge and plane failure stability analyses

In view of these difficulties, the Author proposes the following procedure for rock slope wedge and plane failure stability analyses:

a) to identify from the discontinuity survey the discontinuities that should not intersect (which can be called “genetic”): i.e. bedding planes in sedimentary rocks.
b) with all the discontinuities, carry on wedge kinematic analyses to identify all possible wedges for a slope.
c) with all identified kinematically possible wedges, carry on stability analyses and obtain factors of safety.
d) identify the wedges that have a factor of safety less than a predetermined value.
e) for these critical wedges find stabilizing tension forces or other stabilizing measures

If it is desired to find the friction stable slope in a specified direction then:

b) with all the discontinuities, carry on wedge kinematic analyses to identify all possible wedges for a 90° inclined slope in the specified direction

c) with all identified kinematically possible wedges and c´= 0, ϕ´ = ϕ´min, carry on stability analyses and obtain factors of safety.

d) identify the wedges that have a factor of safety less than a minimum (Fs < Fs min).

e) in a stereonet, find the slope inclination which does not allow outcropping of any critical wedge

f) to verify, carry on new stability analyses, for the specified slope direction and obtained inclination, and check that factors of safety comply with Fs > Fs min.

With this procedure a more detailed scrutiny of all possible wedges is obtained and the possibility of missing the critical planes is minimized.

3. Practical implementation of the all-wedge stability analysis procedure

Since the proposed procedure can involve great amount of data, the Author wrote the program ALLWEDGE in FORTRAN-77 code which can handle all the tasks in an ordered fashion [Gonzalez, 1996].

For the stability analyses the program uses the Hoek-Bray complete wedge method (but without tension crack) which is published in Appendix 2 of Rock Slope Engineering [Hoek and Bray, 1977].

Main ALLWEDGE program features are:

(1) It hand handle up to 400 discontinuities and 30 slopes, which means theoretically 79,800 wedges for each slope.

(2) Common values for all slopes are: water unit weight (which defines units), water pressure and earthquake accelerations: vertical (+downwards) and horizontal (+outwards), which are in the direction of the intersection of the wedge main planes.

(3) For each discontinuity, data are: dip direction (°), dip angle (°), effective cohesion (c´), effective friction angle (ϕ´).

(4) For each slope data are: slope dip direction (°), slope dip angle (°), slope upper terrain dip direction (°); slope upper terrain dip angle (°), rock mass unit weight, slope height, slope maximum width (which limits wedge height), factor η (η =1.0 if slope is positive, η = - 1.0 if slope is negative)

(5) For each slope, additional data are: external force, external force dip direction (°), external force dip angle (°)

The program outputs: title; discontinuity data (number, dip direction, dip angle, c´ and ϕ´); slope data (number; dip direction, dip angle, upper terrain dip direction, upper terrain dip angle, rock unit weight, slope height, slope width, maximum Fs); wedge data if no tension is requested (number, plane 1, plane 2, wedge dip direction, wedge dip angle, wedge central angle, factor of safety, contact plane- 101 if in both planes); wedge data if tension is requested (same as before but added of 3 optional tension forces, minimum tension force, all with tension force dip direction, tension force dip angle and contact plane(s) after minimum tension is applied), This file can be named *.res and also, if desired, another text file, which can be named *.txt, delivers data to import into a spreadsheet.

4. Example problem data

In order to clarify the main point of this paper, an example of the stabilization of a road cut is presented.

The road cut is an existing 52m high rock cut in tertiary sandstones and sandy claystones, with general slope angle of 57.5° (Figures 1 and 2), which presented some block failures.

Due its height and inclination, and also because the road was in use, it was very difficult to try to stabilize it with rock bolts and shotcrete, due to accesibility and personnel safety problems. Therefore, after preliminary calculations, it was decided to stabilize it by further excavation.

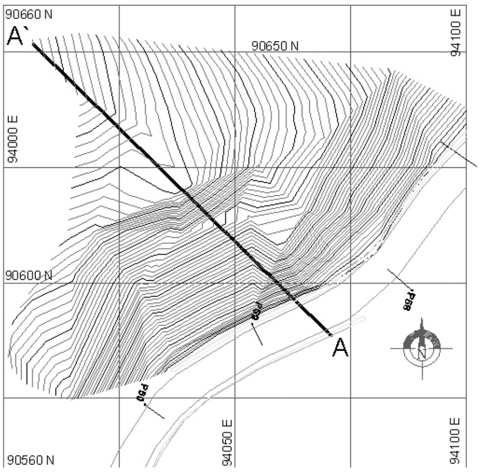

Fig. 1. Road cut - Plan view

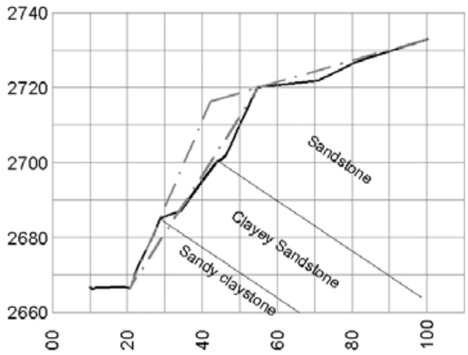

Fig. 2. Road cut – Cross-section AA´

Dimensions in Figures 1 and 2 are in meters, slope dip direction is 134.38° (the same of cross -section AA´) and for the purpose of some analyses the dash-dot profiles in Figure 2 were adopted.

Geological data were also difficult to obtain and a crane was used to put the geologist in front of the cut face to measure discontinuities. The obtained data consisted of 10 bedding and 40 joint measurements, which are listed in Appendix A.

5. Pole counting wedge analyses

5.1. *Pole counting*

Pole counting was done by several methods but only three of them are summarized in Table 1: the geologist made his own assigment and the Author made pole counting with DIPS [Rocscience, 1995] (Figure 3) and with vector averaging, which the Author considers the best method and whose data were used for analysis

Table 1. Pole counting- Families of Discontinuities- DD= dip direction (°); Dip= dip angle (°)

	Geologist		DIPS		Vector Avg	
Family	**DD**	**Dip**	**DD**	**Dip**	**DD**	**Dip**
Bedding	285	40	285.80	37.05	286.22	37.36
1	180	75	179.66	70.53	182.92	74.43
2	135	90	134.99	89.43	135.00	90.00
3	55	90	55.00	90.00	55.00	90.00
4	85	65	85.33	65.81	85.43	66.10
5	110	55	106.33	56.50	106.48	58.87
6	-o-	-o-	180.00	89.71	184.99	90.00

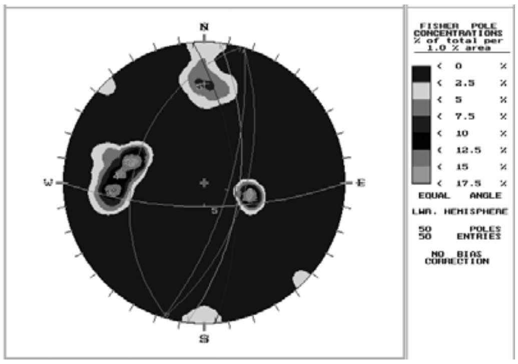

Fig. 3. Road cut - Pole counting- DIPS

5.2. *Unit weight and strength parameters*

Unit weight of rock, from density tests, was adopted as 25 kN/m^3. From inclined plane tests, rugosity descriptions and some direct shear tests in cut samples, the following strength data was adopted (Table 2):

Table 2. Adopted discontinuity shear strength parameters

Family	Effective cohesion c´ (kPa)	Effective friction angle ϕ´ (°)
Bedding	3.73	28.3
1, 2, 5, 6	3.71	20.4
3	2.93	31.0
4	3.98	32.6

For kinematic-friction analyses, a minimum friction angle ϕ´min of 15° was adopted for bedding planes and of 20° for joint planes.

5.3. *Wedge analysis*

Wedge analysis was made using the minimum friction angles, a 90° slope and ALLWEDGE program. At the time of the discontinuity survey the magnetic declination angle was –5.33°, and this was taken into account. The following results were obtained (vector diagrams):

(a) 10 kinematically possible wedges (Fig.4)

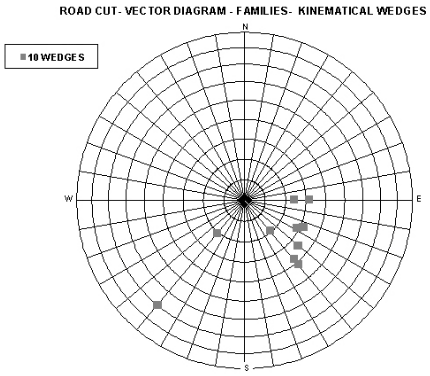

Fig. 4. Road cut - Pole counting- 10 kinematical wedges

(b) 9 kinematically possible wedges with factor of safety Fs < 1 (Figure 5)

(c) With these wedges a 50° inclined slope is possible (Figure 5)

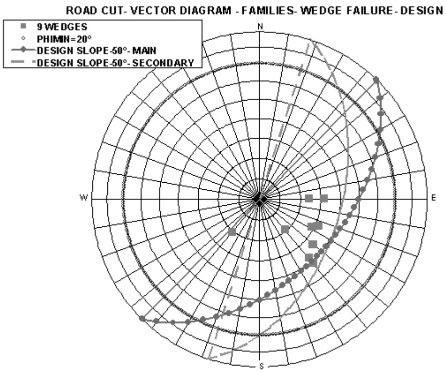

Fig. 5. Road cut - Pole counting- Design slope

(d) An analysis with the adopted strength parameters (Table 2) indicates that for the 50° slope there are no wedges with Fs < 1.6 and that Fsmin = 2.724

(e) Therefore a 134.38° / 50°, 57.7m high slope is adopted based on pole count analysis.

6. All-wedge analyses

6.1. *Discontinuities and strength*

Eliminating repeated data from the original discontinuity survey, 5 bedding planes and 32 joint planes were used. Unit weight is 25 kN/m^3 and strength parameters from Table 2 were assigned to joints depending upon the family in the vector averaging analysis (Appendix A).

6.2. *Wedge analysis*

Wedge analysis was made using the minimum friction angles, a 90° slope and ALLWEDGE program, taking into account the declination correction. The results were (vector diagrams):

(a) 389 kinematically possible wedges (Fig.6)

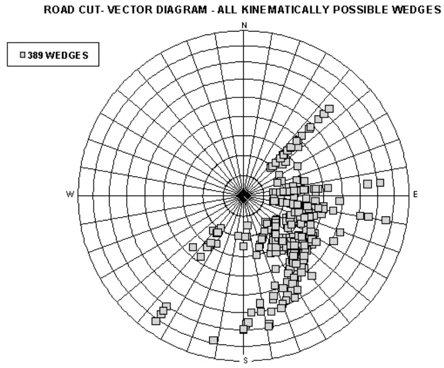

Fig. 6. Road cut – All-wedge- 389 kinematical wedges

(b) 303 kinematically possible wedges with factor of safety Fs < 1 (Figure 7)

(c) With these wedges a 45° inclined slope is possible (Figure 7)

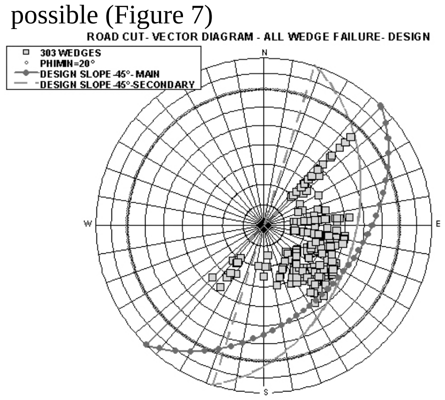

Fig. 7. Road cut – All-wedge- Design slope

(d) An analysis with the adopted strength parameters (Table 2) indicates that for the 45° slope there are no wedges with Fs < 1.6 and that the minimum Fs = 1.986

(e) Therefore a 134.38° / 45°, 61.5m high slope is adopted based on all-wedge analysis.

7. Planar failure analyses

The planar failure, which somehow is taken into account in ALLWEDGE program results (when there is wedge contact only in one plane), is not critical in this road cut case, neither for the pole counting method (Figure 8) nor for the all-wedge method (Figure 9)

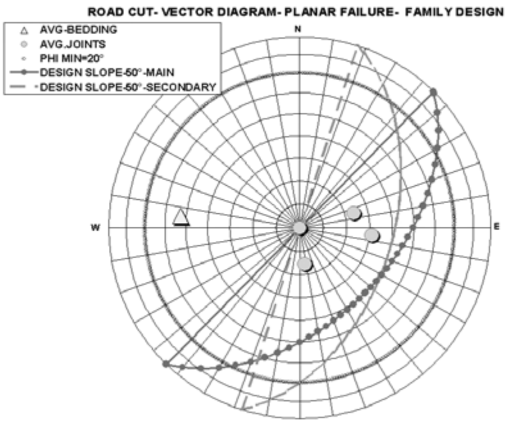

Fig. 8. Road cut – Pole counting- Planar failure

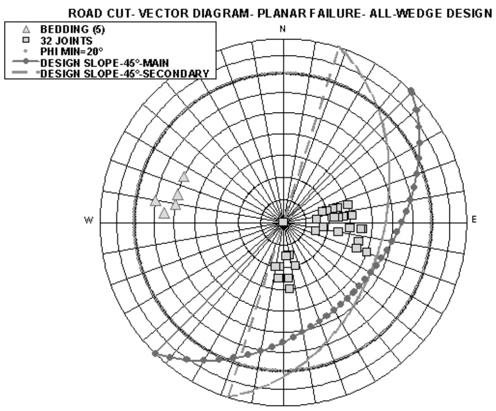

Fig. 9. Road cut – All-wedge- Planar failure

8. Final design

With the all-wedge results the adopted slope was at 45° inclination (Figures 10 and 11), which gave approximately 20,000m^3 of excavation, whereas the 50° slope required about 15,000m^3.

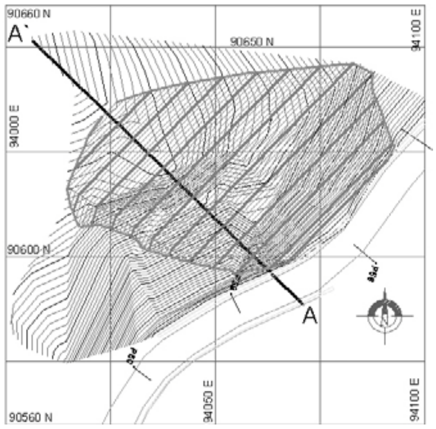

Fig. 11. Road cut – Final design – Plan view

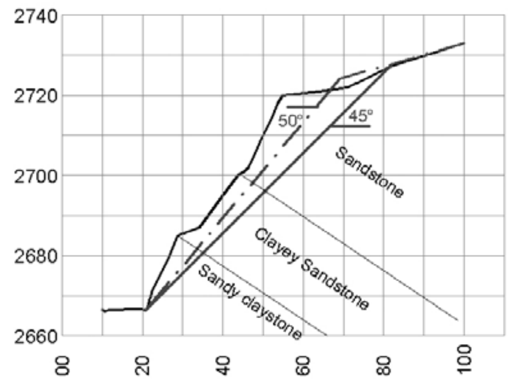

Fig. 11. Road cut – Final design- Cross-section AA´

9. Comparison and conclusions

For the road cut example, the pole counting method provides a 57.7m high 50° slope, whereas the all-wedge method gives a 61.5m high 45° slope (Fig.11)

Apparently there is no essential contradiction between the two results, with only 5° difference in inclination, but the all-wedge slope results in larger excavation volume. Is it worth to do it ?

If an analysis is run for the 50° slope in ALLWEDGE, with all the discontinuities, the following results emerge:

a) There are 87 kinematically possible wedges
b) There are 16 wedges with Fs < 1.6, of which 5 have Fs < 1.0.
c) Minimum factor of safety is Fsmin=0.792

Therefore, from these results, it is readily concluded that the pole count procedure can lead to unsafe slope stability results.

There is always room for discussion about the persistence of all the discontinuities in the whole rock mass or the presence of local variations in their orientations, but with all the uncertainties involved in discontinuity surveys and analyses, the Author believes that to use all the surveyed discontinuities in rock slope stability analysis results in sounder and safer designs.

References

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Appendix A

Table A1. Road cut raw discontinuity data.

No	Dip Dir. (°)	Dip Angle (°)	Family
1	280.0	35.0	Bedding
2	280.0	35.0	Bedding
3	280.0	35.0	Bedding
4	285.0	30.0	Bedding
5	285.0	40.0	Bedding
6	285.0	40.0	Bedding
7	285.0	40.0	Bedding
8	290.0	40.0	Bedding
9	290.0	40.0	Bedding
10	300.0	40.0	Bedding
11	180.0	75.0	1
12	180.0	90.0	1
13	180.0	90.0	1
14	195.0	90.0	1
15	195.0	70.0	1
16	190.0	65.0	1

Table A1 (continued) Road cut raw discontinuity data.

No	Dip Dir. (°)	Dip Angle (°)	Family
17	190.0	70.0	1
18	180.0	65.0	1
19	170.0	70.0	1
20	175.0	75.0	1
21	180.0	60.0	1
22	180.0	75.0	1
23	140.0	90.0	2
24	130.0	90.0	2
25	55.0	90.0	3
26	90.0	65.0	4
27	90.0	67.0	4
28	90.0	65.0	4
29	90.0	59.0	4
30	90.0	75.0	4
31	90.0	63.0	4
32	80.0	65.0	4
33	80.0	60.0	4
34	80.0	67.0	4
35	80.0	70.0	4
36	80.0	72.0	4
37	105.0	65.0	5
38	105.0	65.0	5
39	110.0	55.0	5
40	115.0	55.0	5
41	115.0	50.0	5
42	100.0	54.0	5
43	100.0	55.0	5
44	100.0	60.0	6
45	100.0	55.0	6
46	110.0	55.0	6
47	102.0	72.0	6
48	110.0	55.0	6
49	110.0	75.0	6
50	110.0	55.0	6