The paper was published in the proceedings of the 11th Australia New Zealand Conference on Geomechanics and was edited by Prof. Guillermo Narsilio, Prof. Arul Arulrajah and Prof. Jayantha Kodikara. The conference was held in Melbourne, Australia, 15-18 July 2012.

Spoil Piles - Comparison of Limit Equilibrium Stability Analyses

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ABSTRACT

A study has been undertaken by the author to confirm appropriate analysis methods applicable to the design of granular waste materials and specifically to that of "spoil piles" developed during open pit coal mining. This paper addresses limit equilibrium stability analysis software that would be commonly utilised, as well as the use of two "numerical based" approaches for comparison. The authors' experience with spoil pile stability is that the critical failure mechanism is that of a two wedge mechanism in accord with that highlighted in the literature. However, analysis requires careful consideration of the underlying assumption of combination of spoil shear strengths and the angle of the "rear" scarp adopted. To highlight these considerations the author presents a hypothetical case of a spoil pile design for varying floor dips. The results are presented as overall spoil pile angle indicated by the use of different software, stability method and "rear" scarp assumptions. The example case highlights that provided a rigorous stability method is utilised, for a given rear scarp assumption, the results of the analyses are insensitive to the software utilised. As such, assessment of spoil pile stability should not be predicated by use of one particular software or stability method.

Keywords: spoil piles, stability, two wedge mechanism

1 INTRODUCTION

A study has been undertaken by the author to confirm appropriate analysis methods applicable to the design of granular waste materials and specifically to that of "spoil piles" developed during open pit coal mining. This paper addresses limit equilibrium stability analysis programs that would be commonly utilised, as well as the use of two "numerical based" approaches for comparison.

The study is based on a hypothetical case, albeit one which is considered typically representative, that has allowed a comparison of differences between software packages and underlying assumptions.

2 BACKGROUND AND HISTORY OF OBSERVATIONS – SPOIL FAILURES

2.1 Two Wedge Mechanism

It has been recognised that the controlling failure mechanism within embankments and structures comprised of largely granular materials (particularly where there is a strong geometric control of at least one interface) is that of a two wedge mechanism (Sultan and Seed 1967, CANMET 1977, Coulthard 1979, O'Regan *et al* 1981, Campbell 2000; Simmons and McManus 2004).

Historically there are several approaches that would be utilised in assessing the stability of such a mechanism, for example use of either a "force-polygon" approach or utilising the Sarma method with non-vertical slices (Sarma 1979).

Figure 1 presents the geometry and forces utilised in the force-polygon approach (Sultan and Seed 1967, CANMET 1977, Coulthard 1979 and Campbell 2000). A key consideration is the assumption of mobilised shear force on the three key faces. Equations 1 to 3 present the mobilised shear force equations and with Table 1 providing a summary of assumptions utilised by various authors (where FoS represents Factor of Safety) in the application of the approach.

Acting on rear scarp $S_1 = [c_1 l_1 + N_1 \tan(\phi_1)]/FoS_1$ (1)

Acting on interface $S_{12} = [c_{12} l_{12} + N_{12} \tan(\delta)]/FoS_2$ (2)

Acting on base $S_2 = [c_2 l_2 + N_2 \tan(\phi_2)]/FoS_3$ (3)

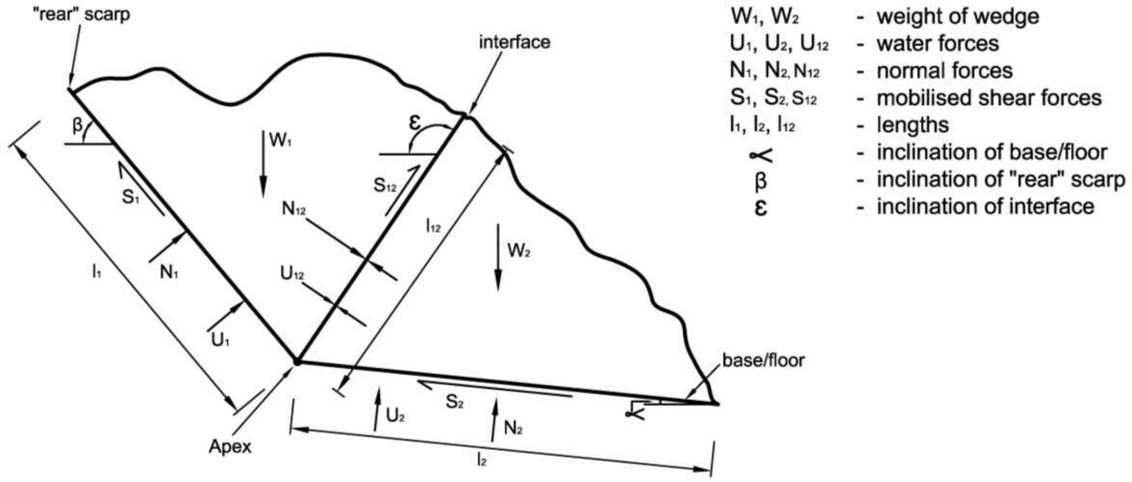

Figure 1. Two wedge mechanism.

The author has created a spreadsheet which assesses stability of a two wedge mechanism by both the force polygon approach and the Sarma method for non-vertical slices. The spreadsheet allows; variation on assumption of the degree of mobilisation of the interface shear force, control on the location of the apex and iteration of geometry of both rear scarp and interface. The spreadsheet has been verified with published results (Hoek 1987; Simmons and McManus 2004).

Table 1: Assumption of mobilised shear forces on wedge, see Figure 1.

Author	Rear scarp	Interface	Base
Sultan and Seed (1967)	$FoS_1 = FoS$	$c_{12} = 0$, $\delta = \phi_{12}$, $FoS_2 = FoS$	$FoS_3 = FoS$
CANMET (1977)	$FoS_1 = FoS$	$\varepsilon = 90$, $c_{12} = 0$, $\delta = \phi_{12}/3$, $FoS_2 = 1$	$FoS_3 = FoS$
Coulthard (1979)	$FoS_1 = FoS$	$c_{12} = 0$, $\delta = \phi_{12}$, $FoS_2 = FoS$	$FoS_3 = FoS$
Campbell (2000)	$FoS_1 = 1$	$\delta = \phi_{12}$, $FoS_2 = 1$	$FoS_3 = FoS$
Alejano *et al* (2011)	$c_1 = 0$, $FoS_1 = 1$	$c_{12} = 0$, $\delta = 0$	$c_2 = 0$, $FoS_3 = FoS_A$
	$c_1 = 0$, $FoS_1 = 1$	$c_{12} = 0$, $\delta = \phi_{12}$, $FoS_2 = 1$	$c_2 = 0$, $FoS_3 = FoS_B$
	Overall $FoS = (FoS_A + FoS_B)/2$		
Duran (2012)	$FoS_1 = FoS$	$\delta = \phi_{12}$, $FoS_2 = 1/\%$[a]	$FoS_3 = FoS$

a % - percentage of interface shear mobilised

Where spoil shear strength has non-zero cohesion assigned, use of the last approach and appropriate selection of the percentage of interface shear mobilised is required for a rigorous solution.

2.2 Rear Scarp and Interslice

Available literature, coupled with observations of failures by the author, indicates the rear scarps of spoil failures are typically steep. The following rear scarp angles have been reported:

- 67°, 62° and 61° for three case studies of spoil failures with heights of 77m, 86m and 91m respectively (Coulthard 1979).
- 64° for one case study of a spoil failure 80m high (O'Regan *et al* 1981).
- Median rear scarp measured on numerous spoil failures to be about 63° (2V:1H) (Simmons 2011).
- 55° for a 170m high dump placed on very steep terrain (Campbell 2000).

Although the above suggests the median value of 63° appears appropriate for spoil piles created by draglines, there is a trend of reducing rear scarp angle with increasing overall spoil/dump height.

There is consensus (Coulthard 1979, O'Regan *et al* 1981, Campbell 2000; Simmons and McManus 2004) the interface is non-vertical and typically at a complimentary angle to the rear scarp, for example and with reference to Figure 1, for β = 60°, ε = 120°.

2.3 BMA Spoil Shear Strength Framework

Simmons and McManus (2004) presented the BMA spoil shear strength framework which provides a methodology of assigning spoil shear strengths for materials based on typical characteristics and for different modes of strength as a result of placement conditions. Simmons and McManus (2004) highlight that the strengths involved rigorous back-analysis, using the Sarma method with non-vertical slices and with observed failure geometries. Although not specifically specified it is implied the BMA spoil shear strength parameters have an underlying caveat that the rear scarp is set at nominally 63°.

3 CASE STUDY

3.1 Preamble

A case study has been undertaken to highlight differences in results of limit equilibrium stability analysis programs that could be commonly utilised, as well as the use of two "numerical based" approaches for comparative purposes.

The author has limited the comparison to that of one case study with singular values of spoil and floor strengths, as an exhaustive array of analyses was not considered warranted. It would be expected that similar relationships between the analyses would be encountered for different combinations of spoil and floor strengths and spoil heights.

3.2 Case Study Definition

The case study, considered to be representative of that which could be encountered, comprised evaluating the required overall spoil pile angle to achieve a Factor of Safety (FoS) of 1.20 for a 60m high spoil for floor dips in the range of 2 to 14°. The spoil pile was assigned parameters of 30kPa cohesion, friction angle of 28° and density of 18kN/m^3. The base/floor of the spoil pile was assigned zero cohesion and friction angle of 18°. Such a case represents the main body of spoil with Category 2 unsaturated BMA spoil shear strength (Simmons and McManus 2004). The base/floor representing a strength that may be assigned to either a sub-floor shear or under conditions where the spoil was placed under less than ideal conditions onto mud/water and represents a remoulded strength in the BMA spoil shear strength framework. Experience has shown that the inclusion of a groundwater level a few metres above the spoil floor typically causes only a minor reduction in FoS. As such, for simplicity no groundwater was included within any analyses herein.

3.3 Rear Scarp Assumptions

Two scenarios were considered for the assumption of the rear scarp within the analyses. Firstly, assuming that the rear scarp was fixed at 60° (designated as Group A for discussion purposes) and secondly allowing the rear scarp to vary to provide a minimum FoS (Group B). The former approach follows the guidelines as provided by Simmons and MacManus (2004) whilst the latter approach presents a scenario where the caveat on the BMA shear strengths has been ignored.

3.4 Analyses Undertaken

Table 2 provides a summary of the analyses that were undertaken and methods selected. Analyses using Galena, the authors' spreadsheet, SLOPEW and SLIDE utilised either a non-circular or two wedge mechanism and with iteration on the apex location for minimum FoS.

The author has applied the spoil pile design chart as presented by Rosengren (1981) and notes the design chart is independent of spoil height.

Galena analyses utilised the default setting on interface angle, review of results indicating the interface angle was typically 120° for all analyses.

Table 2: Analyses Undertaken

Software/ Reference	Methods Applied	Rear scarp fixed at 60°	Rear scarp for minimum FoS
Rosengren (1981)	Design chart used directly		
GALENA	Sarma	YES	NA
Duran (2012)	Force Polygon and Sarma[a]	YES	YES
SLOPEW	Sarma - Vertical slices* Morgenstern & Price (MP)	YES	YES
SLIDE	Morgenstern & Price (MP)	YES	YES
LimitState:Geo	Upper-bound limit analysis theory	NA	YES
$Phase^2$	Finite Element	NA	YES
Alejano *et al* (2011)	Force Polygon	YES[b]	NA

a All other uses of Sarma with non vertical slice boundaries
b Fixed at 59° using guidelines provided within Alejano et al of $45+\phi_1/2$

Two groups of analyses were carried out using the authors' spreadsheet. Firstly, with rear scarp fixed at 60° and with interface iterated for minimum FoS. Secondly, an iterative search on minimum FoS allowing variations in both rear scarp and interface. A common feature of the spreadsheet analyses was excellent agreement between the Sarma and force polygon solutions.

For both SLOPEW and SLIDE two groups of analyses were carried out; firstly, with a rear scarp fixed at 60°, secondly, with the rear scarp allowed to iterate to search on minimum FoS.

LimitState:Geo uses rigorous upper-bound limit analysis theory to automatically identify the critical layout of slip-lines within the mass. Only three analyses were carried out to provide relative comparison with other methods. LimitState:Geo is based on Eurocode 7 and partial factors on all input strengths were utilised to provide an equivalent FoS.

$Phase^2$ analyses were carried out on three selected analyses and utilising the Strength Reduction Factor (SRF) technique. SRF effectively iterates all input strengths by a given factor until model instability is indicated (ie non-convergence) and with the critical SRF being an indicator of FoS.

In both $Phase^2$ and LimitState:Geo the critical failure path is provided during the analyses. As such it would be anticipated that the analyses would be in accord with results of other analyses in Group B.

A final set of analyses was undertaken utilising the methodology as set out by Alejano *et al* (2011) and modified by the author to take account of cohesion within the spoil.

3.5 Analysis Results

Figure 2 provides a summary of analyses results. A striking feature of the analyses was the insensitivity to change in the overall angle of the spoil such that, typically, a 1° change in overall angle resulted in a change of 0.03 in FoS.

The following conclusions are drawn from the results of Group A:

- Results of Galena, SLOPEW with Sarma and the authors' spreadsheet are essentially similar, C in Figure 2. This result is not surprising as all utilise implementations of the Sarma method with the same rear scarp angle of 60°. However, each uses a different assumption on the interface angle, viz Galena typically at 120°, SLOPEW fixed at 90° and with the authors' spreadsheet searching for interface angle providing minimum FoS. The authors' spreadsheet indicated interface angle (for minimum FoS) near 105° for a 2° floor dip and trending towards 120° with steeper floor dips. This largely explains the difference between the authors' spreadsheet and Galena for flatter floor dips and why both provide similar results for steep floor dips.

- Analyses of SLOPEW and SLIDE with a rear scarp fixed at 60° using Morgenstern and Price (MP) method, D in Figure 2, provide slightly higher overall spoil angles at low floor dips and conversely slightly lower overall spoil angles at steeper floor dips than the above Group A methods.
- The analyses utilising the approach of Alejano *et al* (2011) provided appreciably steeper overall spoil angles. The author considers the approach is not rigorous and needs to be utilised with extreme caution.

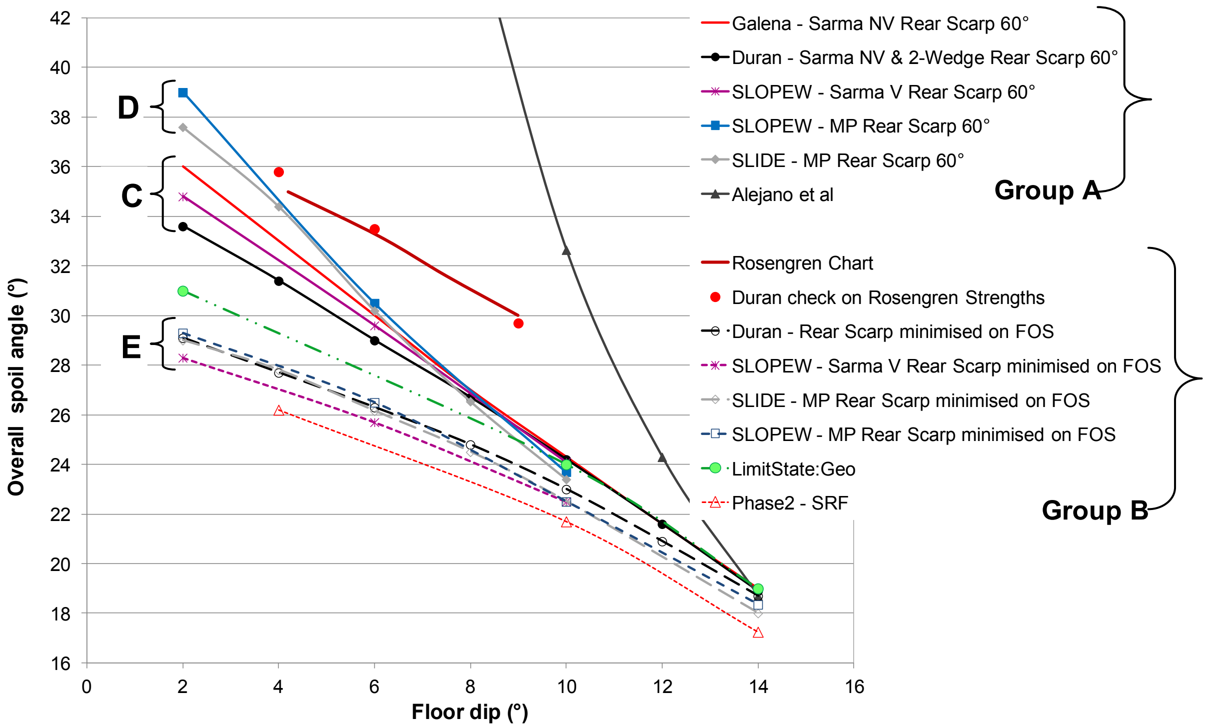

Figure 2. Comparison of analyses, Groups: A (rear scarp 60°) and B (rear scarp for minimum FoS).

The following conclusions are drawn from the results of Group B:

- Use of Rosengren (1981) provided consistently higher overall spoil angles, probably as a result of a higher spoil shear strength utilised in the creation of the design chart. Check analyses using the authors' spreadsheet, Figure 2, suggests spoil strength of nominally 38kPa cohesion and friction angle of 35°. The strength is notably higher than that used in the case study and somewhat contradicts the findings of Rosengren *et al* (2010) that "*stability of the pile is not very sensitive to spoil material strength".*
- Results of all other limit equilibrium methods, authors' spreadsheet, SLOPEW with Sarma, and both SLOPEW and SLIDE with Morgenstern and Price (MP) all provided very similar results and with essentially "parallel" curves, E in Figure 2.
- Phase^2, using the SRF method, provided consistently lower overall spoil angles (of the order of 1.5°). This is probably a function of the manner in which Phase^2 attempts to capture "instability" in the finite-element model as it approaches limit equilibrium and resulting in slightly conservative results.
- LimitState:Geo, provided consistently higher overall spoil angles (of the order of 2°).

The following conclusion is drawn from comparison of results between Groups A and B in Figure 2 and ignoring the results from Rosengren (1981) and the approach of Alejano *et al* (2011):

- At low floor dips, all Group B analyses, relative to Group A, provide conservative results and with overall spoil angles lower by up to 6°.
- With steeper floor dips the difference between Group A and B is less pronounced and negligible for floor dips above 12°.

4 CONCLUSION

The case study has highlighted the implications of the assumptions of both rear scarp and interface angles on spoil stability analyses. Although the findings are limited to that of one case study it is considered that they are probably applicable to other combinations of spoil and floor strengths and spoil heights.

Use of BMA spoil strengths needs to be cognisant of the caveat on the rear scarp inclination, with Simmons and MacManus (2004) recommending the "*Sarma method based on observed failure geometries*". Based on Figure 2, and cognisant that a 1° change in overall angle equates to nominally a 0.03 change in FoS, the following methods could be utilised with the rear scarp appropriate to that of observed failure geometries:

- A two wedge solution with appropriate consideration of the interface shear mobilised.
- Use of Sarma method with vertical slices.
- "Block-slide" with Morgenstern and Price method, although it is likely the results will be slightly optimistic for low floor dips and slightly conservative for steep floor dips.
- Although not specifically analysed by the author, both LimitStage:Geo and Phase^2 could also be utilised with careful consideration of anisotropic strength functions.

The author acknowledges that other software implementing appropriate rigorous methods may be also suitable and it would be prudent to carry out checks prior to embarking on wider use.

5 ACKNOWLEDGEMENTS

The author acknowledges the enthusiasm, encouragement and guidance provided by Mr Garry Mostyn in the use of the two wedge solution. This ultimately led to the implementation and creation of a "Macro driven" spreadsheet solution for use within the authors' firm.

The author also acknowledges comments provided by Mr John Simmons which assisted in a better understanding of the use of the BMA shear strength framework in relation to Galena and comments on the rear scarp inclination based on his many years of observations within industry.

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