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Undrained behaviour in spoil piles

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Abstract

Stability of spoil piles has been traditionally undertaken with the use of drained strength parameters and utilising groundwater profiles within the spoil which are appropriate. Moreover, whilst the author's experience suggests this is by far generally the case, review of recent failures at two strip mining operations suggests scenarios where there is a strong indication that undrained strength parameters could be assigned. The author presents seven case studies. As an alternative to undrained strength parameters, the author has considered; low strength shears in the sub-floor or spoil loading providing short term pore pressure increases in the sub-floor. The former provides unrealistic estimates of shear strengths applicable at both operations whilst the latter requires invoking groundwater assumptions, which although appearing reasonable, are difficult to readily implement in stability analyses.

Accepting that undrained behaviour is appropriate, based on the seven case studies this paper highlights three key aspects: scenarios where undrained strengths are developed; materials that are likely to allow development of undrained strengths; and typical values of undrained shear strength indicated by back−analysis.

1 Introduction

This paper presents seven case studies of spoil pile instability. Review of stability indicated the failures were often deep seated and suggested a strong indication of 'undrained' shear strength behaviour at the spoil base. In each case the stability of adjacent spoil, or of spoil in the previous strip, has been utilised to highlight the critical triggers in each failure.

The experience has indicated three key aspects:

- Scenarios where undrained strengths are developed.
- Materials that are likely to allow development of undrained strengths.
- Typical values of undrained shear strength indicated by back-analysis.

2 Background

2.1 Spoiling process

Strip mining by dragline is utilised to move blasted overburden from the current strip into the previous void, thereby exposing coal and with the dragline advancing along the strike of the strip. Figure 1 presents an overview of the process and highlights there are several steps involved in the spoiling process. Draglines provide a very efficient means of overburden transport. Of interest in this paper is that the spoil piles created are of the order of 60 to 100 m high and with lineal rates of advance along the strip of 10 m/day not uncommon. In view that the spoil piles are created in a short time frame, the spoiling process is essentially one of rapid loading of the spoil pile base.

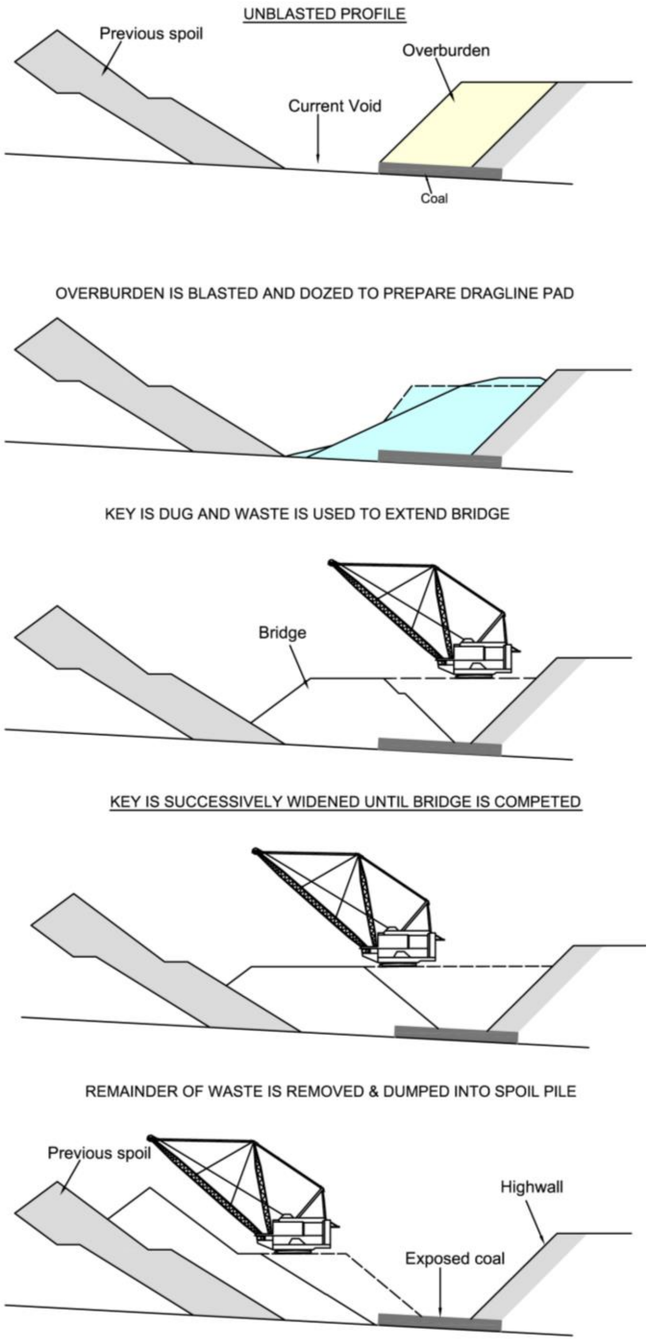

Figure 1 Overview of the spoiling process

2.2 Assessment of spoil stability

Simmons and McManus (2004) provide an overview of the BMA spoil shear strength framework (BMA Spoil Framework). The approach can be used in estimating shear strength parameters for spoil, has widespread use in the Bowen Basin of Queensland and has been found to be applicable for coal measure rocks elsewhere. The author has successfully utilised the approach during back-analysis of numerous failures and three key aspects are of note. Firstly, the failure mechanism is that of a two wedge failure and requires appropriate analysis (Seed and Sultan, 1967; Campbell, 2000; Simmons and McManus; 2004 and Duran, 2012). Secondly, the BMA Spoil Framework provides an appropriate basis in assigning shear strength parameters of the spoil. Thirdly, and most importantly, stability is largely dictated by the floor or sub-floor conditions on which the spoil is placed. Adverse stability is typically the result of either: placing spoil into water or over mud, or the presence of shears, clay seams or other geological features that provide ‘bedding parallel weak layers' in the sub-floor. For the former, although such an approach is clearly undesirable from the point of view of spoil stability, is sometimes carried out operationally either due to timing issues or difficulty arising in removing such material from the pit floor. For the latter, such features may not be evident until stability issues manifest and investigations are instigated to confirm the character and strength.

3 Overview of cases

3.1 Geological setting

Both strip mining operations obtain thermal coal from the Permian aged Rangal Coal Measures. The overburden stratum typically comprises sandstones and siltstones. At one operation the issues are confined to an area where the Permian overburden is recognised as being of lower intact strength and more prone to slaking than seen elsewhere in the deposit, as well as having a mantle of Tertiary clays. At the other operation, intact strengths of Permian overburden are typically less than 10 MPa and with palaeo channels infilled with Tertiary aged basalt flows separated by tuffs/alluvials.

Both operations operate with relatively low floor dips. All cases of instability are associated with floor dips in the range of 2 to 3°.

3.2 Case 1

For Case 1 there was some uncertainty as to the extent of mud placed within historic 'mud cells' placed against the remnant coal toe. During development of the strip, failure of the lower bench occurred in the proximity of the operating dragline bench. The lateral extent of failure along the strip was relatively minor.

3.3 Case 2

For Case 2 there had been flooding of the pit prior to spoiling being undertaken. The pit was largely dewatered prior to spoiling being undertaken. Failure occurred over a strike length of about 150 m of the pit and with the back scarp at the first spoil peak. There was evidence to suggest that Tertiary clay, locally thicker in the area of instability, may have been placed in the spoil base.

3.4 Case 3

For Case 3, truck dumping was being carried out to the spoil peak in the current mining strip when failure occurred. Such dumping practice is typically avoided in most strip operations. However, of particular note in this case was the relatively low floor dips in addition to moderate overall spoil height. Two aspects were of particular note for the failure, the rear scarp was very steep and the lateral extent of the failure was significant, encompassing about 300 m strike length of pit.

In terms of history, no back-analyses had been undertaken of Cases 1 to 3. Cases 1 and 2 only had minor impacts on operations and were attributed to localised floor conditions, whilst Case 3 was triggered by truck dumps encroaching too close to the active mining strip. Back-analyses for these three cases were carried out during a review after the Case 6 failure to provide an overview of appropriate strengths at the operation.

3.5 Case 4

Case 4 presented a conundrum at the time. The operations personnel where well aware of the risk of spoil failure in the strip as the pit had been inundated. As such, an extensive effort was made to clean up the floor of all mud. In addition, the spoiling in the strip had been carried out during a relatively dry period and with cast blasting of fresh Permian material into the pit void. Although Tertiary materials are present these were double handled to ensure their placement in the upper part of the spoil. Even with the high degree of certainty in the spoil floor conditions, an extensive failure occurred in the strip. Elements of note of the failure were; an extensive lateral extent of 400 m along strike, a very steep rear scarp which had developed in the second spoil peak and a pronounced lateral movement of the lower spoil pile, up to 30 m into the pit void, with thrusting both over and through the exposed coal seam.

3.6 Case 5

For Case 5 very difficult in-pit conditions were experienced. Tertiary clays, which had been placed at the spoil base, had become saturated/inundated during a significant wet season. Although a program of 'mud-replacement' had been utilised (the process involves progressively excavating the mud from the spoil base and replacing the mud with better quality Permian) the program was carried out during further heavy rain periods. Numerous failures occurred in the spoil within the strip, commonly with the back scarp at the first spoil peak but also with evidence of remobilisation of historic failures.

3.7 Case 6

For Case 6 flooding of the pit had occurred prior to spoiling taking place. Pit dewatering had taken place and operations personnel ensured the base of the spoil was placed under ideal conditions. However, a significant failure occurred that encompassed about 200 m of strike length, with the failure scarp located up to 15 m behind the crest of the first spoil peak and partly affecting a low wall ramp into the strip.

3.8 Case 7

Case 7 represents the subsequent mining strip to Case 5. Parallels to Case 4 are present in that a concerted effort was made by operations personnel to ensure the base of the spoil was placed under ideal conditions. Even with the concerted effort, a significant failure occurred that encompassed about 450 m of strike length, with the failure scarp located up to 40 m behind the crest of the first spoil peak and affecting a lowwall ramp into the strip.

4 Potential scenarios

The author has considered five different potential scenarios of floor conditions in the back-analyses of the seven cases. The various scenarios have been utilised to confirm the plausibility of undrained behaviour as the most likely basis for the failures and have comprised:

- Scenario A – where the spoil floor in the current strip comprises mud, it can behave in an undrained manner. Review of the history for each case indicates this is a viable scenario for Cases 1, 2, 3 and 5; where in the areas of failure, the spoil base was either known to have or may have largely comprised detrimental materials.
- Scenario B – the spoil floor in the previous strip has become saturated either as a result of surface water infiltration or upwelling of groundwater from the sub-floor. Using the BMA Spoil Framework the spoil near the floor would be assigned a 'saturated' strength. However, the author has considered that the saturated spoil of the previous strip behaves in an undrained manner as a result of the rapid loading from the spoiling in the current strip. The undrained strength has been applied as a fixed value. Figure 2 presents the postulated scenario. Extending the description of the saturation process on fill material

  "when significant quantities of water enter void spaces within the soil mass, the interparticle contacts and even the particles themselves are likely to slake, soften, and weaken" (Simmons and McManus, 2004).
- The author considers there may be cases when the extent of softening is sufficient to result in creation of a matrix supported material akin to a 'mud'. For this scenario, the strengths adopted in the immediate floor of the current spoil have been based in keeping with observations. The scenario is considered plausible for Cases 2 to 7.

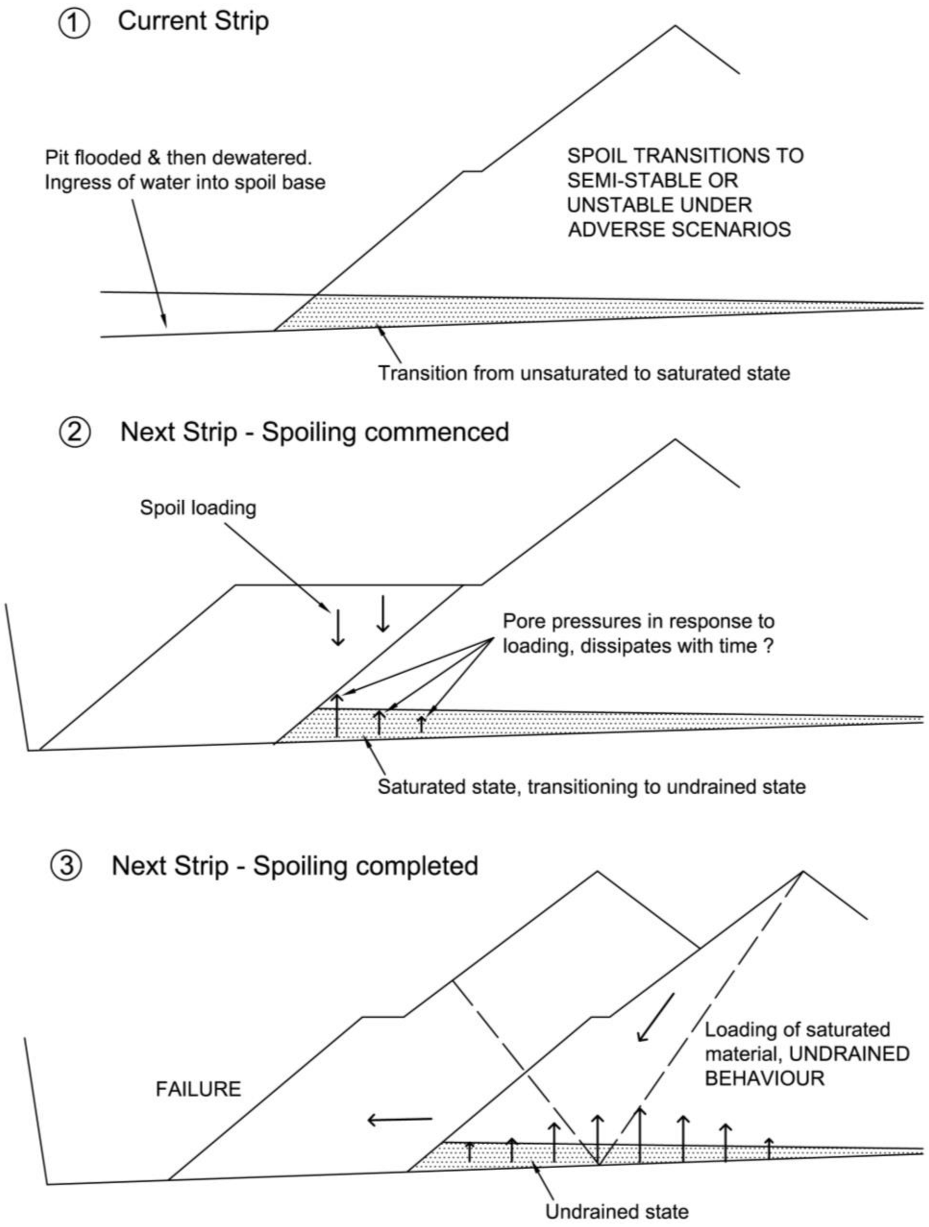

Figure 2 Concept of mechanism by which undrained behaviour is invoked at base of spoil pile

- Scenario C – failure has been triggered by the presence of a sub-floor shear in the pit floor, considered plausible for all Cases.
- Scenario D – failure has been triggered by presence of a ‘weak layer’ in the pit floor coupled with transient pore pressures developed in the sub-floor in response to spoil loading from the current spoil, considered plausible for all Cases. For this scenario it was assumed the pore pressure increase was directly in proportion to the one-dimensional spoil surcharge from the current spoil and assuming a B-bar of unity, Figure 3.

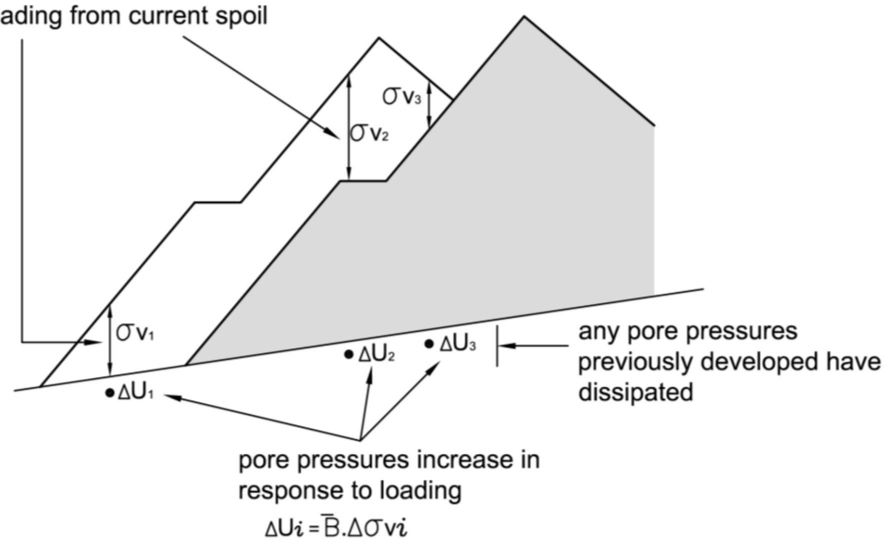

Figure 3 **Pore pressure response in sub-floor as a result of spoil loading**

- Scenario E – identical mechanism to Scenario B. However, the undrained strength (Su) has been assigned as a normalised undrained shear strength ratio (Su/σ_v) (Osterman, 1959). Moreover, the available consolidation (σ_v) has been assigned by the author on the basis of the one-dimensional spoil surcharge at the base of the previous spoil, Figure 4. Prior to saturation occurring, material at the base of the spoil has undergone consolidated. The author considers that during the saturation process, where the breakdown of interparticle contacts may have formed mud, there is settlement and redistribution of the vertical loading.

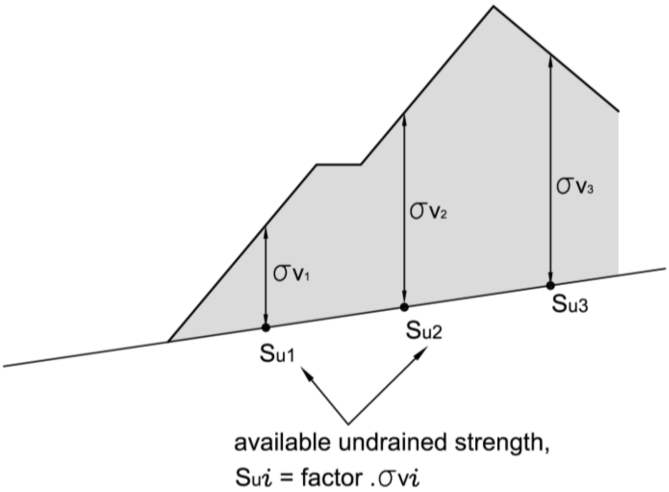

Figure 4 **Approach utilised in assessing the available undrained shear strength at base of previous spoil based on consolidation (σ_v)**

5 Back-analyses

The back-analyses were all carried out in SLIDE (Rocscience Inc., 2013), utilising the 'block-search' option, adopting the Morgenstern-Price method of slices and with the rear scarp fixed at 63°, (i.e. in keeping with the recommendations presented in Duran, 2012). The shear strength within the main body of spoil was based on appropriate consideration of the BMA Spoil Framework and consideration of material present in each case. For each scenario, iteration of the appropriate strength parameter was carried out until a Factor of Safety (FS) of close to unity was obtained, Table 1.

Table 1 Summary of back-analyses

Case	Scale and Failure Height		Strengths at Base of Spoil	
		Scenario*	Current Strip	Previous Strip
1	Lower bench only 25 m	A	C = 32 kPa phi = 0°	NA
		B	Not considered	
		C^{o}	C = 0 kPa phi = 10.7° entire floor	
		D^{o}	C = 0 kPa phi = 35° entire floor	
		E	Su = $0.08\sigma_V$	NA
2	First Peak 80 m	A	c = 90 kPa phi = 0° entire floor	
		B	Not considered	
		C	c = 0 kPa phi = 10.7° entire floor	
		D^{o}	c = 0 kPa phi = 14.7° entire floor	
		E	Su = $0.17\sigma_V$ entire floor	
3	20 m back from crest 67 m	A	c = 95 kPa phi = 0° entire floor	
		B	c = 0 kPa phi = 18°	c = 100 kPa phi = 0°
		C^{I}	c = 0 kPa phi = 11.1° entire floor	
		D^{I}	c = 0 kPa phi = 18° entire floor	
		E^{I}	Su = $0.19\sigma_V$ entire floor	
4	Second peak 80 m	A	Not considered	
		B	c = 30 kPa phi = 28°	c = 100 kPa phi = 0°
		C^{I}	c = 0 kPa phi = 12.5° entire floor	
		D^{I}	c = 0 kPa phi = 20° entire floor	
		E	c = 30 kPa phi = 28°	Su = $0.22\sigma_V$
5	First peak 70 m	A	c=116kPa phi=0° entire floor	
		B	c=15 kPa phi=23°	c=86 kPa phi=0°
		C	c = 0k Pa phi = 11.7° entire floor	
		D	c = 0k Pa phi = 14.1° entire floor	
		E	c = 15 kPa phi = 23°	Su = $0.18\sigma_V$
6	15 m back from first peak, 72 m	A	Not considered	
		B	Sheared floor [3]c = 0 kPa phi = 18°	c = 100 kPa phi = 0°
		C^{I}	c = 0 kPa phi = 10.6° entire floor	
		D^{I}	c = 0 kPa phi = 13.7° entire floor	
		E	Sheared floor c = 0 kPa phi = 18°	Su = $0.35\sigma_V$
7	Up to 40 m back from first peak, 70 m	A	Not considered	
		B	Sheared floor c = 0 kPa phi = 18°	c = 76 kPa phi = 0°
		C^{I}	c = 0 kPa phi = 11.4° entire floor	
		D	Non sensible result	
		E	Sheared floor c = 0 kPa phi = 18°	Su = $0.20\sigma_V$

* Superscript o - Scarp location from back-analysis occurs well beyond observed failure scarp.

* Superscript I - Scarp location from back-analysis occurs well inside observed failure scarp.

For each case, several cross-sections had been assessed by the author in reporting to each of the mine operators. For simplicity the results of only one cross-section are presented which highlights key aspects of each case.

Figures 5 to 11 present the cross-sections utilised in the back-analysis of each case. Each cross-section presents; the geometry of current spoil and previous spoil where appropriate, any internal sub-division of different materials in the spoil pile, the extent of floor conditions for each scenario, the piezometric line assigned solely to the sub-floor for Scenario D (assessed using the approach outlined in Figure 3), the spoil surcharge assumed to be applicable in assessing the undrained shear strength for Scenario E (assessed using the approach outlined in Figure 4) and nominal locations of the rear scarp for the critical failure mechanism encountered in the back-analysis of each scenario.

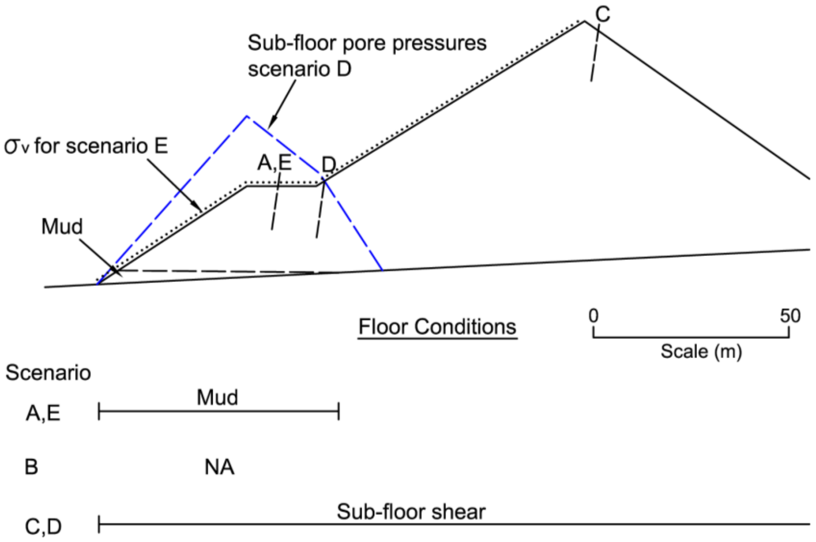

Figure 5 **Case 1: failure scarp observations in accord with results of analyses from scenario A, E and D**

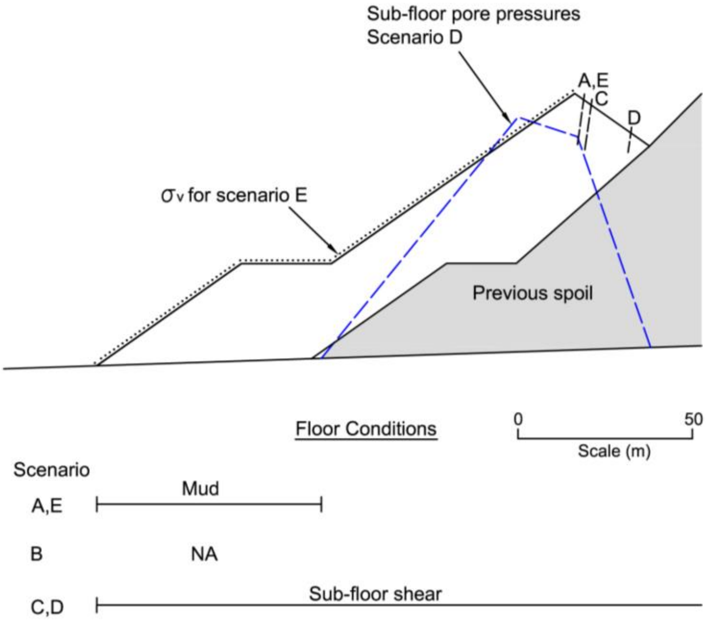

Figure 6 **Case 2: failure scarp observations in accord with results of analyses from scenario A, C and E**

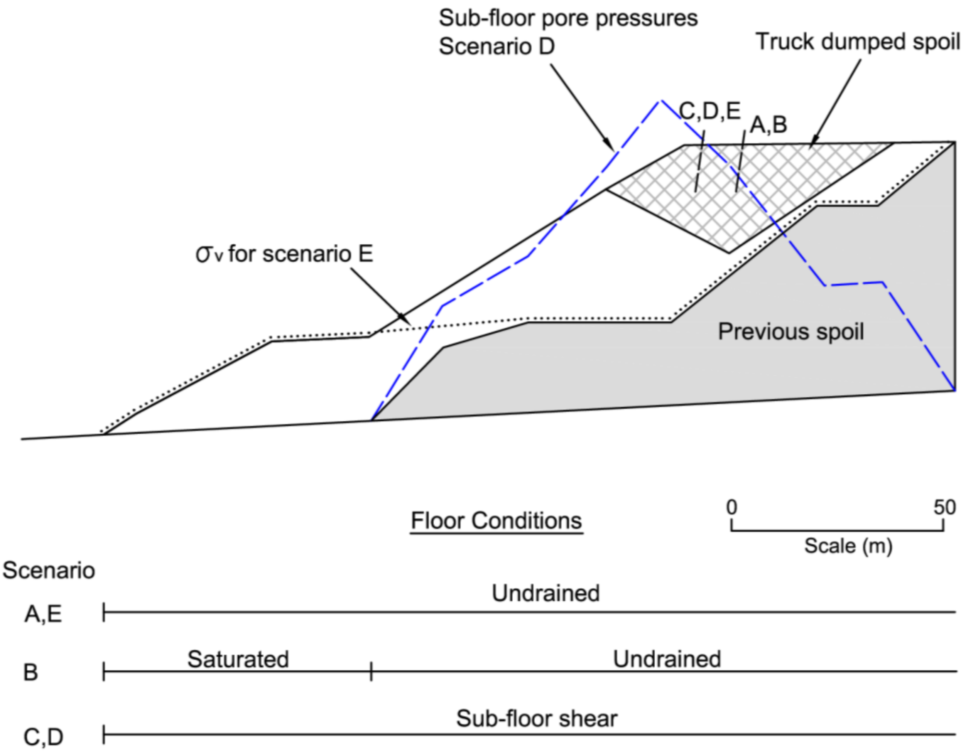

Figure 7 Case 3: failure scarp observations in accord with results of analyses from scenario A and B. For scenario E, accepted that initial phase of current spoiling assisted in consolidation of floor material

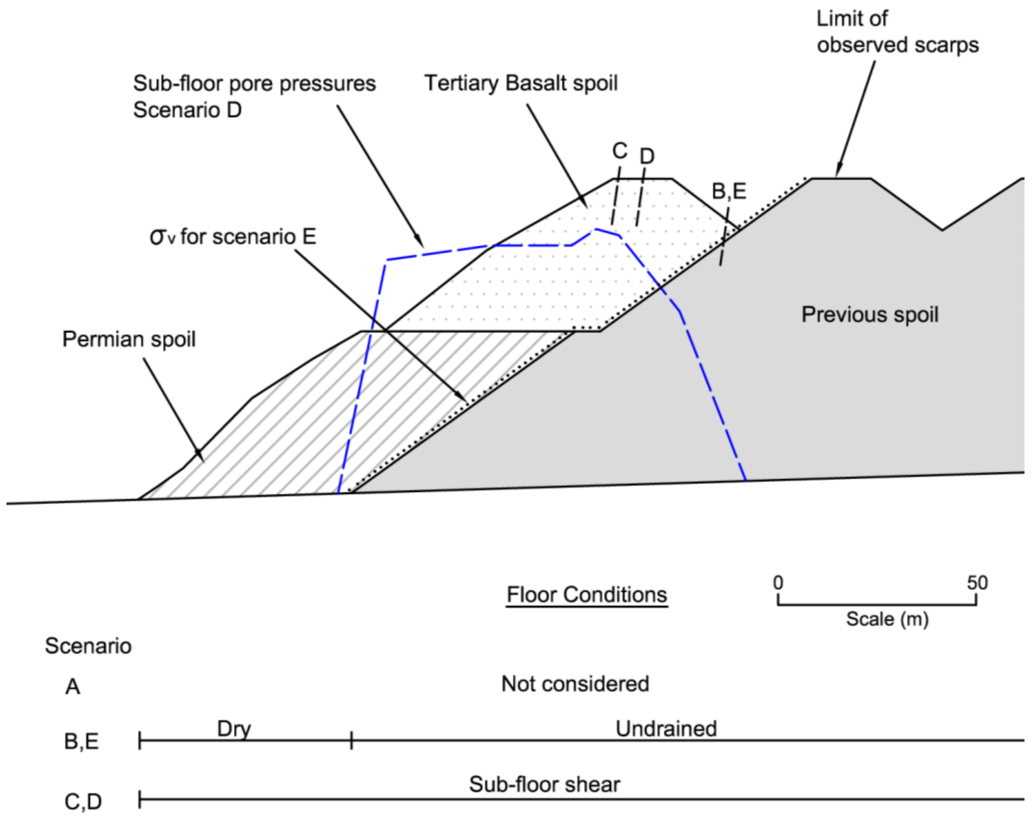

Figure 8 Case 4: failure scarp observations in accord with results of analyses from scenario B and E

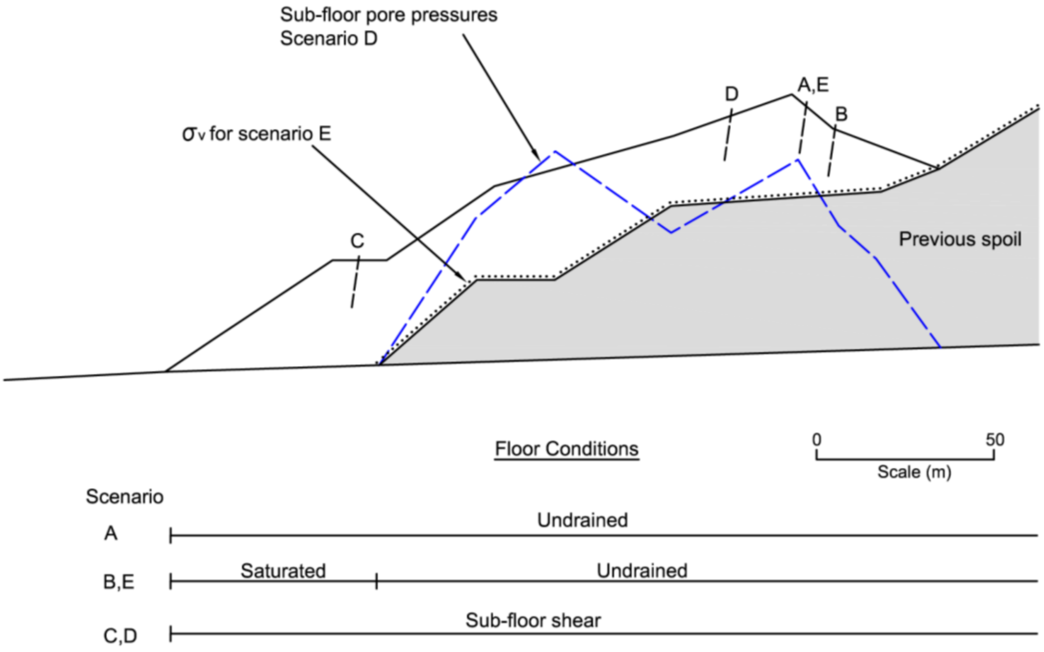

Figure 9 Case 5: failure scarp observations in accord with results of analyses from scenario A, B and E

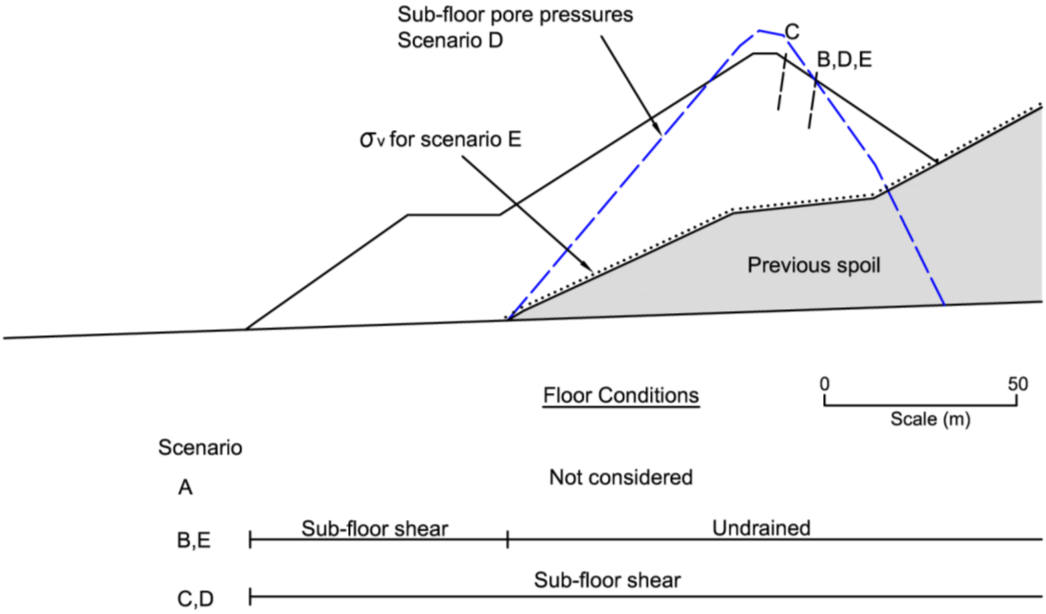

Figure 10 Case 6: failure scarp observations in accord with results of analyses from scenario B, D and E

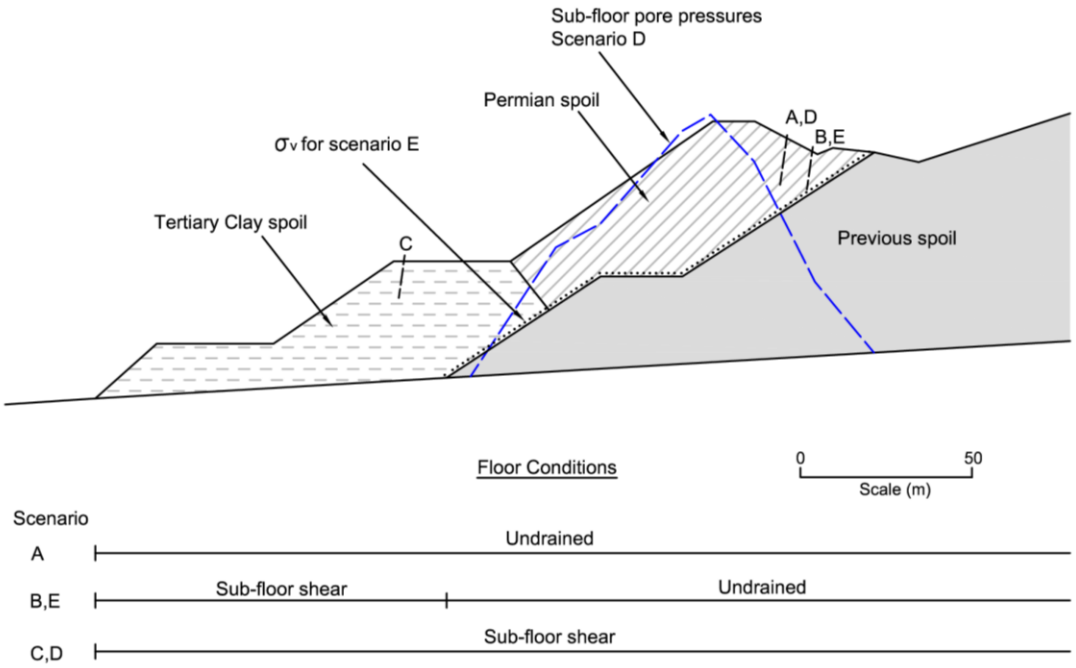

Figure 11 Case 7: failure scarp observations in accord with results of analyses from scenario B and E

Six of the cases are from one operation and limited Atterberg Limits testing of the Permian and Tertiary clays provided similar results and with a Plasticity Index of nominally 40. At the other operation, extensive Atterberg Limits testing of the Permian indicated a Plasticity Index in the range of 20 to 60. Figure 12 presents a selected portion of a graph presented within Lamb and Whitman, (1969) summarising the work of Osterman (1959). It is interesting to note that the relationship assigned to Marine clays (Osterman, 1959) provides an excellent fit to the range of back-analysed normalised undrained shear strength ratios from results of the Atterberg limits testing. A similar range in normalised undrained shear strength ratios was reported (Seedsman et al., 1988) from testing elsewhere in the Bowen Basin.

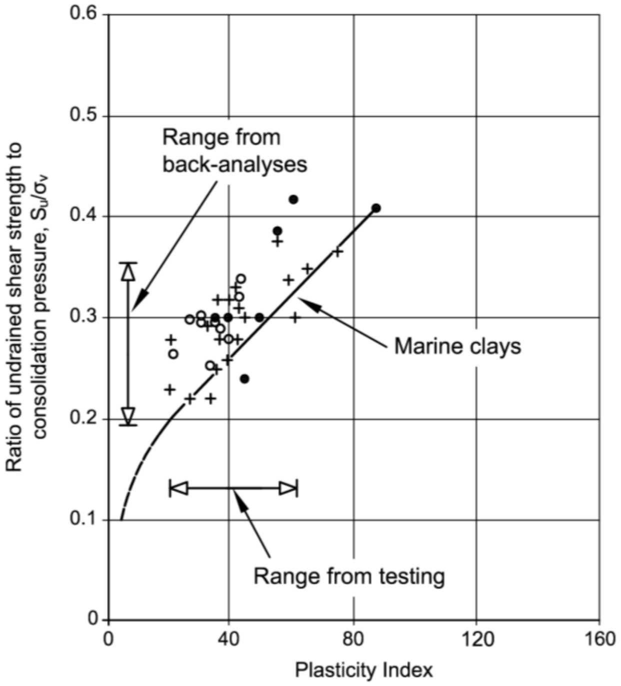

Figure 12 Normalised undrained shear strength ratios for Marine clays as presented by Lamb and Whitman, (1969), after Osterman, (1959)

6 Discussion of results

The author accepts that in practice it is possible to select various combinations (pairs) of cohesion and friction angle that satisfy a FS of near unity. However, not all pairs will provide a rear scarp location that is in keeping with the failure observation or have values that are considered credible for the local geotechnical conditions. As such, comparison of the critical failure path relative to the observed failure scarp was a key consideration. Where the indicated scarp of critical failure path was either well beyond or well inside the observed scarp, this is highlighted in Table 1. For all other back-analyses there was a reasonable match between the indicated scarp from back-analysis and the observed scarp.

For Case 3, the results of the back-analyses were also utilised to assess the stability of the initial dragline spoil prior to the truck dumping having taken place. For scenarios A, B, D and E the analyses indicated Factors of Safety (FS) of nominally of 1.14 and in accord with the observed performance of the spoil prior to the truck dumping taking place. However, for Scenario C a FS of 1.04 was indicated suggesting such a scenario was unlikely for Case 3.

For Scenario D, ignoring Case 1, reasonable strengths are indicated for Cases 3 and 4. However, for Cases 2, 5, 6 and 7 very low shear strengths are indicated. In view that such low shear strengths are not in keeping with the floor materials present at both operations, the author considers Scenario D is an unlikely explanation for the majority of cases.

For Scenario C extremely low shear strengths are indicated for all cases and with a friction angle of nominally 11°. Such sub-floor shear strengths have been reported as residual strengths in areas where there is known thrust faulting in the Rangal Coal Measures (Seedsman et al., 1995). The Cases reported herein are from areas of benign tectonics and as such the author considers such low sub-floor shear strengths are unlikely to be present. It is interesting to note that for Case 3, assuming a 'worse-case' scenario within the BMA Spoil Framework (main body comprising Category 1 with cohesion of 20 kPa and friction angle of 25° and the spoil base comprising Category 1 remoulded with zero cohesion and friction angle of 18°) analyses indicated a FS of 1.36 prior to the truck dumping and a FS of 1.32 post tuck dumping. The latter observations and results of Scenario C highlight that typical 'drained' back-analyses of most of the above cases would have been at odds with typical experience.

The author highlights that both scenarios C and D typically provided the poorest match between the critical scarp location and observations as well as commonly suggesting very low shear strengths out of character with the geotechnical setting. Moreover, such low shear strengths would suggest a greater extent of spoil instability at the operations than has been encountered.

Scenario A was not considered feasible for three cases. Where otherwise applicable, two ranges are evident. Firstly, where spoil had been placed over thick mud, an undrained strength of 32 kPa was assessed for one case. Secondly, where mud was probably thin and more widespread across the pit floor, results of the back-analyses indicated undrained strengths in the range of 90 to 116 kPa.

For Scenario B, there was an excellent match between the critical failure paths and the observed scarp locations for almost all the Cases. The back-analyses indicated undrained strengths in the range of 86 to 100 kPa.

For Scenario E, there was an excellent match between the critical failure paths and the observed scarp locations for almost all the Cases. The back-analyses indicated normalised undrained shear strength ratios in the range of 0.08 to 0.35 and typically between 0.18 and 0.22.

For most stability analysis software packages the author recognises that Scenario B would be easier to implement than Scenario E.

7 Conclusions

The author highlights that for Cases 3, 4, 5, and 6 prior to spoiling in the current strip the previous spoil had been inundated through pit flooding. For Case 7, flooding was known to have occurred for a limited portion of the pit and away from the area from which the cross-section has been presented. However, heavy rainfall during spoiling may have led to localised flooding. In view of the latter observation and the character of the materials present in all cases the author concludes the following aspects are required for undrained behaviour to be considered in spoil:

- Materials highly prone to slaking.
- Applicable to previous spoil that has undergone flooding and with undrained behaviour applicable to areas where additional spoil loading occurs in the current strip, Figure 2.

The author has found that in practice, the results of analyses are very sensitive to the extent of spoil that is assigned undrained behaviour and the strength parameters adopted. As such, the author recommends careful consideration of the extent of undrained behaviour and that a value towards the lower end of the range in the above undrained strengths is adopted.

Acknowledgement

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