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Rainfall Affected Stability Analysis of Maddingley Brown Coal Eastern Batter Using Plaxis 3D --Manuscript Draft--

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Rainfall Affected Stability Analysis of Maddingley Brown Coal Eastern Batter Using Plaxis 3D

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Abstract

Rainfall is a common factor that triggers instability of Victorian brown coal (VBC) open pits which facilitate some of the largest brown coal mining operations. There has been no relevant study on rainfall-induced slope instability of VBC open pits in literature. In this paper, three-dimensional (3D) two-phase (fluid-solid) coupled finite element method (FEM) was employed to investigate the stability of Maddingley Brown Coal (MBC) eastern batter under different rainfall conditions. It was found that the batter tends to lead a circular failure path during large rainfall. With the increase in either precipitation period or rainfall intensity, the deformation, excess pore pressure, active pressure increased, while the matric suction decreased. The hydrostatic force in the confined aquifer underlying the brown coal seam increased during rainfall, meanwhile the resisting force decreased. As a result, the shear strength decreased and thereby the stability of the batter decreased. The safety factor and the critical failure path of the eastern batter simulated in this study were consistent with previous study on the Northern batter. This study is a strong supplement to the literature on rainfall-induced instability of VBC batters. In the meantime, it is significant to provide reference to the application of sophisticated 3D numerical modelling for studying slope instability of brown coal and similar mineral deposits.

Keywords: *Stability, Brown Coal, Numerical simulation, Open-pit mining, Rainfall*

Introduction

Slope failure is a common and major geotechnical problem in an open pit mine (OPM). Froude and

Petley (2018) summarized 423 failure events occurred in mines or quarries. Slope failure is also called failure of batter in open pit coal mines. OPM has been the primary mining method to win coal in Australia. Nearly 80% of coal has been produced by OPM in Australia and 100% in Victorian brown coal (VBC) due to the shallow depth of the coal seam, compared with 40% in the world (Australia's Mineral Resource Assessment, 2013). VBC deposits are the largest of their type in the world, approximately 430 billion tonnes reserved (Department of Economic Development, Jobs, Transport and Resources 2016). Brown coal has been used as a cheap power resource for almost one hundred years in Victoria. Due to high productivity of OPM, numerous pit walls have been formed resulting from mining activities over the past century in the area. As reported by Langmore (2016), Loy Yang brown coal mine in Victoria has reached a depth of 200 meters. As a result, instability of open pits has become a major concerned geo-hazard in Victoria (Hutchings et al. 1977; Learmonth 1985; Hepburn 2014). Previous failures caused property damage and environmental destruction. As a complex mechanism driven geological disaster, the occurrence of slope failure is associated with many triggering factors, such as erosion, floods, earthquakes, precipitation, human activities (Kazmi et al. 2017), among which rainfall is regarded as a frequent one in many regions, particularly in tropical, sub-tropical areas (Elkamhawy et al. 2018), and mountainous regions (Lo et al. 2016; Lin and Cm 2018). It is noted that many cases of VBC batter instability occurred soon after heavy rainfall events (Mining Warden 2008; Neison 2014; Hepburn 2014). To make things worse, it is expected an increased number of heavy rainfalls would occur in the future, as a result of the global warming and climatic changes (Lacasse and Nadim 2009). Therefore, more attention need be paid to the rainfall induced slope failure in VBC mines.

As rainfall is a major and common factor causing slope failure all over the world, studies on their correlation has important implications in better understanding and predicting rainfall-induced failures (Chae et al. 2017). Nevertheless, there exists a great challenge as slope failure involves many factors, such as rainfall pattern, environmental conditions, internal and external structures of slope, soil softening, seepage, stress redistribution, and erosion (Zhou et al. 2009; Wu et al. 2015). Conventional empirical method or mathematical model is widely used, but is somewhat problematic in analysing complex geotechnical issues, such as rainfall related large-scale and deep-seated ground failures. Theoretical analysis is a common methodology to interpret a geological disaster, which is on the basis of the collected data from field investigation, monitoring, aerial photograph, statistical data, and geographical

information system (GIS) database (Jeon 2014; Zhi et al. 2016; Wu et al. 2017). But this method is hardly to provide a detailed clarification on the variation of a slope failure during a rainfall process, e.g. the variation in pore water pressure. A laboratory test is another popular way to analyse the mechanism of rainfall-induced slope instability by simulating an artificial rainfall process on a scaled-down physical model (Fazlina et al. 2018; Wu et al. 2018). This method can give a direct insight into the variation of failure with respect to rainfall infiltration process, pore water pressure and water content change, by using sensors buried in the physical model. Nevertheless, the simplified scaled-down physical model is difficult to simulate the complex geological configuration and structure. Furthermore, scale effect cannot be avoided for a large geological structure in experiments.

With the technical development in electronic computation, numerical simulation has become a popular and economic way to solve complex geo-engineering problem (Xu and Zhang 2010; Zhang et al. 2015; Li et al. 2017). This method has been well-known for its powerful data processing capacity and user-friendly interface. The methodology is able to analyse a slope failure under the conditions as close to reality as possible by employing full-scale modelling. More importantly, this method is continuously evolving with the computer technology, which is advantageous over conventional methods. So far, the limit equilibrium method (LEM) encoded in commercial programs has been the most popular numerical method due to its simplicity. However, LEM has disadvantages such as assumption-dependent when compared with FEM (Ozbay and Cabalar 2015). The advantages of FEM are summarized as follows: (1) the critical failure surface can be generated automatically by using the shear strength reduction method; (2) no assumption required for the inter-slice shear force distribution; (3) multiple failure surfaces are applicable; (4) structures (e.g., reinforcement, cable, beam) and interfaces can be included; (5) FEM is adaptable for cases under complex conditions and it can provide important analytical data such as stress, displacement and pore water pressure variation, which are impossible to achieve by LEM (Cala and Flisiak 2001; Cheng et al. 2007; Chen et al. 2014). Benefiting from the rapid development of the high-performance computer technology, the progress of numerical simulation for geo-problem is not only transferring applications from LEM to FEM, but also advancing from two-dimensional (2D) modelling to three-dimensional (3D). Land failure problems were analysed by 2D FEM and LEM numerical studies, respectively, and both methods were proved being effective to solve such a geotechnical problem (Maiorano et al 2014; Chen et al. 2014). Chandrasekaran et al. (2013) investigated a series of rainfall-

induced ground failures using 2D FEM, and found the failures were mainly attributed to increased ground water table caused by rainfall. The instability of slopes in Himalayan Terrance tends to occur in the wet season, this was concluded using Plaxis 2D from the study by Vishal et al. (2015). 3D numerical methodology is superior to 2D for applications of complex configuration of geological structures (Chang and Huang 2015; Jamsawang et al 2016; Usluogullari et al 2016). Despite the progresses, the configuration and internal structures of 3D models were overly simplified and difficult to represent the real conditions in most cases (Chang and Huang 2015; Jamsawang et al. 2016; Forcellini et al. 2018); and the 3D numerical simulation was to conduct static safety analysis.

In this paper, the stability of MBC eastern batter under rainfall conditions was investigated through hydro-mechanically coupled finite element analysis based on 3D numerical models. The 3D model was successfully developed and analysed using Plaxis 3D FEM program. The study investigated the changes of factor of safety, batter deformation, pore water pressure, suction of the batter under different rainfall conditions. This study would provide valuable practical implications on the management of slope instability in MBC and Victorian brown coal open pits. From this study, the full-scale three-dimensional numerical model was proved to be an effective and economic way to analyse the complex geo-engineering problem. The paper first introduced the literature and MBC mine site to address the research question, and then demonstrated the development of the 3D model and the results of numerical calculation. Finally, some conclusions were made from the study. The flow chart of research methodology is illustrated in Fig. 1.

Figure 1 Flow chart of research methodology

Site description

1. MBC

MBC is a typical VBC open pit, which is located 2 km south of Bacchus Marsh township and approximately 60 km to the northwest of Melbourne. The open pit mining commenced in 1940s in MBC and landfilling operation in mined pit started from 1970s (MBC 1994). The current mining activity is on the north batter and towards west, while the landfilling is in operation in the south part of the pit. The pit depth ranges between 20 m and 30 m at MBC, where slope instability is also a considerable geotechnical issue. The relative location of MBC in Victoria, Australia, is shown in Fig. 2.

Figure 2 Relative location of MBC open pit mine in Victoria, Australia (URC Australia 2013)

2. Geological and hydro-geological settings of MBC

Figure 3 Structural features of the region and isopachs of Maddingley coal seam (Holdgate et al. 2002)

The brown coal deposits in Parwan occur within the embayment of the Port Phillip Basin, which formed during the Tertiary period. This embayment is bounded to the west by the Rowsley Fault and to the south-east by the Mesozoic rocks of the Bellarine Peninsula. Outcrops of Palaeozoic sediments and granites mark the edge of the basin to the north and south respectively. The brown coal at Bacchus Marsh is

referred to as the Maddingley Coal Seam and is considered to be Early Miocene in age. The structural features of the region and isopachs of Maddingley coal seam is shown in Fig. 3.

The original geological units within the MBC mine site included Quaternary age sediments, Newer Volcanic basalt, Fyansford formation, Werribee formation, and Maddingley coal seam (Golder Assoc 2014a). With the large overburden removal activity in the mine site, the current geological units are mainly Fyansford formation, Maddingley brown coal seam, and Werribee formation. The Fyansford formation underlies undisturbed Quaternary aged sediments at the site and is reportedly exposed along the mine walls. Due to site mining operations, sediments of the Fyansford formation have been removed as overburden. The Fyansford formation was found to consists predominantly of marine silts, sands and clay with subordinate angular to sub-angular quartz gravel. The MBC coal seam surrounds the base and walls of the landfill. It is expected at the current coal extraction area and attains a thickness of up to approximately 60 m at mine site. The coal which makes up the MBC coal seam is predominantly a dark brown earthy variety of lignite, with areas of abundant plant remains and woody material. The seam is generally massive. In general, there is little impurity within the main seam, although towards the base of the seam, a small percentage of the matrix may be silty or sandy. The coal is rarely fractured. The occurrence of steeply dipping of joints is sometimes found within coal seam (URS 2014). These joints were thought to be related with the stress relief and lithification of brown coal. The opened joints are cracks which could significantly affect the pit stability. The Werribee formation underlain the coal seam consists predominantly of silty and clayey quartz sand and sandy gravel with minor sandy and silty clay (Golder Assoc 2011). The Werribee formation is extensive across the site and its base has not been intercepted, so the thickness of this formation is not known. The MBC schematic geological cross-section is shown in Fig. 4.

Regional groundwater flow is expected to be in a north to north easterly direction towards the Werribee and Lerderderg rivers. In MBC, the groundwater flow towards the pit bottom. The main hydrostratigraphic units are Fyansford formation, MBC coal seam, and Werribee formation in MBC. The Fyansford formation aquifer acts predominantly as an unconfined aquifer. The MBC coal seam acts as an aquitard and confining unit to Werribee formation due to its low hydraulic conductivity. The Werribee formation is seen as a confined aquifer (Golder Assoc 2011).

Figure 4 MBC schematic geological cross-section (URS 2014)

3. *MBC northern coal batter*

The MBC northern batter is the current brown coal extraction area, with a slope angle of between 70 and 80 degrees. The mining operation might result in a medium to high geotechnical risk condition due to the expected depth of coal extraction and potential to extract coal near the Parwan Creek (Golder Assoc 2011). This batter had remained in place for five decades by 2013. Mining activity commenced on the northern batter in early 2013 and major cracks were observed about 20 m away from the batter crest in late 2013. These cracks were caused from the stress relief due to overburden removal and coupled with the effect of groundwater flow in the unconfined aquifer. The instability of batter had been controlled benefiting from an emergency buttress immediately constructed. However, large movements after a strong rainfall were monitored in early 2014 (Golder Assoc 2014b). A numerical study on this rainfall-induced movements was conducted (Zhao and You 2020). The simulated deformations of the batter were well agreed with the field monitored data (Table 1). The deformations were mainly induced by the combined effects of surface run-off and suddenly increased groundwater level. Some rebound of the deformations was observed, which is attributed to the recession of hydrostatic pressure in the cracks. In conclusion, the 3D numerical study on the northern batter by Zhao and You (2020) validated the reliability of the 3D numerical model developed.

Table 1 Observed and simulated movements along the crack on the northern batter

Field survey markers	M1	M2	M3	M4	M5	M7	M8
Monitored deformations (mm)	56	65	55	15	7	61	18
Simulated deformation (mm)	48	52	48	32	4	28	20

4. MBC eastern batter

The MBC eastern batter is near the east boundary of mine site (Parwan Creek) (Fig. 5) and has been exposed for over ten years. A major slope failure (300 m across, 100 m long and 50 m high) was observed in October 1994 and was believed to be resulted from ingress of water from Parwan Creek into the tension cracks in the south corner slopes (Golder Assoc 2011). The batter currently acts as an access road and a flood levee of the pit. As a result, the stability of this batter is significant to the mine.

Figure 5 MBC Eastern batter (aerial view)

Three-Dimensional Model Development

Baes on the aerial map and hydrogeological surveying report of MBC, a 3D geological and hydrogeological model was extracted and modified for the eastern batter. Different precipitation scenarios were designed and modelled to find out the effects of rainfall on the stability of the eastern batter.

1. Theoretical model

In 1923, the effective stress for saturated soil was proposed by Terzaghi (Eq. 8.1).

$$\sigma = \sigma' + p_w \quad (\text{Plaxis 3D 2018}) \quad (\text{Eq. 8.1})$$

Where σ is total stress; σ' is effective stress; p_w is pore water pressure.

Considering most soils are unsaturated in practical engineering projects, a modified equation was proposed by Bishop (Eq. 8.2),

$$\sigma' = \sigma - u_a + \chi(u_a - p_w) \quad (\text{Plaxis 3D 2018}) \quad (\text{Eq. 8.2})$$

Where u_a is atmospheric pressure; χ is the matric suction coefficient; $u_a - p_w$ is matric suction.

In Plaxis, total stress is divided into effective stress, σ' , and active pore pressure, p_{active} .

$$\sigma = \sigma' + p_{active} \quad (\text{Plaxis 3D 2018}) \quad (\text{Eq. 8.3})$$

$$p_{active} = S_{eff} \cdot p_w \quad (\text{Plaxis 3D 2018}) \quad (\text{Eq. 8.4})$$

Where S_{eff} is the effective degree of saturation (when soil is full saturation, S_{eff} is 1).

$$S_{eff} = (S - S_{res}) / (S_{sat} - S_{res}) \quad (\text{Plaxis 3D 2018}) \quad (\text{Eq. 8.5})$$

Where S represents degree of saturation; S_{res} is defined as residual degree of saturation; S_{sat} is saturated degree of saturation, usually is 1.0 in Plaxis.

In Plaxis, the parameter χ from Eq. 8.2 is supposed to be equal to S_{eff} . Thus, Bishop's effective stress

Eq. 8.2 can be expressed as Eq. 8.6 in Plaxis.

$$\sigma' = (\sigma - u_a) + S_{eff} \cdot (u_a - p_w) \quad (\text{Plaxis 3D 2018}) \quad (\text{Eq. 8.6})$$

When put the Eq. 8.6 into the Mohr-Coulomb criteria Eq. 8.7 Eq. 8.8 is obtained, which is the expression of Bishop's effective stress equation in Plaxis

$$\tau = c + \sigma' \tan \varphi \quad (\text{Plaxis 3D 2018}) \quad (\text{Eq. 8.7})$$

Where τ is shear strength; σ is effective stress; c is the cohesion; φ is friction angle.

$$\tau = c + (\sigma - u_a) \tan \varphi + S_{eff}(u_a - p_w) \tan \varphi \quad (\text{Plaxis 3D 2018}) \quad (\text{Eq. 8.8})$$

When soil is unsaturated, $suction = u_a - p_w$, and the value is positive; when soil is saturated, $u_a = p_w$.

2. Safety analysis

Safety analysis in Plaxis is governed by strength reduction (phi/c reduction) method which is described in Eq. 8.10 (Plaxis 3D 2018). Shear strength parameters, friction angle φ , cohesion c , and tensile strength are successively reduced till failure occurs. $\sum Msf$ is the value of the soil strength parameters at a given stage in the safety analysis, described in Eq. 8.11 (Plaxis 3D 2018).

$$F.S. = \frac{\text{available strength}}{\text{strength at failure}} = \text{value of } \sum Msf \text{ at failure} \quad (\text{Eq. 8.10})$$

$$\sum Msf = \frac{\tan \varphi_{input}}{\tan \varphi_{reduced}} = \frac{c_{input}}{c_{reduced}} = \frac{S_{u,input}}{S_{u,reduced}} = \frac{\text{Tensile strength}_{input}}{\text{Tensile strength}_{reduced}} \quad (\text{Eq. 8.11})$$

3. Model design and development

97-98 mm/d was the largest rainfall recorded in the town of Bacchus Marsh during the past 100 years. Accordingly, different precipitation scenarios were designed for this study, which are 50 mm/d, 75 mm/d, 100 mm/d, and 125 mm/d lasting for 1 h, 5 h, and 1 d, respectively. The simulation of precipitation was achieved by employing the fully coupled flow-deformation calculation function encoded in Plaxis 3D. This function is able to analyse the simultaneous development of deformations and total pore water

pressures (the sum of steady-state and excess pore pressures) in saturated or partially saturated soils in accordance with time-dependent hydraulic boundary conditions (Plaxis 3D 2018). For partially saturated soils, the suction and unsaturated soil behaviour above the phreatic level can be well interpreted through the fully coupled flow-deformation calculation (Plaxis 3D 2018). In this research, the initial state of the modelling was defined as gravity loading calculation. The initial stage and each rainfall calculation stage was followed by a safety analysis stage. In summary, total 26 calculation stages were included in this modelling design, e.g. an initial stage, 12 fully coupled flow-deformation calculation stages (rainfall simulation stages), and 13 safety analysis stages.

The developed model is shown in Fig. 6, which was 300 m in length, 300 m in width and 103m in height. The 3D model consisted of five layers which are from top to bottom overburden (RL 73-103 m), brown coal seam (RL 50-73 m), engineering fill (RL 55-60 m), broken brown coal (RL 50-55 m), Werribee formation (RL 0-50 m), respectively. The groundwater table was set from RL 91 m in the overburden to almost RL 60 m near the surface of the pit bottom (layer of engineer fill) from the monitored data of the field borehole. Groundwater flow towards the pit bottom.

Figure 6 Meshed 3D numerical model of the eastern batter

VBC is featured as highly deformable, low-density, high organic content and low permeability (10^{-8} m/s) (Xue and Tolooiyan 2012; Liu et al. 2014). The strength of this material is between normal engineering

soil and rock; its stiffness is similar to very stiff clay. The unit weight of dry MBC brown coal is about 5 kN/m³ while the saturated unit weight is about 11.5 kN/m³, which is slightly heavier than water. The average tensile strength of VBC is 101.4 kPa and 112 kPa from direct tensile tests and Brazilian tests, respectively (Tolooiyan et al. 2014). The low density of the brown coal tends to be very susceptible to the water pressure from groundwater or rainfall runoff, and the deformable character tends to cause the formation of cracks and open of existing joints in Victorian brown coal. The overburden mainly consists of silts, sands and clay and the Werribee formation underlain the coal seam mainly consists of silty soils and sands. Geotechnical parameters were adopted from direct shear tests, triaxial tests, permeability tests, back analysis, and technical reports provided by MBC, and are listed in Table 2.

Table 2 Soil properties employed in the 3D numerical modelling

Parameters	Unit	Fyansford Formation	Brown Coal	Buttress and Fill	Broken Brown Coal	Werribee Formation
Drainage Type	-	Drained	Undrained A	Drained	Drained	Drained
Saturated unit weight	kN/m ³	19	11.5	18	11.5	20
Unsaturated unit weight	kN/m ³	16	5	15	5	17
Young's modulus	MPa	130	37	15	37	95
Poisson's ratio	-	0.3	0.27	0.3	0.27	0.3
cohesion	kPa	9	174	5	20	5
Friction angle	degree	27	33	30	33	30
Horizontal permeability k _x	m/day	0.0086	0.0086	0.1	0.1	0.00086
Horizontal permeability k _y	m/day	0.0086	0.0086	0.1	0.1	0.00086
Vertical permeability k _z	m/day	0.00086	0.00086	0.1	0.1	0.00086

Results and Discussion

From the safety analyses, all obtained safety factors (S.F.) are listed in Table 3. It can be seen that the safety factor of initial state was 1.333, which illustrated the model was in a stable state. This exemplifies the reality that the eastern pit wall has been exposed for over ten years and is stable. In contrast, a S.F.

of 1.29 was obtained from a two-dimensional cross-section simulation (Golder Assoc 2011) using LEM by SLOPE/W. The S.F., 1.29, was slightly smaller than 1.333, which was a reasonable agreement on the basis of the fact that S.F. of a two-dimensional model is generally smaller than that of a corresponding three-dimensional model. The S.F. decreased to some extent under designed rainfall conditions. With the increase in rainfall intensity and lasting time, the S.F. tended to decrease. The obtained safety factors showed that the model was stable in most rainfall situations, except for the 24-h 100 mm/d and 125 mm/d rainfall. The S.F. dropped a lot after the 24-h 100 mm/d rainfall and eventually the model failed under the condition of the 24-h 125 mm/d rainfall.

Table 3 Safety factors obtained from numerical simulations

Rainfall conditions	0 mm/d (initial state)	50mm/d	75mm/d	100mm/d	125mm/d
S.F. at 1h	1.333	1.321	1.297	1.266	1.244
S.F. at 5h	1.333	1.318	1.290	1.252	1.235
S.F. at 1d	1.333	1.284	1.251	1.100	0.8360

Table 4 shows the maximum phase deformations along y-axis of the model (towards pit bottom) under each rainfall condition. The reference model for measuring the deformations is the initial phase of the model (0 deformation). It is clearly shown that the batter had a significant movement towards pit bottom after the 24-h 125 mm/d rainfall when the batter failed. With the increase in rainfall intensity and lasting time, the batter deformation tended to increase. Fig. 7 demonstrates the increased deformations of the eastern batter after the precipitation of 100-mm rainfall, from which the largest deformation generated in the south part of the batter and the whole batter had a circular failure path. Furthermore, the critical failure path became more recognizable and the deformation along the critical failure path became larger with the increased precipitation period under the 100 mm/d intensity (Fig. 7). The simulated critical failure mode agrees with the studies and experiences related to the VBC open pits where the sandwiched brown coal batter with overburden tends to take a circular failure mode while the failure mode of brown coal batter after overburden removal is attributed to block failure (Washusen and Fraser 1982; Learmonth 1985; Zhao and You 2018).

Table 4 Simulated maximum phase deformation towards pit bottom (y axis-negative)

Rainfall conditions	50mm/d	75mm/d	100mm/d	125mm/d
Maximum deformation at 1h (mm)	2.70	5.04	8.18	12.48
Maximum deformation at 5h (mm)	6.00	10.07	13.97	16.28
Maximum deformation at 1d (mm)	19.67	29.14	33.90	62.83

Figure 7 Phase displacement along y-axis: a. 100 mm/d rainfall lasting 1 h; b. 100 mm/d rainfall lasting 5 h; c. 100 mm/d rainfall lasting 1 d

Fig. 8 illustrates the variation in the excess pore pressure with the extension of the period under the 100 mm/d rainfall, from which the magnitude of excess pore pressure was increasing with the rise of the precipitation. From other simulation results, the magnitude of excess pore pressure also increased with the rise of rainfall intensity during the same precipitation period. The rise of the excess pore pressure increased the pore water pressure and resulted in effective stress decreased (see Eq. 8.7) and thereby the stability of batter decreased. The simulated results shows that both pore water pressure and active water pressure increase with the increase in the period and the intensity of rainfall.

Figure 8 Excess pore water pressure: a. initial stage; b. 100 mm/d rainfall lasting 1 h; c. 100 mm/d rainfall lasting 5 h; d. 100 mm/d rainfall lasting 1 d

Fig. 9 shows the variation in matric suction distribution in the batter with the increased rainfall period. The overall suction decreased with the accumulation of precipitation. From Eqs. 8&9, the loss of the matric suction decreased the shear strength of the soil. In short, all the variations discussed above caused the decrease of shear strength and effective stress of the brown coal batter and thereby the stability dropped.

Figure 9 Suction distribution: a. initial stage; b. 100 mm/d rainfall lasting 1 h; c. 100 mm/d rainfall lasting 5 h; d. 100 mm/d rainfall lasting 1 d

The hydrostatic force in the confined aquifer underlying the brown coal seam will increase during rainfall, meanwhile the resisting force will decrease. As a result, the shear strength decreased and thereby the stability of the batter decreased, and circular failure is triggered under rainfall (Fig.10). The circular failure is the most substantial failure mode in brown coal batters when the overburden is not stripped. VBC is a low unit weight and highly deformable material, after losing the confining force from the overburden, block failure tends to occur in the coal batter during coal extraction.

Figure 10 Circular slide of MBC batter under rainfall conditions

There are some limitations in this study, for example, the brown coal and other materials were assumed as homogenous and isotropic. In practice, there would be existence of joints and clay seam in the brown coal seam that were not reflected in the 3D numerical models. These weak structures could affect slope stability and decrease the safety factor of the Eastern batter. For the rainfall simulation, the precipitation was assumed to be evenly distributed during the rainfall duration. This may be different from the reality. And the groundwater flow conditions were far more complicated in practice than the defined groundwater flow conditions in the numerical study. The differences would affect the accuracy of results and findings. In essence, further field investigation, monitoring, and analysis would be required to fulfil the gaps in knowledge.

Conclusion

In this study, a complex 3D model was developed to study the stability of the MBC eastern batter under different rainfall conditions using the FEM program encoded in Plaxis 3D. The following conclusions have been summated.

1. The eastern batter of MBC is in a stable state (S.F. 1.333) without any rainfall condition. It is in line with the S.F. 1.29 from 2D modelling. From the study, the eastern batter might have a circular failure path when the precipitation reached a critical threshold, and this failure path was consistent with the

overburden failure mode of the Northern batter (Zhao and You 2018). The model was marginally stable after a 24-hour 100 mm/d rainfall (100-year peak rainfall intensity) and the model would fail under the condition of a 24-hour 125 mm/d rainfall.

2. The results of numerical simulation have revealed variations of stability of the eastern batter during and after rainfall. With the increase in either rainfall period or intensity, deformation, excess pore pressure, pore pressure, and active pressure increase, while the matric suction decreases. The hydrostatic force in the confined aquifer underlying the brown coal seam increases during rainfall, meanwhile the resisting force decreased. As a result, the shear strength decreases and thereby the stability of the batter decreases.

3. Considering current very limited studies of 3D numerical simulation of slope stability, this research can provide significant reference to the application of sophisticated three-dimensional numerical modelling of coal (and similar deposits) batter instability. It also provides valuable practical implications on the management of slope instability in MBC and Victorian brown coal open pits.

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List of Notation

σ total stress

σ' effective stress

p_w pore water pressure

u_a atmospheric pressure

χ matric suction coefficient

p_{active} active pore pressure

S degree of saturation

S_{eff} effective degree of saturation, when soil is full saturation, S_{eff} is 1

S_{res} residual degree of saturation

S_{sat} saturated degree of saturation, usually is 1.0 in Plaxis

τ shear strength

c cohesion

φ friction angle

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Response by Authors to Reviewer #1's Comments

Rainfall Affected Stability Analysis of Maddingley Brown Coal Eastern Batter Using Three-Dimensional FEM

Lei Zhao, Greg You

The authors would like to appreciate reviewers' comments to the manuscript AJGS-D-19-02428R1. A revised manuscript is submitted addressing all the comments to the Journal of *Arabian Journal of Geosciences* for possible publication.

	<i>Reviewers' Comments</i>	<i>Authors Response</i>
1	Reviewer #2: The authors addressed concerns raised in the original review. The paper would have to go through Professional English Editing Process.	The reviewer's support and contribution to the manuscript is highly appreciated. The entire manuscript has been language-edited by a native language speaker.
2	Reviewer #4: All comments have been addressed properly, so the article suggested to publish with its present form.	The reviewer's support and contribution to the manuscript is highly appreciated.