Study on the stability of brown coal batter with opened cracks on Maddingley brown coal mine

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Abstract

After a 26-mm precipitation in February 2014, noticeable ground movements were recorded on the north batter of Maddingley brown coal open pit, Victoria. To investigate the rainfall effect on the stability of the brown coal batter with opened cracks, a three-dimensional geologic model was developed, and the finite element program encoded in Plaxis 3D was employed to conduct a complex two-phase (fluid–solid) coupled numerical simulation. It was found that the simulated deformations were well agreed with the field survey data. There were ground movements along the length of cracks on both sides of the crack with larger movement towards the pit bottom. The coupled effect of hydrostatic forces from the crack in the rear of the batter and from the clay layer underlain the batter caused the block to slide, or batter failure. From the results, it revealed that both short-term high rainfall intensity precipitation and long enduring low rainfall intensity precipitation could cause the brown coal batter with opened cracks instable.

Keywords Crack · Rainfall · Deformation · Brown coal · Open-pit mining · Batter stability

1 Introduction

Victoria, Australia, is known as its huge brown coal reserves in the world. Brown coal has been mined by open cut mining method in Victoria, Australia, almost over a century. Due to the long-term mining activity, coal batter instability has become one of the major geo-hazards in Victoria, and batter failures have not been rare in this area. Both geological structures and hydrogeology affect the pit stability in Victorian brown coal mines. The strength of weak seams beneath coal, the orientation of joints and bedding planes, high-level underground water and water pressure in joints were believed as the main reasons to cause slope failure in Victorian brown coal open pits [1]. Brown coal batter with overburden tends to lead a circular sliding while the coal batter after overburden removal has a blocking slide trend at Maddingley brown coal mine, Victoria [2]. High tensile strain behind the batter and high

shear strain underneath the coal seam could be developed after the overburden is stripped in the brown coal batter, and cracking propagation is a result of stress relief due to the overburden removal [2]. The unique batter failure type, block failure, often occurred not long after cracks (opened joints) emerging on coal batter surface and heavy rainfall event in Victorian brown coal open pits, as reported in Yallourn mine in 1950 [1] and 2007 [3]. It is noted that batter failures are prone to occur in summer or close to summertime in Victoria. There is a significant amount of rainfall throughout the year in Victoria; an average annual rainfall amount is between 1800 and 2500 mm, with heavy downpours in summer months. The recorded highest rainfall in a single day was 375 mm in the Otway Ranges in 1983 (rainfall by region: Victoria, n.d.). Water plays a critical role in the initiation of brown coal batter instability due to the relatively low unit weight of Victorian brown coal.

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Rainfall can accelerate the cracking propagation process in the brown coal batter [4].

Rainfall is a major and frequent factor causing landslides all over the world, as well as in Victorian brown coal open pits. Rainfall is the leading trigger factor of landslides, and 79% non-earthquake fatal landslides were caused by rainfall [5]. The rainfall-induced landslides often cause serious catastrophe disaster, e.g. 15,000 people, representing approximately 5% of local population, were killed by large landslides triggered by a storm in northern Venezuela in 1999 [6]. Making clear its occurring mechanism is crucial in the risk prevention and control. Although many individuals and organizations have been involved in the relevant study, most of the study is based on the conventional empirical method or simple mathematical model that are somewhat incompetent in analysing complex geotechnical issues, especially for the analysis of the large-scale and deep-seated landslide with the effects of rainfall. An adequate and integral study of slope instability issue requires comprehensively considering the complex interaction of all affecting factors. Numerical simulation method is an economic and promising way to solve such a kind of complex geo-engineering problem [7, 8]. Particularly, different from other traditional methods numerical simulation has become more and more capable of calculating complicate geo-engineering problem with the evolution of computer technology.

Numerical software based on limit equilibrium (LEM) and finite element method is popular to analyse the stability of soil slope. LEM software has been widely used due to its simplicity, such as SAS-MCT [9] and SlopeW [10]. However, the advanced FEM has considerable advantages over LEM, like no assumption required for the inter-slice shear force distribution, automatically generated critical failure surface, inside structures and interfaces which can be included, multiple failure surfaces being applicable, complex conditions and more output options being applicable [11–14]. Two-dimensional (2D) computer programs are most preferred to conduct numerical simulation due to its simplicity and less time consumption, but it is difficult to process complex geological and hydrogeological conditions of slopes in many cases. And 2D models are conservative [15]. A more sophisticated numerical simulation program is required to solve the complex geotechnical problem with multi-influencing factors. Benefiting from the rapid development of computer techniques, numerical software with function of three-dimensional (3D) model has become a more powerful tool to investigate slope instability problems. Compared to the 2D model that can only demonstrate horizontal or vertical sections, 3D numerical modelling is able to give more realistic results and conduct more comprehensive analysis of sliding mechanism, especially in such a case with

non-uniform resistance distribution [16, 17]. In addition, 3D model simulation enables better 3D visualization and details such as estimated sliding volume. From [16], their 3D analyses revealed the features that cannot be obtained in 2D analyses; for example, the sliding surface was not symmetric with the steeper portion on the east side, and the displacements around the boundary fractures were somewhat smaller than those in the middle portion. 3D model is more capable of presenting the full geometry and structures inside and outside of a slope, so it can better interpret the correlation between slope stability and its surroundings. FLAC 3D is likely the most popular software being used in mining engineering, but for the numerical simulation of soil material considering water flow Plaxis3D is more suitable. Plaxis 3D is a finite element package that has been developed specifically for the analysis of deformation and stability of soil material coupled with the influence of water flow in geotechnical engineering projects. It is based on strength reduction method (ϕ - c reduction) to calculate safety factor. In this approach, the shear strength parameters $\tan \phi$ and c of the soil as well as the tensile strength are successively reduced till failure of the structure occurs.

The application of numerical simulation in studying slope stability issues had been reporting by scholars over past years [18–21], and the results were positive and promising. However, the numerical study with complex three-dimensional models is still limited. On the other hand, there are no studies on the slope stability study of Victorian brown coal open pits with the effects of cracks and rainfall. With the literature gaps, this paper was to investigate how rainfall affects the stability of the buttress supported cracked brown coal batter on MBC by analysing a three-dimensional geologic model accompanied by field monitored data. The modelled batter is sandwiched by confining beds, with opened joints in the coal seam. The powerful finite element program encoded in Plaxis 3D was employed to conduct the complex two-phase (fluid–solid) coupled numerical simulation.

2 MBC description

MBC is a typical Victorian brown coal open pit, located on the southern outskirts of the township of Bacchus Marsh and 60 km northwest of Melbourne, Australia.

2.1 Geologic and hydrogeologic settings

The Maddingley coal seam at Bacchus Marsh is a stratum of the Werribee formation and is generally underlain by the gravel layer of Lerderberg formation or undifferentiated sediments of the Lower Werribee formation (LWF).

The coal may be conformably overlain by fluvial clays, sands and minor gravels of the Werribee formation, marine silts, sands and clay of the Fyansford formation and by Quaternary basalts to the south and south-west. The Fyansford formation is generally overlain by Quaternary Newer Volcanics and/or Quaternary-aged sediments which were deposited as river terrace or alluvial river deposits. Quaternary basalt in the area belongs to the Newer Volcanic Group and was deposited across much of the Werribee Plains area as a sheet like lava flow. Sandy, silty and clayey gravels (predominantly sub-rounded quartz and

quartzite gravel) of the Bullengarook gravels may also be found in the region overlying the Fyansford formation and were deposited contemporaneously with the Newer Volcanic Group and can be found to interfinger with these basalt flows. Basement rocks in the region are considered to be Ordovician sediments and Devonian granodiorite rock [22]. The geological sequence related to the site is shown in Fig. 1.

There are three main hydrostratigraphic units (Table 1) underlying the mine site. The uppermost aquifer, Fyansford formation, consists mainly of clay, silty clay with infrequent

Fig. 1 Geological sequence of MBC mine site: **a** Geological sequence **b** Geological legend

GEOLOGICAL LEDEND

Qrt	LOW LEVEL RIVER TERRACES, 2 TO 8m ABOVE Qra. CLAY, SILT, SAND, GRAVEL (CLASTS 0 BASALT, QUARTZ, SANDSTONE, QUARTZITE, SLATE & IRONSTONE)
Qra	STREAM ALLUVIUM AND VERY LOW LEVEL TERRACES. CLAY, SILT, SAND, GRAVEL (CLASTS 0 BASALT, QUARTZ, SANDSTONE, QUARTZITE, SLATE & IRONSTONE)
Qrm	SWAMP DEPOSITS, IN SLIGHT DEPRESSIONS. DARK GREY TO DARK BROWN CLAY & SILTY CLAY OFTEN WITH PLANT REMAINS
Qrc	COLLUVIUM, ALLUVIAL FANS & GULLY ALLUVIUM. POORLY SORTED GRAVEL, SAND, SILT, CLAY
Qd	DOLOMITE, SILICEOUS, OF LACUSTRINE ORIGIN. WHITE TO BUFF FINE GRAINED, SOFT AND HARD BANDS, UP TO 2m THICK. OVERLIES NEWER VOLCANICS
Qpt	HIGH LEVEL RIVER TERRACES, GENERALLY 10 - 40m ABOVE Cra GRAVEL, CLAYEY GRAVEL SAND: USUALLY RED IN COLOUR
Qps	ALLUVIUM, CLAY, SANDY CLAY, SAND & GRAVEL: GREY TO RED UP TO 3m THICK
Qpg	ANGULAR & ROUNDED QUARTZ GRAVEL, SAND & CLAY. OVERLIES BULLENGAROOK FLOW. NORTH OF MT. BULLENGAROOK
Qvn	OLIVINE BASALT, COMMONLY VESICULAR, WITH MINOR SCORIE. TUFF AND AGGLOMERATE, COLUMNAR JOINTING COMMON
Qvs	SCORIA, TUFF, AGGLOMERATE (BLOCKS OF SANDSTONE, QUARTZ CLAYSTONE), WITH LESSER BASALT. FORMS SCORIA CONES AT MT. BULLENGAROOK, MT. DARRILL & THE BUFF
Tpg	GRAVEL, SANDY, SILTY & CLAYER GRAVEL (CLASTS PRECOMINANTLY QUARTZ, ALSO SANDSTONE, BASALT), WITH LESSER SAND & CLAY. LOCAL FERRUGINISATION & SILICIFICATION. UNDERLIES, OVERLIES OR INTERLINGS WITH NEWER VOLCANICS
Tmv	OLIVINE BASALT, DENSE DARK GREY, UP TO 24m THICK. INTERBEADED IN THE UPPER PART OF THE WERRIBEE FORMATION, OUTCROPS IN PARWAN CREEK. INTERSECTED IN BORES 6.4 & 6.5 PARISH OF PARWAN
Tew	CLAY. IGNEOUS CLAY, SANDY & SILTY CLAY, WHITE TO GREY WITH SAND AND QUARTZ GRAVEL. MINOR TUFF, BROWN COAL, DOLOMITE, PYRITIC & SILICA SAND. COMMONLY WITH IRONSTONE BANDS & FOSSIL PLANTS OF THE CINNAMONUOS FLORA. LOCAL SILICIFICATION. SHOWS REGIONAL TREND, MORE SANDY BEDS IN THE WEST, LESS SANDY IN THE EAST
Tmd	DOLOMITE OF LACUSTRINE ORIGIN. YELLOW TO WHITE, WITH HARD & SOFT BANDS. MINOR DARK GREY BANDED CLAY, DOLOMITIC SAND & GRAVEL, TUFF. MAXIMUM THICKNESS OF OVER 20m
Tmg	GRAVEL (CLASTS PREDOMINANTLY QUARTZ, ALSO SANDSTONE, QUARTZITE). MEDIUM TO COURSE SAND, MINOR WHITE TO GREY CLAY. CROSS-TEDDING COMMON, LOCAL FERRUGINISATION
Tmy	BROWN COAL SEAM, EXPOSED IN MADDINGLEY No2 OPEN CUT THINS & SPLITS TO THE NORTH & WEST OF THE OPEN CUT. MAXIMUM THICKNESS OF OVER 43m. COAL LOCALLY PYRITIC. PLANT REMAINS COMMON, MINOR CLAY
Tml	GRAVEL & SAND, MINOR GREY CLAY. UNDERLIES MADDINGLEY COAL SEAM EAST OF BACCHUS MARSH. SUBSURFACE ONLY
Tmf	SHALLOW MARINE. BLUE & YELLOW CLAY, SANDY CLAY & LIMESTONE, FOSSILIFEROUS. INTERFINGERS WITH MADDINGLEY COAL SEAM, INTERSECTED IN BORES 4 & 7 PARISH OF PARWAN, IMMEDIATELY SOUTH OF MAPSHEET AREA
Tvo	ALKALI OLIVINE BASALT TO NEPHELINE, GENERALLY DENSE, DARK GREY, RARELY VESICULAR, MINOR TUFF. SECONDARY CALCITE & MAGNESITE IN VESICLES & JOINTS. ASSOCIATED BASIC DYKES. INCLUDES VOLCANICS IN THE PENTLAND HILLS - GREENDALE AREA & SMALL OUTCROPS AT COIMADAI AND IN PARWAN VALLEY
R	FELDSPATHIC SANDSTONE, MEDIUM TO FINE GRAINED, CREAM TO BROWN, FRAGMENTARY FOSSIL PLANTS: INTERBEDDED LENSES OF QUARTZ CONGLOMERATE. DISCONFORMABLY OVERLIES BACCHUS MARSH FOUNDATION
P	TILLITE, SANDSTONE, PEBBLY SANDSTONE, MUDSTONE, PEBBLY MUDSTONE, CONGLOMERATE. SHOWS SYNDEPOSITIONAL FAULTING, SOFT SEDIMENT FOLDING & SEDIMENT DYKES. ERRATICS OF GRANITE, QUARTZ, HORNFELS, SANDSTONE, PORPHYRY, CHERT, SLATE, UP TO 7m DIAMETER, COMMONLY STRIATED. PLANT FOSSILS OF THE GLOSSOPLERIS FLORA (BALD HILL) & MARINE BRACHIOPODS
Pc	MARINE CONGLOMERATE (CLAST OF QUARTZ, HORNFELS, SLATE, SANDSTONE, GRANITE UP TO 20cm DIAMETER), MINOR MUDSTONE & SANDSTONE. LENICULAR, UP TO 5m THICK, OUTCROPS AT BALD HILL, MYERS CLIFF & KORKUPERRIMUL CREEK
Dgr	GRANITE, MEDIUM TO COURSE GRAINED. INCLUDES A SMALL INCRUSION 2.5 km NORTH OF COIMADAI ASSOCIATED ACID DYKES
O	SLATE, SHALE, SILTSTONE, INTERBEDDED SEQUENCE OF TURBIDITIC CHARACTER. TIGHTLY FOLDED. CONTAINS GRAPTOLITE ASSEMBLAGES OF LANCEFIELDIAN TO DARRIWILLIAN AGE. SPOTTED SLATE, HORNFELS IN METAMORPHIC AUREOLES OF GRANITIC INTRUSIONS

Fig. 1 (continued)

Table 1 Hydrostratigraphic units in MBC

Hydrostratigraphic unit	Function within the regional groundwater system
Fyansford formation	Unconfined aquifer
Brown coal seam	Aquitard and confining aquifer
Werribee formation	Confined aquifer

and relatively thin beds of clayey sand. This formation acts as an unconfined aquifer. The top of the unconfined aquifer is the ground surface, and base is defined by the Maddingley coal seam. The thickness of Fyansford formation is between 5 and 20 m. The aquifer is likely to be highly heterogeneous, both in yield and in hydraulic properties. Hydraulic conductivity is likely to be up to 10^{-7} m/s. The unconfined aquifer is mainly recharged by rainfall and is discharged into the Parwan Creek. The mine dewatering system controls the groundwater flow within this aquifer. This unconfined aquifer will be removed with the stripping activity. The Maddingley Coal Seam (upper Werribee formation) is regarded as an aquitard separating the upper unconfined Fyansford formation from the lower confined Werribee formation, due to its high clay content and low hydraulic conductivity (10^{-8} m/s). The lower Werribee formation is extensive across the site, and its bases have not been intercepted, so the thickness of this formation at the site is not known. It consists of silty sands, sands and sandy clays with minor gravels, and it is known as a confined or semi-confined aquifer [23].

2.2 MBC north batter stability

Cracks (Fig. 2) were observed in the northern batter in MBC in November 2013. MBC north batter had been stable for many decades until the early 2013 mining activity commenced. It was a single bench, about 25 m high and extended over approximately 150 m in length orientated from west to east, at a slope angle $> 80^\circ$. These cracks were located about 20 m from the batter crest, when there was a large scale of overburden stripping commenced in early 2013 and minimal mining of coal. The length of these cracks was almost throughout the overall length of the batter, and the width was from a trace to approximately 150 mm. The cracks opened wider in the east than in the west as there was an old 5-m high buttress left at the toe of the western end of the batter.

To monitor the ground movement, eight survey markers were installed along the major cracks in November 2013. The locations of these survey markers (from Marker 1 to Marker 8) are demonstrated in Fig. 3. The monitored data were collected weekly. Monitored data are shown in Fig. 4.

Fig. 2 Major cracks on north batter observed in November 2013 **Fig. 3** Survey markers (M1–M8) on MBC north batter

Meanwhile, the emergency buttress was constructed immediately after the observation of the cracks. According to the monitored data, movements were well controlled with the construction of the emergency buttress, except that some new minor cracks (Fig. 3) appeared in the south of the cracks. From the monitored data (Fig. 4), the ground deformation on the north batter was limited within 10 mm in both north and south directions in the following 3 months after the installation of survey markers. However, a 26-mm rainfall occurred on 14 February 2014

Fig. 4 Monitored ground deformations on north batter (marker M6 was broken during mining)

(1 day after the buttress was fully completed), and noticeable movements (in Fig. 4, south movement is negative and north positive) were observed. The movements were 56 mm, 65 mm, 55 mm, 15 mm, 7 mm, 61 mm and 18 mm towards pit bottom (south), seen from survey markers 1–8, respectively (survey marker 6 was destroyed prior to the rainfall event due to mining activity). Rebound (Fig. 4) of the deformations was also observed, which is attributed to the recession of hydrostatic pressure in the cracks.

3 Three-dimensional model and numerical study

To study the stability of the brown coal batter with opened cracks under rainfall conditions, a three-dimensional geological model of MBC north batter was developed based on the MBC north batter on 13 February 2014 when the emergency buttress had been in place and crack deformations had been monitored. One day later, a 26-mm rainfall event occurred. The model was 400 m in length from west to east and 250 m in width from north to south. The grid division diagram of the model after fine meshing is shown in Fig. 5. The model covered the whole north batter, part of east and west batter of MBC open pit.

From top to the bottom, the model consisted of 5 layers that were Fyansford formation (overburden, RL 87 m to RL 100 m), brown coal layer (RL 50 m to RL 87 m), emergency buttress (RL 60 m to RL 72 m) and engineering fill layer (RL 55 m to RL 60 m), broken brown coal layer (RL 50 m to RL 55 m) and Werribee formation (RL 0 m to RL 50 m). Groundwater flew towards pit bottom. Based on the measured borehole logs in the field, the top groundwater level was set at RL 92 m in the Fyansford formation at the initial state, which flew down to the

pit bottom (RL 60 m). The opened cracks in the model included the major crack and the subsequent minor cracks, which are shown in Fig. 6. The major crack was approximately 20 m back from the coal face, and the two minor cracks were on the south of the major one.

The numerical modelling was designed to simulate the initial state of the coal batter (after buttress in position and before the recorded 26-mm rainfall event), the state after the 26-mm rainfall, the states with 26 mm/day rainfall intensity lasting for 3 days, 6 days, 9 days and 78 mm/day rainfall intensity lasting for 1 day, 2 days, 3 days, respectively. The simulated deformations after the 26-mm rainfall were compared with the monitored batter movements. With the purpose of studying the effect of precipitation, rainfall intensity and lasting time on the cracked batter stability, three total precipitation conditions (78 mm, 156 mm, 234 mm) were set and each precipitation was reached by 26 mm/day and 78 mm/day rainfall intensity for different lasting times, respectively. To be specific, the calculation conditions of 26 mm/day for 3 days and 78 mm/day for 1 day were designed to reach 78-mm precipitation; 26 mm/day for 6 days and 78 mm/day for 2 days were for 156-mm precipitation; in terms of the 234-mm precipitation, the simulation conditions were 26 mm/day for 9 days and 78 mm/day for 3 days. There were three calculation types involved in the model simulation. Gravity loading was to simulate the initial phase of the model. The fully coupled flow-deformation calculation type was employed to calculate the rainfall process on the model. All precipitation was assumed being evenly distributed in the set lasting term. Each calculation phase was followed by a safety analysis phase that was to compute the global safety factors of the model. As a result, there were total 16 calculation phases (Fig. 7) included in the integrated simulation

Fig. 5 Grid division diagram of the model after meshing

Fig. 6 Meshed three-dimensional model of north batter

design of the model, namely 1 gravity calculation phase (initial state), 7 fully coupled flow-deformation

calculation phases (rainfall process) and 8 safety analysis phases.

Fig. 7 Designed calculation phases of the model

Victorian brown coal is a material with high organic content and low permeability [24, 25], whose strength is between normal engineering soil and rock, and its stiffness is similar to very stiff clay. It is also a highly deformable and low-density material. The unit weight of saturated MBC brown coal is about 11.5 kN/m^3 while the dry unit weight is about 5 kN/m^3 . The low density means the batter stability is very susceptible to the water pressure from groundwater or rainfall run-off, and the deformable character tends to cause the formation of cracks and open of existing joints in Victorian brown coal [9]. Table 2 lists the adopted geotechnical parameters in the model. These parameters are

from direct shear tests, triaxial tests, permeability tests and technical reports provided by MBC.

4 Results and discussion

From the simulation results, the safety factor of initial phase was 1.340. It illustrated the north batter of MBC with opened cracks and supported by the emergency buttress was in a stable state. After the 26-mm rainfall event, noticeable movements were generated along the length of both sides of cracks in the direction perpendicular to the cracks, while no apparent lateral movements in the direction parallel to the cracks (Fig. 8). The cross-sectional view of the crack deformation is shown in Fig. 9, from which the deformations were mainly located on the shallow part of the coal seam. The monitored data of deformation after the rainfall event were recorded by the survey markers that were installed and distributed along the major crack (four on north side, two on south and two on lateral). The monitored deformations were 56 mm, 65 mm, 55 mm, 15 mm, 7 mm, 61 mm and 18 mm from markers 1–8, respectively, excluding marker 6 as it was damaged during mining activity. Correspond to the monitored data from the seven survey markers, the simulated values were 48 mm, 52 mm, 48 mm, 32 mm, 4 mm, 28 mm and 20 mm, respectively. The comparison of monitored and simulated deformations is shown in Fig. 10, from which the simulated result was in good agreement with the monitored data, with comparatively less southern movements than the observed data except for marker 4. The safety factor was decreased to 1.316 after this rainfall event from the safety analysis. It illustrated the coal batter was still in a stable state after the 26-mm precipitation in 24 h. Figure 8 shows the largest movement towards open pit (south) appeared close to the north of the major crack, reaching up to 52 mm. The

Table 2 Mechanical prosperities adopted in the three-dimensional simulation

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

Fig. 8 Movement of cracks after a 26-mm rainfall lasting for 24 h

Fig. 9 Cross-sectional view of the crack deformation

Fig. 10 Comparison of observed and simulated movements along the crack

Fig. 11 Relation between crack propagation and accumulated precipitation of 26 mm/day in 24 h

deformation about 28 mm, also towards open pit, was seen in the north of the two minor cracks, whereas in the opposite side (south) of the minor cracks, only smaller movements, less than 8 mm, towards north were simulated. The movements between the major and minor cracks were the overlapping effects of both south and north movements resulted from the major and minor cracks after rainfall. There was up to 24-mm positive (towards north) movement in the central south of the major crack, where a gap between the two minor cracks existed.

The ground appeared to move towards the centre line of the crack, and the deformation was larger in the north of the crack than in the south. The ground movements mainly concentrated in the vicinity of cracks, while there was no noticeable movement in other parts of the batter. The surface run-off entering cracks exerted a hydrodynamic force on the initially unsaturated coal seam part; as a result, the deformation tended to move towards the centre line of the crack. The overall water flow was towards pit bottom (south). Thus, the suddenly risen groundwater level in the cracks and brown coal seam increased the south direction hydrodynamic force and horizontal hydrostatic water pressure to the brown coal seam, resulting in larger south direction movement. The deformation generated around the major crack was larger than the

deformation around the minor cracks. It was inferred that the deformation could be larger with the increase in the crack's depth.

With the accumulation of precipitation, the cracks widened. The deformation of cracks from numerical simulation versus rainfall time is presented in Fig. 11. From the figure, the deformation propagated slowly in the beginning of the rainfall, but the process was accelerated after 0.3 day. When the water level in the crack reached the maximum, the rate of the deforming induced by the increased hydrostatic forces could reach the highest. The deformations of cracks at 0.2425, 0.5425 and 0.8425 day are presented in Fig. 12a–c, respectively.

In summary, the failure mechanism of rainfall-induced block sliding of brown coal batter with cracks is graphically summarized in Fig. 13. When a large rainfall event occurs, the hydrostatic forces in the exposed crack and in the aquifer underneath the coal seam will both increase, the former increases the driving force, and the latter decreases the resisting force. The compounded results of hydrostatic forces from the crack in the rear of the batter and from the clay layer underlain the batter is pushing the block to slide towards the pit bottom, or batter failure, e.g. the factor of safety is dramatically declined to less than 1.0.

With the increase in precipitation and rainfall lasting period, the safety factor (Fig. 14) of model dropped. The coal batter failed with the 26 mm/day rainfall intensity lasting for 9 days. To be specific, the safety factor was decreased from the original 1.340–1.248 with 26 mm/day rainfall intensity lasting for 3 days, and it dropped to 1.066 and 0.999 after 6 days and 9 days, respectively; when the rainfall intensity was 78 mm/d, the safety factor dropped to 1.295, 1.099 and 1.047 after 1 day, 2 days and 3 days from the initial state, respectively. Thus, under the same quantity of precipitation, the safety factor dropped more at a smaller rainfall intensity over a longer period than at a larger rainfall intensity over a shorter period, e.g. the safety factor 1.066 caused by the 6 days 26 mm/day precipitation was smaller than the safety factor of 1.99 resulted from the 2 days 78 mm/day precipitation. As the smaller rainfall intensity took longer time to reach the same precipitation, the coal seam and crack affected by the high-level water pressure for a longer period became more instable. On the other hand, the larger rainfall intensity caused the coal batter more instable than the smaller intensity during the same rainfall period, e.g. the 3-day 78 mm/day rainfall resulted in a safety factor of 1.047 that was far lower than the safety factor of 1.248 caused by the 3 days 26 mm/day rainfall. It can be seen from the results that both the short-term strong rainfall intensity and long enduring low rainfall intensity could lead the brown coal batter with opened cracks to a weaker and instability state.

Fig. 12 Deformation of cracks at **a** 0.2425 day, **b** 0.5425 day, **c** 0.8425 day

(a)

(b)

(c)

Fig. 13 Victorian brown coal mine block sliding mechanism

Fig. 14 Relation between safety factor and accumulated precipitation of 26 mm/day and 78 mm/day in 9 days

5 Conclusions

A three-dimensional model was developed using Plaxis 3D to study the effects of rainfall on the brown coal batter stability with open cracks in Maddingley brown coal open pit, Victoria. The following conclusions can be made.

1. The simulated deformations after the recorded 26-mm rainfall event were well agreed with the observed data from the seven field survey markers, which in

turn verified the three-dimensional numerical model developed.

2. From the safety analysis, the safety factor of the batter was 1.340 at the initial state (with cracks and buttress). After the 26-mm precipitation in 24 h, the safety factor dropped to 1.316. This rainfall event did not cause the batter instable; even some deformations were observed by the surveying markers installed around cracks. Some rebound of the deformations was attributed to the recession of hydrostatic pressure in the cracks. With the further increase in precipitation and

rainfall lasting time in the numerical study, the safety factor continuously dropped under the conditions of both 26 mm/day and 78 mm/day rainfall intensity. The coal batter would fail with the 26 mm/day rainfall intensity lasting for 9 days. It revealed that both the short-term high rainfall intensity precipitation and long enduring low rainfall intensity precipitation could lead the brown coal batter with opened cracks to an instability state.

3. From this study, the hydrostatic forces in the exposed crack and in the aquifer underneath the coal seam could both increase under the condition of rainfall, the former increased the driving force, and the latter decreased the resisting force. The compounded results of hydrostatic forces from the crack in the rear of the batter and from the clay layer underlain the batter were pushing the block to slide towards the pit bottom, or batter failure, e.g. the factor of safety was dramatically declined to less than 1.0.
4. In this study, the precipitation was evenly distributed during the precipitation period, e.g. the simulation of the 26-mm precipitation in 24 h. This might be different from the reality. The groundwater flow conditions were more complicated in practice than the defined groundwater flow conditions in the numerical study. These differences could affect the accuracy of results. With accurate monitored rainfall data, the model can achieve a simulation of the variation in the precipitation in time by defining a flow function encoded in the fully coupled flow-deformation calculation in Plaxis 3D.

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Compliance with ethical standards

Conflict of interest The authors confirm they have no competing interests.

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