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A new approach to identify and analyse key blocks in pit slopes

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Abstract

The stability analysis of rock wedges in pit walls has primarily focused on assessing blocks that form at the exposed face of the pit. Historically, this has been limited to the analysis of fully daylighting wedges through kinematic analysis. Recent work (Lawrence et al. 2020; Valerio et al. 2020) has extended the assessment to non-daylighting wedges, identified by developing discrete fracture network (DFN) models of structural conditions. However, in existing open pits, sequential failure of blocks has been observed to result in a domino-effect failure that starts with the 'key block' – a block whose failure and removal triggers the movement of subsequent blocks. Even though this is a well-known phenomenon, there has been limited investigation into the identification of key blocks in pit slopes, an approach to evaluate key block stability, or the stability of the wedges that develop behind the key block. This is considered a critical component of pit wall optimisation in structurally controlled rock slope designs that has not yet been resolved.

In this paper, an algorithm is presented for identifying key blocks within a slope. Collections of blocks are generated using DFN analysis. Once the key blocks are identified, the stability of each block is computed, whether daylighting or not. The stability of remaining blocks is computed using an updated pit design, which includes the scarp of the removed key block. The process is conducted iteratively to assess the impact of sequential failure within a pit slope, yielding a more-robust method for slope optimisation. The key block approach can be applied at a bench, inter-ramp or overall slope scale.

Keywords: *discrete fracture network, key blocks, slope stability, pit wall optimisation*

1 Introduction

Many pit slope instabilities are the result of rock wedge failures from wedges that fully daylight in the slope face. Assessment of these wedges, which are defined by a combination of adverse structural conditions, forms the basis of kinematic approaches to deterministic and probabilistic bench and inter-ramp slope design. Slope instability also occurs when these discrete rock wedges do not daylight, or are not fully formed, by shearing through the rock mass that buttresses the wedge. These types of wedges in traditional kinematic analyses are referred to as 'non-daylighting' and are classified as kinematically inadmissible or non-removable. Methods for the identification of blocks, and their kinematic admissibility or removability, form the basis of block theory presented by Goodman & Shi (1985), and by Goodman (1995) specifically in the context of its application to rock engineering. Evaluation of non-daylighting wedges has typically been completed in more-advanced numerical tools employing discontinuum approaches (discrete element, discontinuous deformation analysis) or continuum approaches. However, kinematic-based methods for non-daylighting failures, and their application to slope design, have recently been presented (Valerio et al. 2020, Lawrence et al. 2020). Discrete fracture network (DFN) models are used in the method to develop representative structural conditions at bench, inter-ramp or wall scale. Daylighting (removable) and non-daylighting blocks (non-removable) are identified using block theory (Goodman & Shi 1985) and algorithms developed within the commercial software FracMan (WSP 2023).

The kinematic stability of both the daylighting and non-daylighting blocks is then assessed using the methodology presented in Lawrence et al. (2020), which establishes a monotonically decreasing slip-surface that fully encompasses the wedge but extends through any rock mass buttress or irregularities. Lawrence et al. (2020) also presents an approach for evaluating assemblies of blocks either combinatorically or using a clustering algorithm (which successively removes blocks from the largest composite block until the minimum Factor of Safety [FoS] is achieved). Neighbour lists are identified using key block theory. The identification of wedges in block theory is based upon the assumption that failure of a block (underground or open pit) will begin at the boundary of the excavation (Goodman 1995) and propagate into the open space (i.e. pit or tunnel). After the first block fails, the updated surface (or boundary) contains a failure scarp, which may or may not daylight additional blocks. This can lead to the successive unravelling of the slope as key blocks fail. The identification of key blocks, the first block to fail, is therefore an important aspect in both open pit and underground mining, as it may prevent larger instabilities from developing or smaller instabilities from progressing into larger failure volumes.

The sequential or successive failure of blocks in mining is a significant challenge to bench and inter-ramp design, as basic kinematic tools only assess the key block (underpredicting the risk to operations). The DFN-based methods of Valerio et al. (2020) and Lawrence et al. (2020) offer an improvement in that non-daylighting wedges and clusters of neighbouring blocks are evaluated, but failure originating from the displacement of the key block and progressing up the slope has yet to be considered. The identification and removability of key blocks form the basis of kinematic analysis, but an efficient method for evaluating the potential recursive nature of rock slope failure and subsequent risk to mining operations has not been developed. This paper presents an algorithm to identify and assess the stability of potential key block chains in open pit mining. The slip-surface identification process, stability evaluation, and subsequent key block stability analysis discussed herein was independently developed by the authors in Python 3.7. Performance of the slip-surface algorithm, the largest computational burden, is enhanced using ray casting algorithms from Intel's open source Embree (Version 3) library (www.embree.org). Multiprocessing libraries are also utilised throughout to achieve parallelisation of the implementation. The implementation uses a 'key block tree structure' to store and recursively navigate the key block chains. The stability of the key block chain, or tree, is evaluated by successively updating the slope with the failure scarp once the key block is removed. Simple examples are presented to demonstrate the approach and algorithm, with more-complex examples derived from real applications.

2 Methodology

DFN models, representing deterministic and/or stochastic discontinuities, are used to identify blocks and associated neighbour lists. This is the starting point of the current algorithm. This identification of key block chains and methodology for the kinematic assessment is presented in the following sections.

2.1 Key block identification

The first step in the key block assessment is identifying which blocks within the slope are key blocks. This identification can be tailored to project specifics based on the observed geometries and failure characteristics, but a general description is presented below.

A key block in the context of the current analysis is a block whose failure (or removal) results in the failure of additional blocks. Since the key block is the first to fail, it must be part of the slope face but not necessarily daylighting. The block can fail by shearing along discontinuities (kinematically admissible) or through a combination of shearing along discontinuities and through rock mass (kinematically inadmissible or non-removable).

The FoS of the key block must be low but not necessarily less than one, as the intent of the algorithm is to evaluate the risk of the progressive failure. A block that is near equilibrium remains a risk if changes in the conditions occur, such as increased water pressure (e.g. precipitation, spring freshet), degradation of fracture surfaces or rock mass (e.g. weathering, blast damage), or increased driving forces (e.g. earthquakes, snow loads and live loads). The FoS constraint applied in the identification of key blocks is based upon the local conditions and risk tolerance of the operation (partly quantified by comparing the FoS against design acceptance criteria [DAC]) and is therefore included as a variable parameter in the analysis.

Finally, for the progressive failure to occur, the subsequently failed blocks must be attached to (or neighbours of) the key block and be physically located up-slope of the key block (i.e. the second block must be above and behind the first so that its stability is impacted by the key block failure scarp). In the current implementation of the algorithm, for a block to be considered up-slope, all points on the subsequent block must be above the minimum point of the key block, with the key block sitting in front, as determined by the slope direction. Improvement of this simple geometrical approach can be considered in subsequent work.

In summary, the pre-requisites for determination of a key block are as follows:

1. Originates at (connected to) the rock slope but not necessarily daylighting.
2. Buttresses other blocks (i.e. there are neighbour blocks above and behind the block).
3. Has an FoS (calculated using a combination of failure through discrete structures and rock mass) less than a user-defined (site-specific) value.
4. Has a minimum volume as defined by the scale and application of interest (bench versus inter-ramp scale).

A simple example is constructed and displayed in Figure 1 to demonstrate this approach, where Block 1 is fully daylighting, and Blocks 2 and 3 are non-daylighting, buttressed by the blocks immediately in front of each. Assuming the FoS and minimum volume constraints are satisfied, Block 1 is considered a 'key block' of Block 2 (i.e. Block 2 is connected both above and behind Block 1, and Block 1 is connected to the slope surface). However, Block 2 is also considered a key block of Block 3, as it meets the same requirements – it is non-daylighting, but this is not required in the identification of key blocks. Therefore, Block 1 indirectly is also a key block of Block 3, but recursively through the progressive failure of Block 2. In summary: (i) Block 1 is a key block of Block 2 and Block 3 (through progressive failure of Block 2), (ii) Block 2 is a key block of Block 3, and (iii) Block 3 is not a key block.

This simple example demonstrates the need for a more-complex data structure that can be used to store and traverse the key block chain and all possible nested permutations.

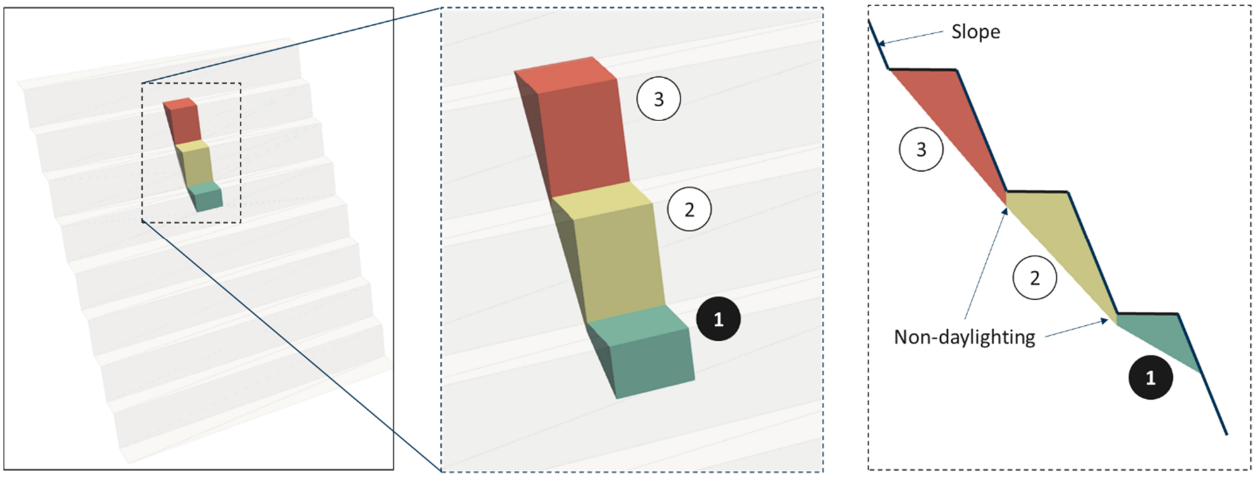


Figure 1 A simple example of the key block concept (blocks randomly coloured by block number)

Note also that different assemblies of the blocks displayed in Figure 1 are also valid failure options. For example, Blocks 1 + 2, 2 + 3 and 1 + 2 + 3 are different neighbour collections that can be evaluated, but these options are already considered through the neighbour algorithm presented in Lawrence et al. (2020). In the neighbour algorithm, different assemblies of blocks are considered with the FoS being evaluated for the larger collection, but the scarp of the potential key block is not considered in the neighbour analysis. For example, the FoS of Block 2 is lower after Block 1 has failed (been removed) and the failure scarp included in the representation of the pit shell.

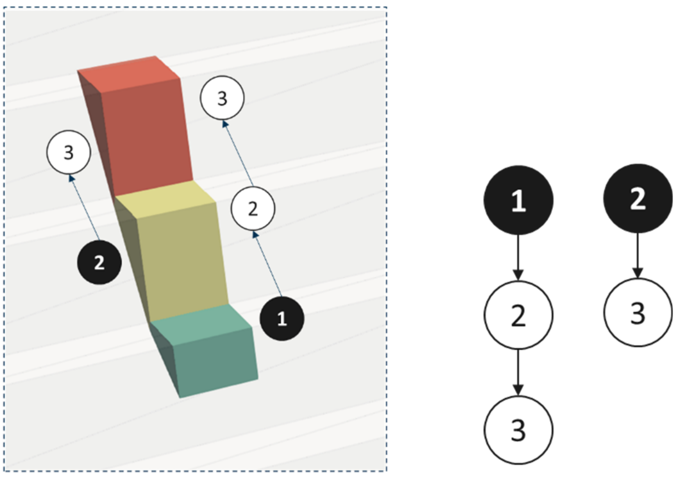
2.2 Key block tree structure

For each block that has been identified as a key block, a tree data structure is created, referred to as a 'key block tree' in further text. These data structures are widely used in computer applications for sorting and traversing nested data. Each key block tree identifies the blocks that the key block is buttressing. Figure 2 displays the key block trees for each block from the example shown in Figure 1.

The key block tree for Block 1 identifies Block 2 as a block to evaluate upon the removal of Block 1 and then Block 3 after the removal of Block 2. The kinematic-based algorithm (from Lawrence et al. 2020) also iterates over the blocks in this order when performing the FoS evaluation as follows:

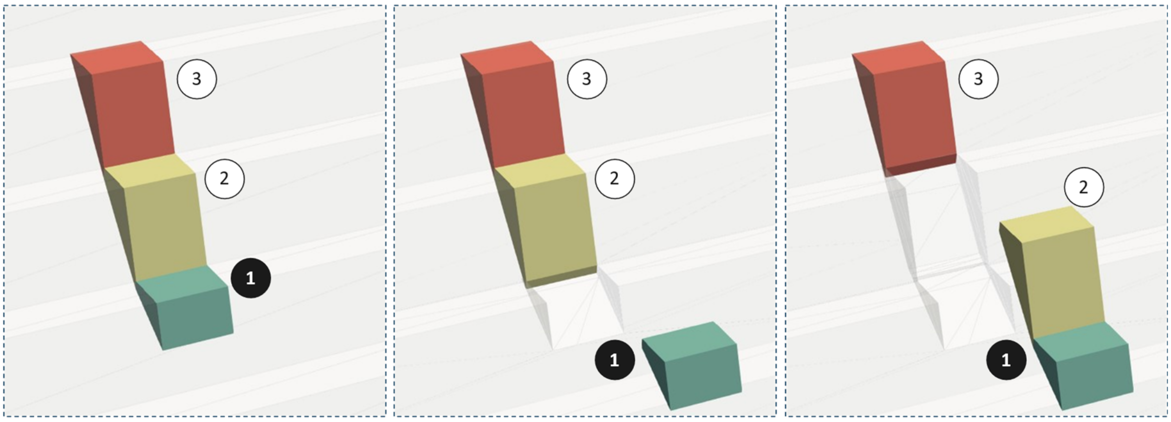
1. The FoS of Block 1 is first evaluated. If it is less than the minimum FoS constraint, it is subsequently identified as a key block, and the data structure in Figure 2 is formed (Figure 3a).
2. The failure scarp formed by the removal of Block 1 is created by merging the scarp (or slip-surface of Block 1) with the pit topography (prior to failure), displayed in Figure 3b.
3. This updated surface is used in the FoS evaluation of Block 2 (i.e. Block 1 failure scarp is removed from the pit topography).
4. The surface representing the failure scarp of Block 2 is then merged into the updated pit surface from Step 2; see Figure 3c.
5. The updated pit topography (from Step 4) is then used to evaluate the FoS of Block 3.

This process is repeated for all blocks that have a non-empty key block tree (i.e. Block 1 and Block 2 both have key block trees). In this example, the same process is repeated for the key block tree of Block 2 (Figure 2b, which has only one block above it, Block 3). When the algorithm evaluates the key block tree associated with Block 2, Block 1 has not been removed from the slope. This provides for a comprehensive assessment of all key blocks that can then be used to produce quantitative metrics, such as total volume or volume-weighted FoS, which inform the risk of progressive slope failure.



(a) (b)

Figure 2 Key block tree structure for simple example key block chain. (a) Key block chain from Block 1 and Block 2; (b) key block tree for Block 1 and Block 2



(a) (b) (c)

Figure 3 Process for recursive evaluation of block stability for Block 1 key block tree. (a) Step 1: evaluate FoS of Block 1, using original slope surface; (b) Steps 2–3: evaluate FoS of Block 2, considering Block 1 failure scarp (Block 1 removed); (c) Steps 4–5: evaluate FoS of Block 3, considering Block 1, 2 failure scarp (Blocks 1 and 2 removed)

2.3 Kinematic evaluation

Table 1 provides the FoS of each block prior to the implementation of the key block algorithm using both the traditional kinematic and composite kinematic (Lawrence et al. 2020) approaches.

Table 1 Stability results for individual blocks

Block	FoS (traditional kinematics)	FoS (composite kinematics)
1	1.00	1.00
2	Kinematically Inadmissible	1.18
3	Kinematically Inadmissible	1.22

To evaluate the FoS of key blocks and the potential for progressive growth along the key block tree, the recursive algorithm presented earlier is then traversed. For each key block, the FoS is then calculated using the composite kinematic assessment method presented by Lawrence et al. (2020). The key block is then removed from the slope (i.e. so that the scarp of the block is now part of the slope), and the FoS for the next block in the key block tree is calculated. This is done iteratively until the FoS of every block in every key block tree has been evaluated. The FoS values for the two key block trees from the simple example (Figures 1 and 2) are provided in Table 2. For the key block tree initiating with Block 1, Block 1 has an FoS of 1.00 (kinematic evaluation, daylighting wedge). When Block 1 is removed, Block 2 has an FoS of 0.54, and then Block 3 has an FoS of 0.50 when Block 2 is removed. Similarly, for the key block tree initiating with Block 2, the individual/kinematic FoS of Block 2 is 1.18. When Block 2 is removed, with the failure scarp of Block 2 considered in the slope geometry, Block 3 has an FoS of 0.50.

The individual FoS values for Blocks 1 and 2 at the initiation of the key block algorithm are consistent with Table 1, but the blocks that follow in the key block tree have significantly lower FoS values than the FoS from the single block kinematic results. Blocks 2 and 3 have FoS values of approximately 0.5, when the key block algorithm is considered.

The process developed by Lawrence et al. (2020) reports the minimum FoS obtained based upon the single key block and any assembly of blocks when the neighbour algorithm is employed. The key block algorithm presented in this study should also be considered in this determination of minimum FoS for each block for more-robust results. For example, the FoS for Block 3 in this example is lower when using this key block algorithm than any FoS reported when using just the neighbour algorithm, which presents greater risk.

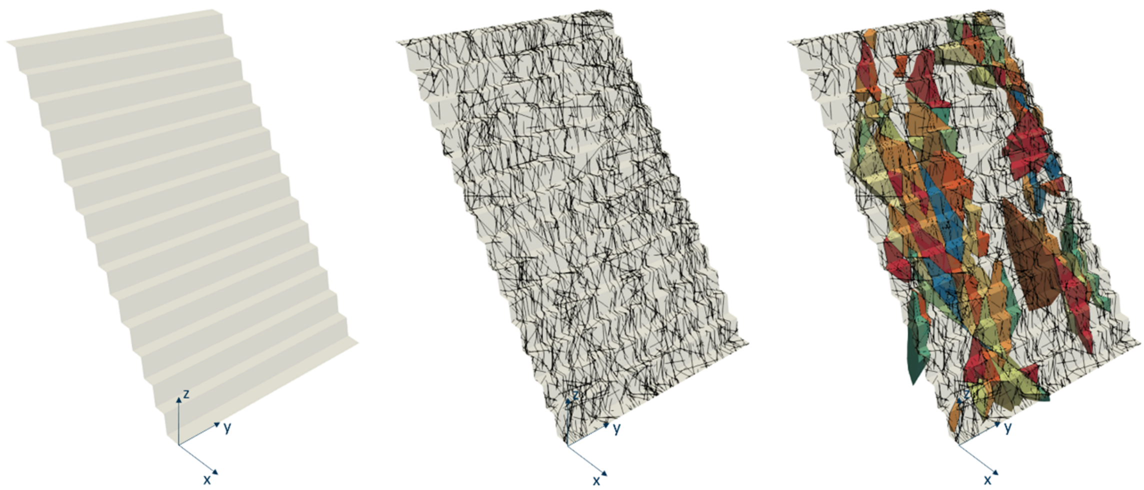
Though it may not be evident in this simple example, the authors have observed this to be the case in more realistic examples.

Table 2 Stability results for the key block tree of Blocks 1 and 2 from the simple demonstration example

Key block tree	Block	FoS in key block chain
1	1	1.00
	2	0.54
	3	0.50
2	2	1.18
	3	0.50

3 DFN-generated examples

The simple block configuration presented in the previous section was useful for demonstrating the key block identification and stability algorithms, but it is not considered representative of the complexity that can be assessed with this approach. In order to provide examples that are more representative, the algorithm has been tested using an inter-ramp scale DFN model, developed with project-specific DFN information. The slope geometry, consisting of 14 15 m high benches at a 45° inter-ramp angle (210 m high), is displayed in Figure 4a. Stochastic features are generated based on realistic fracture properties for an open pit mine, with traces from one realisation displayed in Figure 4b. Rock wedges/blocks resulting from the intersection of the DFN model and the free surface (slope) are then identified in Figure 4c (within FracMan).



(a) (b) (c)

Figure 4 (a) Representative inter-ramp slope configuration used in current analysis; (b) Slope with example traces from single realisation of the DFN model; (c) Slope with traces and blocks formed by intersection of DFN model and free surface (slope)

The blocks selected for demonstration of the key block identification and evaluation algorithm in the following sections were chosen from different realisations of this model configuration.

Assumed rock mass/discontinuity strengths and pore pressure are provided in Table 3. Two geological strength index (GSI) values (GSI = 30, GSI = 50) are used to highlight the impact on the analysis. The low GSI (30) with high disturbance yields strengths comparable (at low stress ranges) to the discontinuity strength, while the higher GSI (50) yields a much stronger rock mass. The different strengths can be used as a sensitivity to assess the impact of localised poorer or stronger rock mass conditions.

Table 3 Strength and pore pressure conditions assumed in the key block evaluation algorithm

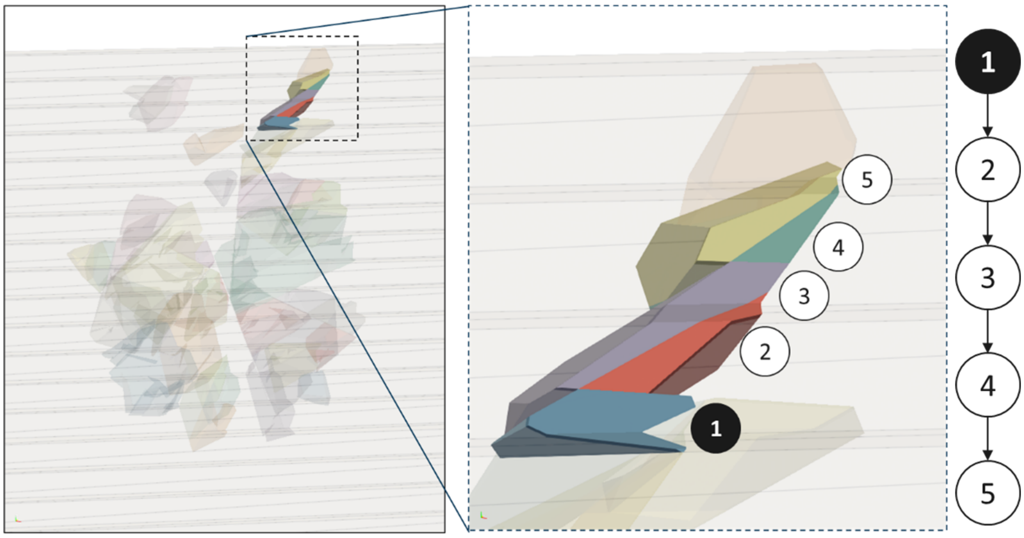
Parameter	Description	Value
Discontinuity strength	Mohr–Coulomb failure criteria	Cohesion = 5 kPa Friction angle = 28°
Rock mass	Hoek–Brown failure criteria	m_i = 9 UCS = 35 MPa GSI = 30 / 50 D = 1.0
Pore pressure	Hu coefficient, phreatic at ground surface	1.0 (fully saturated)

The stability of each block was analysed using the Python-based extended version of the composite failure algorithm (Lawrence et al. 2020), which includes the key block identification and recursive stability algorithms presented herein. Select examples that outline different types of failures are presented in the following sub-sections to demonstrate the application of the algorithm.

3.1 Linear key block tree

The first example of a key block tree illustrates a typical 'linear' or one-dimensional key block tree; in other words, if the key block fails, it allows the next block to fail, which propagates to the next block, and so on along the chain. In this type of failure, each block entry of the key block tree is itself a key block to the remaining blocks (similar to the example in Figure 1) in the slope, apart from the last block. Therefore, the key block tree for this type of failure is a single line of blocks.

An example derived from a DFN realisation is displayed in Figure 5; the slope – and blocks not involved in this specific key block chain – are displayed with transparency in Figure 5a to highlight the spatial location and size of the key block chain. The FoS values for each block, upon recursive iteration along the tree, are presented in Table 4 along with approximate block dimensions, including the failure mass of the block, height and width.



(a) (b)

Figure 5 Example of a linear key block tree, characterised by the occurrence of sequential single blocks along the chain. (a) Key block chain from Block 209; (b) Key block tree

As the blocks are complex, the height and width document the extent of the block as measured along (and up) the bench (i.e. perpendicular to the slope dip direction). Block 1 is the initial key block, with FoS = 1.20

(GSI = 30 scenario) – the FoS limit in this example is set to 2.0 and minimum failure volume is 5 (metric) tons. If Block 1 fails, it fully daylights Block 2, which propagates up the slope to further daylight Block 3, Block 4 and finally Block 5. The FoS values of these blocks are all significantly less than 1.0, indicating that stable Block 1 was the single component that was stabilising the potential multi-bench-scale failure. This key block (Block 1) is relatively small in the context of overall slope stability – bench-scale, approximately, 42 m wide × 6 m high, 2,048 (metric) tons but the collective key block chain is approximately 50 m wide by 45 m high and over 33,000 tons. The volume-weighted FoS of the key block chain is 0.56 with GSI = 30.

Table 4 Block size metrics and FoS results for the key block tree identified for Block 209

Block	Mass (tons)	Approximate dimensions (W × H)	FoS in key block chain (GSI 30)	FoS in key block chain (GSI 50)
1	2,048	42 × 6	1.20	2.41
2	4,700	71 × 20	0.71	1.19
3	7,587	56 × 20	0.54	0.79
4	8,915	60 × 28	0.43	1.27
5	9,982	68 × 18	0.51	1.27
Total mass	33,231	Volume-weighted FoS	0.56	1.22

The FoS of each block depends on local conditions, such as discontinuity, rock mass and pore pressure. Adverse conditions are assumed in this case solely to demonstrate the approach. The results with stronger rock mass conditions (GSI = 50) are also presented in Table 4 for comparison, and they demonstrate the same trend—though the FoS of the key block is much higher. However, even with these stronger rock mass conditions throughout the slope, if poorer conditions were to exist at the toe of the mechanism and Block 1 did fail, all the other blocks within the key block tree of Block 1 would fall below the typical open pit inter-ramp DAC of 1.3. The volume-weighted FoS for the stronger rock mass scenario (GSI = 50) remains low, FoS = 1.22 < DAC = 1.3, which highlights that this linear key block tree (even with stronger rock mass) is a potential risk to operations.

3.2 Cascading key block tree

The second example presents a ‘cascading’ key block tree, where the removal of the key block allows for two or more blocks to become unstable (Figure 6). The cascading key block tree is more complicated, with single blocks branching to multiple blocks, which in turn may itself recursively divide into a linear or cascading tree. In contrast to the linear failure, not every block has a key block relationship to every other block. The tree can deviate into multiple unrelated directions or branches. In tree data structure terminology, the tree and distributed branches define parent and child nodes. In this application, the key block is the parent, which may have many children (i.e. child nodes), which may in turn also have an unlimited number of children. The value of the data structure and potential complexity associated with managing the evaluation of nested key block is apparent in this example, which is also relatively simple and depicted in Figure 6.

Block 1 is the primary key block in this example. When removed, it permits movement of Block 2, Block 3, and Block 4 (cascading tree). When Block 2 is removed, it permits mobilisation of Block 5 and Block 6 (another cascading tree). When Block 3 is removed, a linear key block tree is evaluated along this branch, inclusive of Block 7 and then Block 8. Block 4 is a single smaller block, which achieves the criteria defined in the key block identification algorithm but terminates this smaller branch. The FoS for the key block tree associated with Block 4 is presented in Table 5.

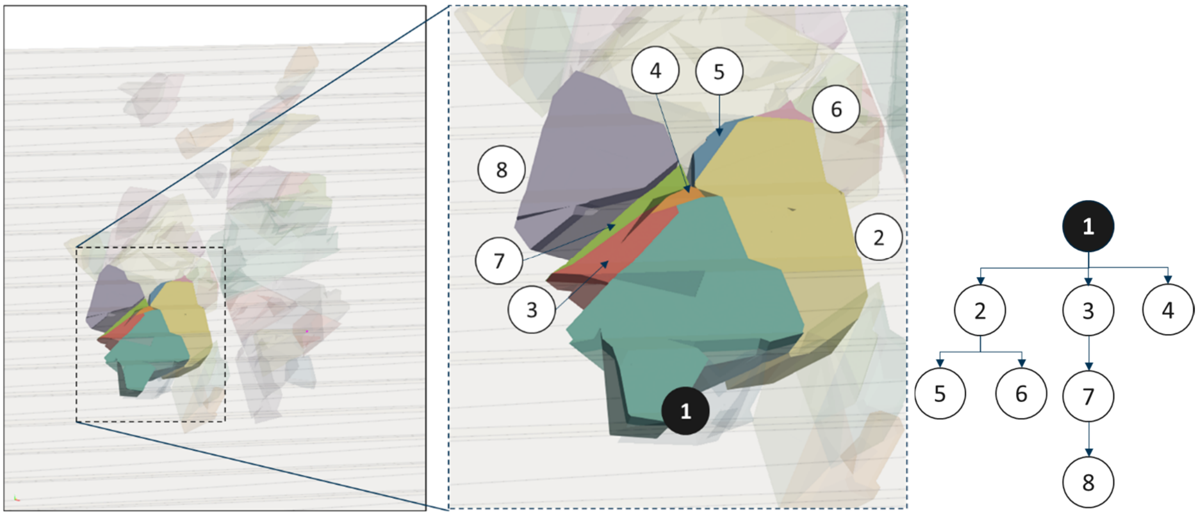


Figure 6 **Example of a cascading key block tree, characterised by the occurrence of multiple blocks behind the key block. (a) Key block chain from Block 4; (b) Key block tree**

Table 5 **Block size metrics and FoS results for the key block tree identified for Block 4**

Block	Mass (tons)	Approximate dimensions (W × H)	FoS in key block chain (GSI 30)	FoS in key block chain (GSI 50)
1	97,299	78 × 29	1.13	2.38
2	96,311	89 × 40	1.02	2.25
5	4,231	38 × 29	0.66	1.59
6	2,430	30 × 31	0.41	0.41
3	11,299	70 × 15	0.59	1.32
7	3,126	52 × 18	0.61	2.14
8	65,453	67 × 34	0.40	0.78
4	3,352	36 × 16	0.67	1.31
Total mass	283,501	Volume-weighted FoS	0.88	1.88

The approximately 100 kiloton Block 1 provides for the potential release of additional blocks that could propagate up the slope to form a failure mechanism approximately three times its original mass (283 kilotons). This highlights that larger key blocks would provide for multidirectional unravelling of the slope if they were to fail. The volume-weighted FoS values for the rock mass scenarios (GSI = 30, 50) are higher than the previous example indicating that the risk is lower—but since the potential failure mass is nearly 10 times the failure mass of the key block chain presented in Section 3.1, the operational consequence and impact on mining is significantly greater.

3.3 Small key block – large failure

The final example from the DFN realisation illustrates how a small key block, which is likely identified by traditional kinematic approaches, can be the catalyst that changes a manageable bench-scale failure into a large inter-ramp-scale mechanism. It has elements of both the linear and cascading failure types but is characterised by a relatively small initial key block, which propagates into many subsequent failed blocks and an overall large failure volume. Figure 7 presents an example of this type of failure. The FoS values for each block, upon recursive iteration along the tree, are presented in Table 6 along with approximate block dimensions. The single bench failure of Block 1 (2,502 tons) would likely be manageable on its own in the context of a large-scale mining operation; however, when this block is removed it triggers a cascading failure (Block 2 to 3 and 4) which transitions into another linear failure (Blocks 6, 9 and 10) and cascading failure (Blocks 5, 7 and 8) for a total of nine additional blocks, resulting in a 3–4 bench 122 kiloton failure. Although the initial key block only presents as a single bench-scale risk (which may be of less concern to a large mining operation), it is important that this type of block be stabilised to prevent inter-ramp scale failure events.

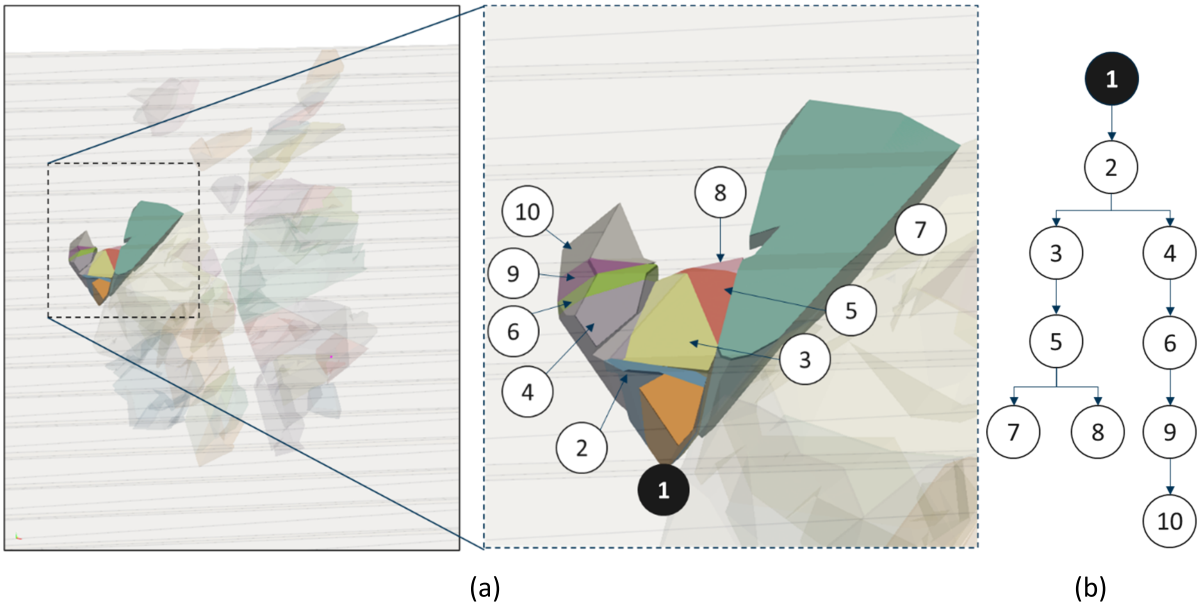


Figure 7 **Example of a small key block propagating into a larger failure. (a) Key block chain from Block 183; (b) Key block tree**

Table 6 **Block size metrics and FoS results for the key block tree identified for Block 183**

Block	Mass (tons)	Approximate dimensions (W × H)	FoS in key block chain (GSI 30)	FoS in key block chain (GSI 50)
1	2,502	24 × 21	0.85	3.39
2	3,237	33 × 24	0.54	2.24
3	10,142	48 × 20	1.13	4.08
5	9,478	32 × 25	0.29	1.03
7	78,393	102 × 59	0.81	1.81
8	2,470	32 × 14	0.22	0.80
4	9,577	48 × 15	0.32	0.96
6	2,498	24 × 24	0.35	0.93
9	1,571	31 × 13	0.30	0.91
10	2,391	45 × 12	0.28	0.54
Total mass	122,260	Volume-weighted FoS	0.71	1.84

4 Conclusion

An algorithm to identify and evaluate key blocks, for the purpose of informing slope stability analyses has been presented in this paper. The formation of the potential blocks and their attributes (which is not the focus of the current study) is provided through DFN modelling of structurally controlled slopes. In addition to the key block itself, the algorithm presented identifies and stores all up-slope blocks that could be impacted by the removal of the key block.

Once the key blocks (and key block chain of successive blocks) are identified, the stability of each block is computed based upon kinematic analysis along an identified slip-surface. The approach (presented in earlier work by the authors) can be used to evaluate the FoS for both removable (daylighting) and non-removable (non-daylighting) blocks, extending traditional kinematic approaches to allow for the evaluation of composite (rock mass and discontinuity controlled) failure mechanisms. As each block, starting with the key block, is removed from the slope, the FoS of remaining blocks is computed recursively using an updated pit topography, which includes the scarp of the removed block (and each subsequent block along the chain). The process is conducted iteratively to assess the impact of sequential and progressive failure within a pit slope.

A tree-based key block data structure is introduced to store and traverse the key block chain, recursively removing each block along the chain during the evaluation. Examples presented demonstrate the complexity involved in the identification and evaluation of even simple key block chains. The growth emanating from the key block can be linear, with each block along the chain providing a release for the block directly behind it or cascading where the removal of one block reduces stability of many blocks that propagate in multiple directions behind the first. Bench-scale blocks, which are considered manageable from an operational mining perspective, have been demonstrated to increase the expected failure mass/volume by a factor of 10 in examples presented. The approach can currently be applied at a bench, inter-ramp or overall slope scale to provide additional insight into design optimisation for kinematically controlled slopes. With additional work, the approach presented in this study could be used to identify key blocks, evaluate the likelihood of their formation based upon local structural conditions, forecast stability margins, and quantify the subsequent risk that these blocks have on mining operations.

This work is considered different from, but complementary to, previous work where clusters of neighbouring blocks may be evaluated to inform slope optimisation. It provides additional information that can be used to refine slope designs, but there is no correlation between the results of this key block algorithm, actual slope performance, and the consequence for or impact on mining. This will be the focus of future work. Extension of the work to underground mining applications and evaluation of the required ground support to limit key block failure is also being considered.

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