Coastal Cliffs Rockfall Analyses and Mitigation Measures Assessment Using RocFall3: A Case Study Along Shortland Esplanade in Newcastle, NSW (Australia)

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Abstract. Rock slope instabilities affecting several coastal cliffs in Australia, such as rockfalls, block topples and wedge sliding failures, pose a significant risk to people and infrastructure located along important national transport networks. Such instability phenomena, mostly driven by pre-existing structures within the rock mass, is expected to increase in the coming years upon the rise of predicted extreme climatic events. An accurate estimation of the likelihood and severity of these instabilities is essential to minimize the risk, assess the efficiency of existing mitigation measures and design the most appropriate protection solutions. This paper presents the case study of a very popular walking path along the Newcastle coastline, also known as Newcastle Shortland Esplanade, located in Newcastle (NSW, Australia). Following a previous significant rockfall event in 2002, rockfall protection measures are currently in place, including rock face bolting and rockfall barriers located at the bottom of the slope. High-resolution three-dimensional models of the site obtained by recent drone surveys and field investigations allowed us to assess potential rock volumes involved. Rockfall simulations using the new software RocFall3 (Rocscience) have been conducted to verify the efficiency of current rockfall barrier installed at the base of the rock face.

Keywords: Rockfall · 3D simulation · Rocscience · Rockfall protection

1 Introduction

Along the Australian coastline, many coastal rock cliffs are prone to hazardous rock slope instabilities including rockfalls, block topples and wedge sliding failures. The sporadic occurrences of such failures, largely governed by the interaction of coastal weathering processes and pre-existing structures within the rock mass, pose significant risks to people and property, particularly when they occur along popular walking paths and transport corridors. To effectively minimize these risks and engineer the most efficient mitigation measures, an accurate evaluation of the likelihood and severity of potential

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instabilities, accounting for the performance of any existing rock slope protection, is essential. With sea levels predicted to rise and severe weather events set to become more frequent, the ability to reliably predict, monitor and manage the risk of future coastal rock slope instabilities is more critical than ever.

This paper used the sub-vertical coastal rock cliff at South Newcastle Beach in Newcastle (NSW, Australia) as a case study. This cliff has been prone to rockfalls in previous decades, resulting in several slope stability investigations (SMEC in 1991 and 1996, RCA in 1998, and GHD in 2002 – 2006 and 2011) and the installation of rockfall mitigation measures (preliminary works prior to 1998 and detailed works in 2005) [1]. In this paper, three-dimensional rockfall simulations using the new software RocFall3 [2] have been conducted to verify the efficiency of the current rockfall barrier installed at the base of the rock face.

2 Site Description

The coastal rock cliff considered in this case study lies along a highly trafficked section of the Bathers Way coastal walkway located at South Newcastle Beach. The rock cliff is about 300 m long and 40 m in height (at its highest point). The site location and key features have been summarized in Fig. 1. Due to the ongoing works on the north end of the cliff, only 170 m of the cliff were used for this rockfall study.

The walkway was originally part of the Shortland Esplanade roadway between Newcastle Beach and King Edward Park, however, following the sudden detachment of a large (8 m^3) sandstone block from 15 m up the adjacent cliff slope onto the roadway in October 2002, both vehicular and pedestrian access were removed by Newcastle City Council (NCC). Subsequent investigation by GHD Geotechnics (GHD) identified and assessed possible rockfall risk mitigation options that would allow for at least the re-establishment of pedestrian access. NCC chose the option consisting of cliff face stabilization (including about 200 fully grouted rock bolts) and localized excavation, followed by the construction of a 1.8m-high rockfall protection fence or wall between the cliff and walkway in 2005 [3]. To design the mitigation measures, two-dimensional

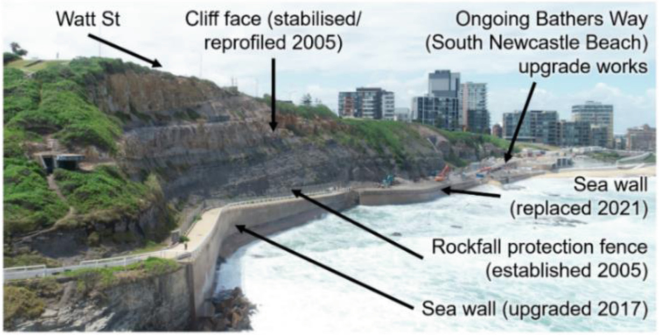

Fig. 1. Looking north to South Newcastle Beach, showing overall site setting, sub-vertical cliff face, current rockfall protection fence, Bathers Way coastal walkway, sea walls and recent works (photo taken on the 16/12/2022)

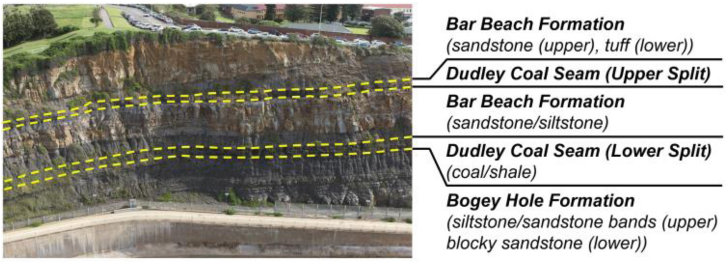

Fig. 2. South Newcastle Beach stratigraphy

rockfall trajectory modelling was performed for four representative cliff profiles in RocFall2 [2]. In recent years, the walkway and skate park at South Newcastle Beach have been updated by NCC, as part of the ongoing Bathers Way coastal revitalization project. A review of aerial imagery (Google Earth) revealed that the walkway and sea wall in the site area were updated between June 2016 and August 2017, coinciding with works on the Newcastle Beach promenade by NCC [4]. Following reassessment by Tetra Tech consulting in 2017 (pers. comm), the height of the rockfall protection fence was increased to 3.2m along the northern end of the site. As of February 2023, NCC is still completing works for the skate park, as part of the South Newcastle Beach Bathers Way works commenced in August 2020 [5].

The sedimentary rock strata found outcropping in the South Newcastle Beach cliff belong to the Newcastle Coal Measures. An image of the relevant stratigraphy has been provided in Fig. 2. As discussed by [6] and [3], the preferential weathering of the fine-grained strata by coastal actions not only leads to the detachment of small rock fragments, but also the undercutting of large blocks from strong sandstone layers. Recent site surveys show that the grouted rock bolts continue to prevent the detachment of large sandstone blocks whilst the rockfall protection fence continues to intercept small blocks.

3 Methodology

The 3D model (mesh) of Shortland Esplanade has been obtained by photogrammetric drone imagery taken using a DJI Phantom 4 RTK which has a 20-megapixel camera sensor. Images were then post-processed in Agisoft Metashape [7] using only the GPS coordinates of the images. The mesh originally contained the rockfall barrier and light posts. These obstacles have been removed using the software CloudCompare [8] and the holes on the mesh have been closed using the software Meshlab [9]. The mesh imported in Rocfall3 had 259,050 faces, it was “repaired” but not “simplified” as suggested by the software to maintain the roughness of the slope.

The input material parameters used for in Rocfall3 are reported in Table 1. Note that the coefficients of restitution used for sandstone and siltstone have been chosen considering the in-situ tests conducted by Giacomini et al. [10] while the parameters for talus cover and concrete have been taken from the Rocfall3 material library. The materials have been assigned using the “Material Region”. Although the software provides different options to select a region, only selections on the plane x-y seem to be

Table 1. Specific rock parameters used during the analysis within RocFall3

Name	Colour	Rn			Rt			Friction angle [°]
		Value	Min	Max	Value	Min	Max	
Sandstone	Orange	1	0.82	1	0.4	0.25	0.55	25
Siltstone	Light Grey	0.5	0.29	0.71	0.7	0.49	0.91	26
Talus cover	Light Blue	0.32	0.17	0.47	0.8	0.62	0.98	30
Concrete	Grey	0.48	0	1	0.53	0.02	1	41.6

working properly. Therefore, the selection of sub-vertical regions representing the strata was challenging and time consuming.

Both “Lumped Mass” and “Rigid Body” analysis have been used in this study. The shapes considered as rigid bodies were: icosphere (32 faces), tetrahedron, cube, octahedron, dodecahedron, icosahedron and all the extruded polygons. The normal scaling factor, scaled by velocity, was always applied and the sampling technique used was Monte-Carlo methods. Further details about these settings can be found in the Rocfall3 documentation [2].

Two types of seeders have been tested in this study: the “Line Seeder” and the “Area Seeder”. Intuitively, in the first type, the rock locations are generated with a uniform distribution along the length of the line seeder while for the second type the rocks are located across a defined area. Although the sandstone layers have a significant number of bolts installed, they constitute the main source of detachment of small blocks, as observed at the slope toe during recent site surveys. Therefore, the seeders have been located on both sandstone layers (the middle and the top layer in Fig. 2). When using the line seeder, it was located on the top of the strata while, when using the area seeder, the entire sandstone stratum was selected. Note that for middle strata, a single area seeder was too big, therefore two areas seeders were used to cover this stratum. A 0.5 m/s (± 0.3 m/s) translational velocity and 90°/s (± 15°/s) rotational velocity were used as initial conditions of the seeders. The number of blocks of the seeder was different depending on the type of analysis used. For “Lumped Mass”, 1000 blocks per seeder were used while for the “Rigid Body”, due to the higher computational time required to do the analysis, this number was reduced to 500. For most of the simulations, the mass of the blocks used was 235 kg (± 60 kg). This reference mass was obtained the by measuring the biggest block observed between the toe of the cliff and the rockfall barrier and using the density of 2347 kg/m^3. One simulation was run considering the unlikely possibility of the failure of one the 200 bolts present on the cliff. In this simulation 50 blocks of 1 m^3 (2347 kg) were used for each seeder. In the following sections, these two block dimensions will be referred to as small and large respectively.

The rockfall barrier was simulated as custom rockfall barrier of 90 kJ capacity. This assumption was based on the type of barrier observed on the site. This barrier is a rigid rock fence with mesh typically suggested by Transport for New South Wales (former Roads and Traffic Authority of New South Wales). Two high-configurations of this barrier were used. The first is a 1.8 m barrier located rightly at 3.2 m from the toe of

Table 2. Summary of the simulations performed using Rocfall3

Simulation	Analysis' type	Seeder type	Block mass	Barrier
S1	Lumped Mass	Line	Small	No barrier
S2	Lumped Mass	Line	Small	1.8m (pre-2017)
S3	Lumped Mass	Area	Small	1.8m (pre-2017)
S4	Lumped Mass	Line	Small	1.8m + 3.2m (current)
S5	Lumped Mass	Area	Small	1.8m + 3.2m (current)
S6	Rigid body	Area	Small	1.8m + 3.2m (current)
S7	Rigid body	Area	Large	1.8m + 3.2m (current)

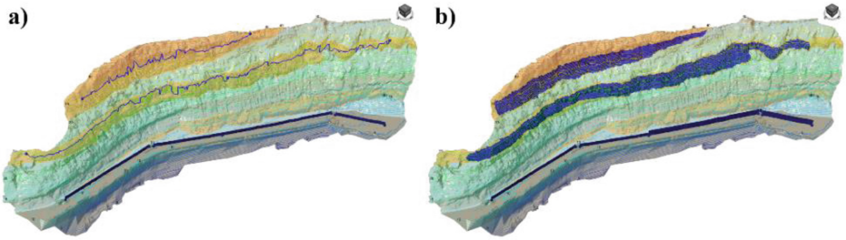

Fig. 3. Representation of the rock cliff in Rocfall3 (see Table 1 for strata key) with **a)** line seeders (blue lines on the cliff) and 1.8m barrier (dark blue) and **b)** with area seeders (light blue areas on the cliff) and the barrier (dark blue) height 1.8 m on the southern side and 3.2 m on the northern side

the rock cliff, which simulates the barrier configuration between 2005 and 2017. The second configuration reflects the current state (after 2017), where the barrier has two different heights: 1.8 m on the southern side and 3.2m on the northern side.

A summary of the simulations performed has been reported in Table 2. Figure 3 shows a representation of the rock cliff in Rocfall3: Fig. 3a illustrates the line seeders on the sandstone strata and the 1.8m-high barrier of at the toe of cliff; Fig. 3b shows the area seeders on the sandstone layers and the current barrier of the site (1.8 m on the southern side and 3.2 m on the northern side).

4 Results

The results of the first simulation without any rockfall barrier showed that more than 60% of the blocks reach the walkway. Hence, the rockfall barrier represents an important mitigation measure for minimising the risk. For conciseness, the results of this simulation are not reported. Results of the other six simulations are reported in Fig. 4.

These results can be summarised as follows:

- The lumped mass simulations using line seeders (S2 Fig. 4a) and area seeders (S3 Fig. 4b) with small blocks and the 1.8m-high barrier showed similar results: about

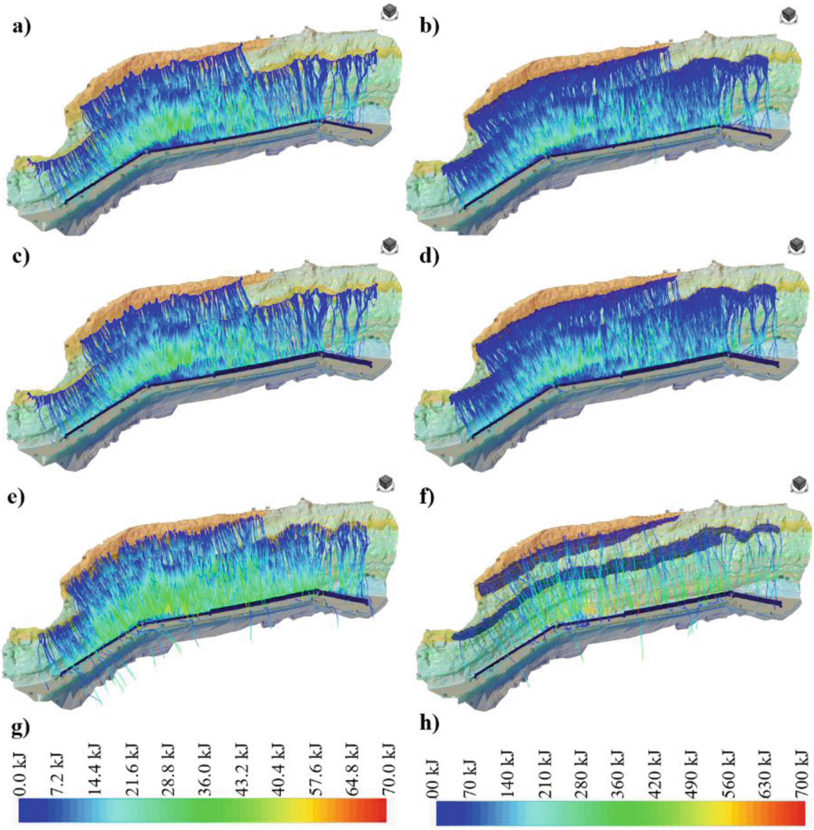

Fig. 4. Rockfall simulations using Rocfall3, result of **a)** simulation S2, **b)** S3, **c)** S4, **d)** S5, **e)** S6 and **f)** S7 (see Table 2 for details of the simulation parameters). Lines represent trajectories of falling blocks. The colour of the trajectories represent the total kinetic energy of the blocks. The scale of total kinetic energy for all simulations but S7 is reported in subfigure **g)** while the scale for S7 is reported in subfigure **h)**

30% of blocks were contained by barrier and only 0.25% of blocks flew over the barrier. The remaining 70% of blocks stopped before hitting the barrier.

- With the current barrier configuration (1.8 m on the southern side and 3.2 m on the northern side), the two lumped mass simulations using line seeders (S4 Fig. 4c) and area seeders (S5 Fig. 4d) and small blocks showed similar results: about 30% of the blocks were contained by barrier and only 2 blocks flew over the barrier for S5. Using the rigid body (S6 Fig. 4e), these percentages were higher. The percentage of blocks hitting (but contained by) the barrier was about 82.5% while the percentage of blocks flying over the barrier was 1.93%.
- The last simulation (S7, Fig. 4f), which considered blocks of a large dimension (1 m^3) using rigid body analysis, showed that 77.3% of the 150 blocks were stopped (17.7%) or contained by the barrier (59.6%), while 2.7% flew over the barrier and the remaining

20% hit the barrier with a total kinetic energy higher than its capacity. Note that for this simulation it was hypothesized the one of the 200 bolts present on the cliff failed.

5 Conclusions

In this paper, 3D rockfall simulations using the new software RocFall3 [3] have been conducted to verify the efficiency of the current rockfall barrier installed at the base of the rock face. A total of 7 simulations were conducted considering both "Lumped Mass" and "Rigid Body" analysis, 2 types of seeders (line and area seeder), 2 configurations of barrier height and 2 block dimensions (small, very likely and large, unlikely). The simulations using lumped mass analysis and small blocks showed that the percentage of blocks that can fly over the barrier is extremely low (less the 0.25%). Despite a slightly higher percentage (but still less the 2%), this finding was also confirmed using rigid body analysis. The simulation with large blocks showed that a significant number of blocks would perforate the rockfall barrier. However, if the bolts are monitored and well maintained this event can be considered very unlikely. Whilst the current rockfall barrier is adequate for the present state of the rock cliff, the rockfall risk could be potentially further reduced by increasing the fence height to 3.2 m along the entire cliff face.

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