

Application of quantitative risk assessment to the Lawrence Hargrave Drive Project, New South Wales, Australia

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ABSTRACT: Lawrence Hargrave Drive between Coalcliff and Clifton, New South Wales has been constructed near the base of a 330 m high coastal escarpment which has been oversteepened by marine erosion. The escarpment, consisting cliffs and intervening steep slopes, is affected by many rock falls, debris slides and debris flows. For safety reasons, the road has been closed and the design solution needs to reduce the annual probability of death from about 10^{-2} to about 10^{-5} . A quantitative risk assessment (QRA) based on landslide process rate models and using an Excel workbook was used to review the slope risks associated with the existing road and to assess the effectiveness of the proposed engineering works. Such approaches allowed the large number and variety of landslide hazards to be addressed, and the component parts of the landslide hazard assessment and the mechanics of the QRA to be explicitly stated and reviewed.

1 INTRODUCTION

Lawrence Hargrave Drive (LHD) is a coastal road that extends between Stanwell Park and Thirroul on the South Coast of New South Wales, about 30km south of the southern outskirts of Sydney (see locality map on Figure 1).

The 1350 m section of coastal road between Coalcliff and Clifton had been constructed about 20 to 45 m above sea level through a coastal escarpment environment consisting of steep cliffs that rise to a height of some 300 m above the road (Figs 1-3). Aggressive marine erosion is taking place at the base of the cliffs causing undercutting of the coastal platform and as a result the road has had a history of severe embankment stability, rockfall and debris flow problems.

On August 29th, 2003, the Minister for Roads closed the road for safety reasons. An Alliance was formed between the Road and Traffic Authority (RTA) (the responsible authority), Barclay Mowlem (civil contractors), Coffey Geosciences Pty Ltd and Maunsell Pty Ltd (consulting engineers) to develop an engineering solution to develop an engineering solution to reduce the risk to 'acceptable' levels.

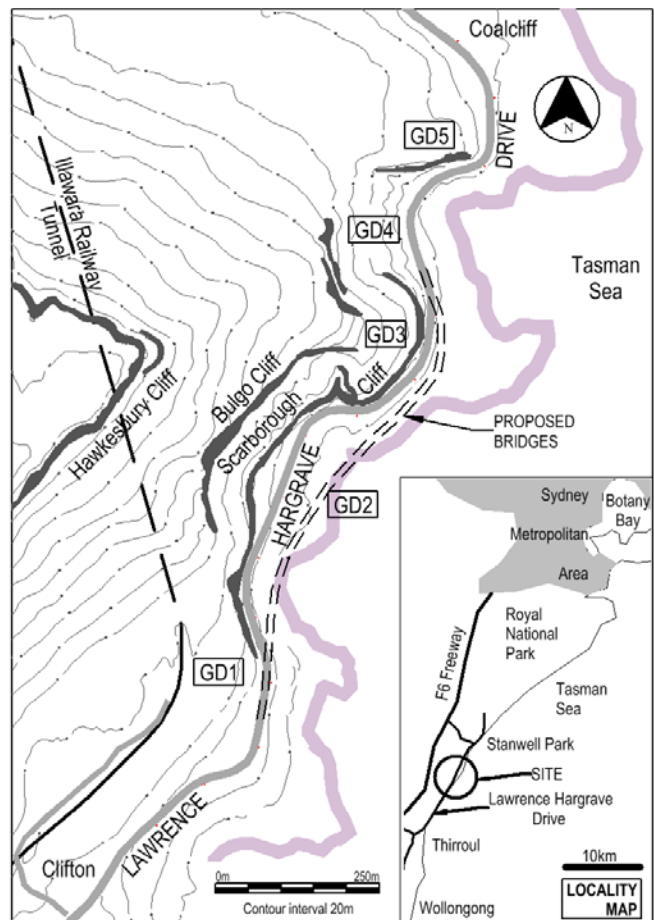


Figure 1. Site plan

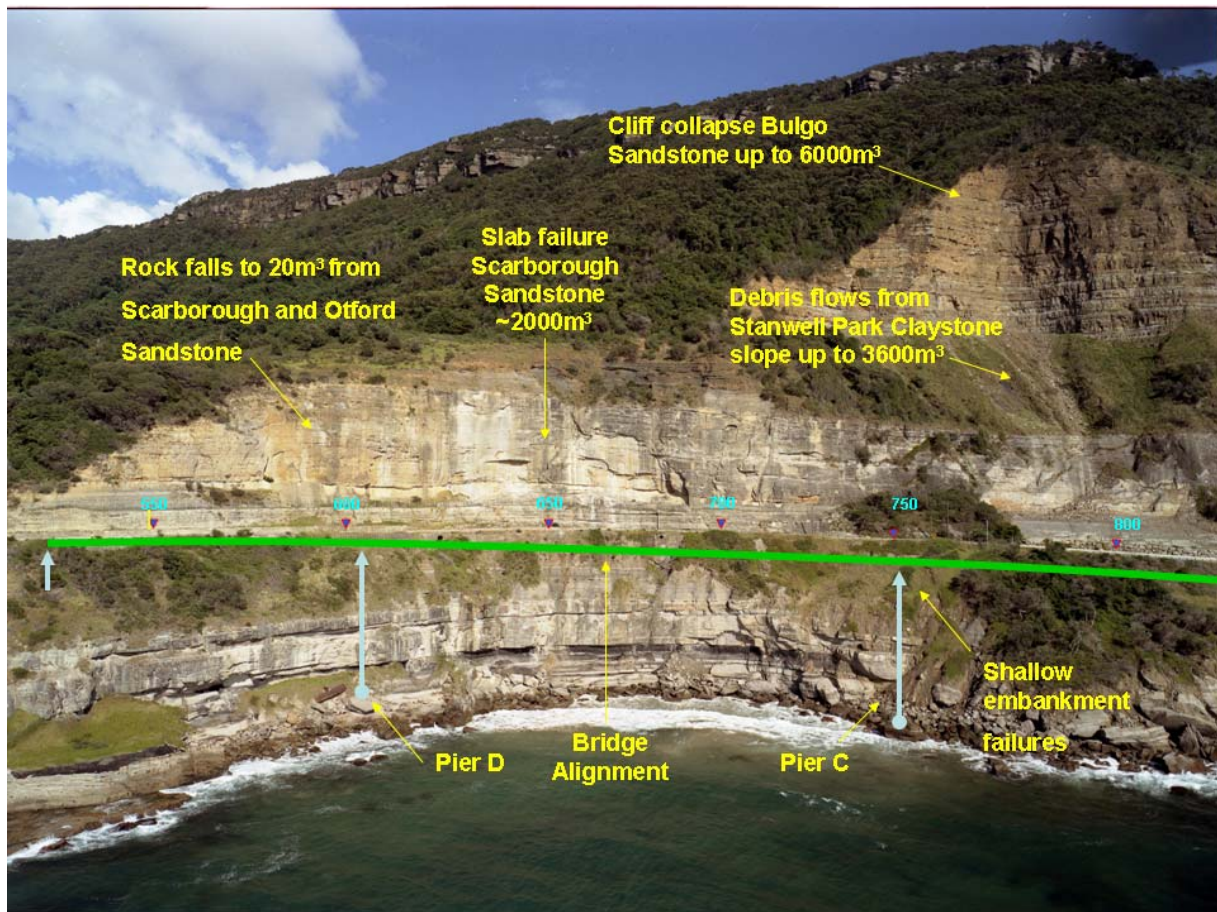


Figure 2. Oblique aerial photograph of Geotechnical Domains GD1 and GD2. The road lies about 40m above sea level and the skyline cliffs lie about 300m above sea level.

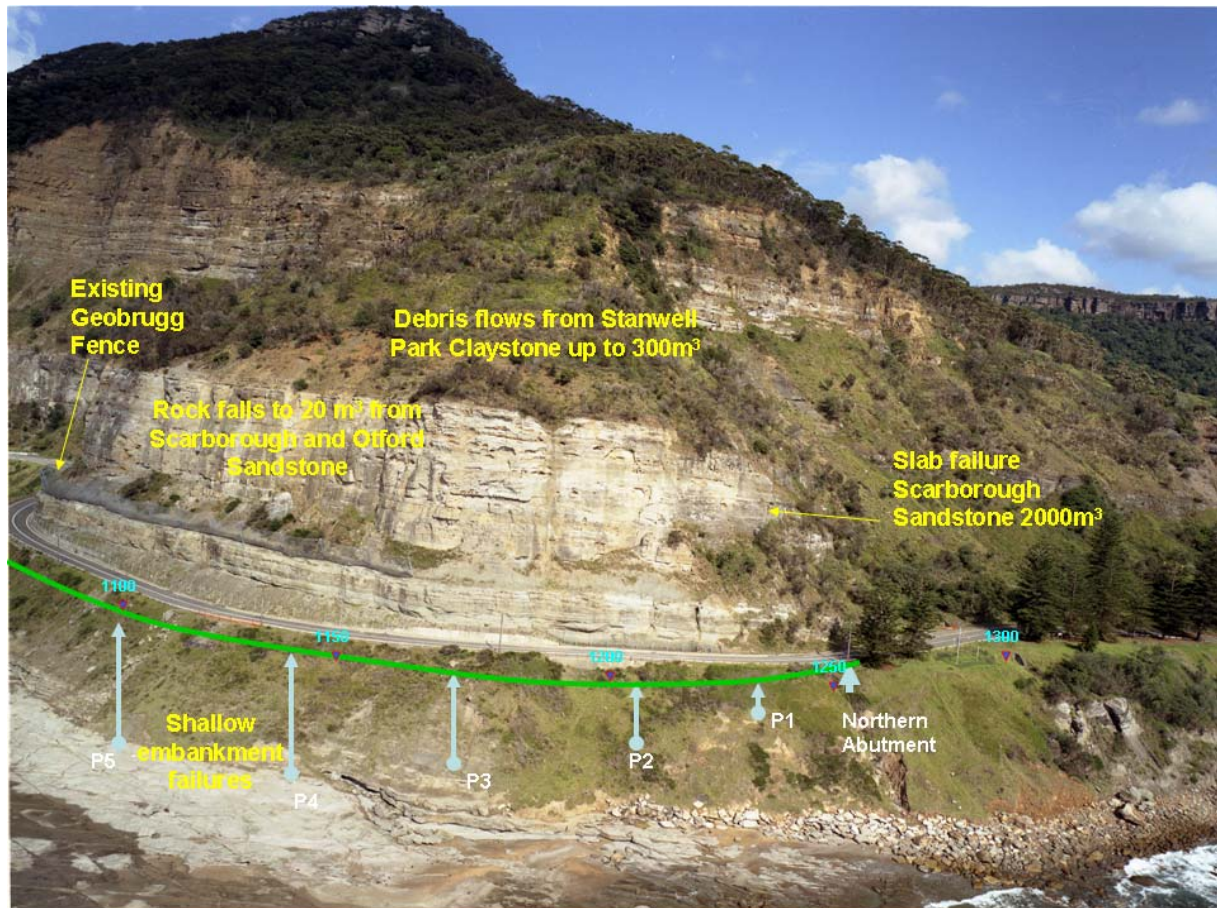


Figure 3. An oblique aerial photograph of Geotechnical Domain GD3 and part of GD4.

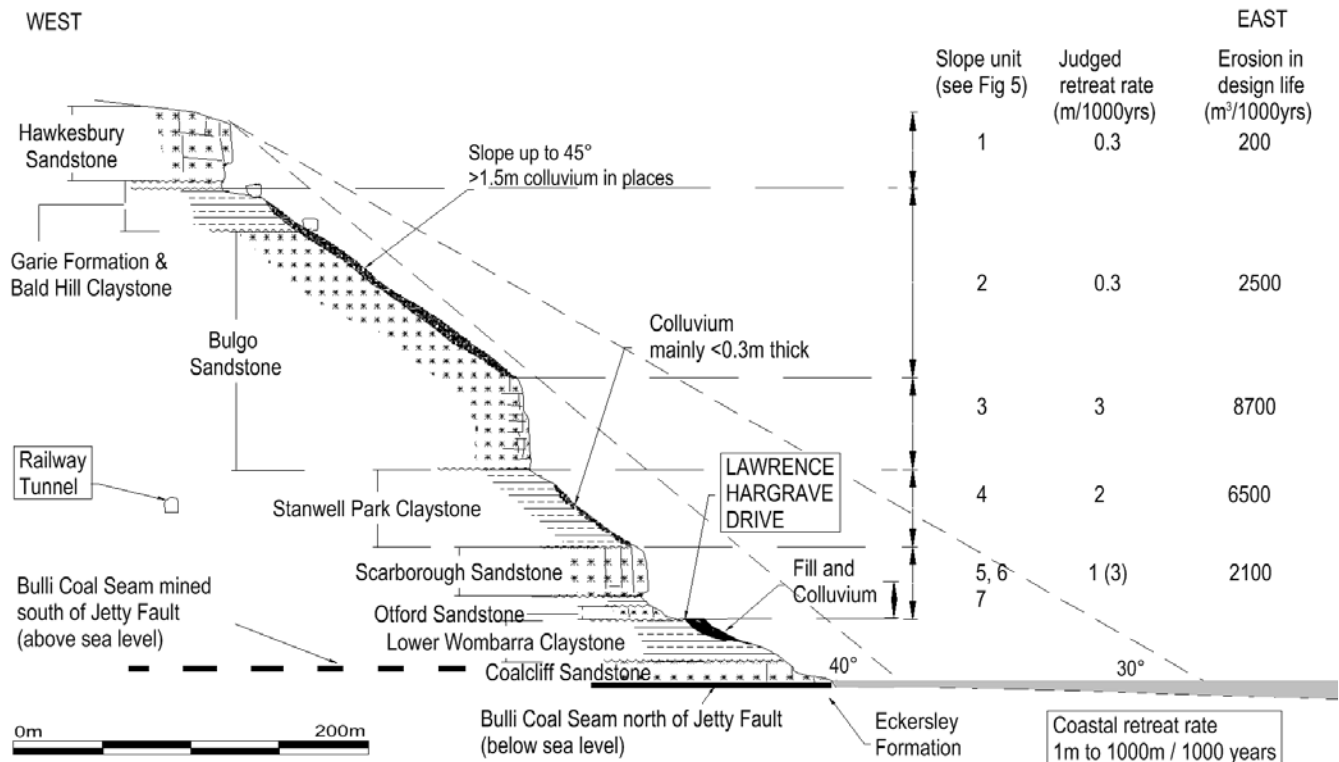


Figure 4. Cross section through GD2 that illustrates the landforms, geology and slope retreat rates

2 LANDFORMS AND GEOLOGY

Over the closed section of the road (the site), there are three headlands separated by two bays. These features have been used to separate the site into five geotechnical domains (Fig. 1):

- GD1 - Southern Headland
- GD2 – Southern amphitheatre (Bay)
- GD3 – Middle Headland
- GD4 – Northern Amphitheatre (Bay)
- GD5 – Northern Headland.

The geology of the site is described by Hendrickx et al. (in prep.). In brief, the bedrock geology comprises a thick sequence of sandstone and claystone units of Permian to Triassic age that generally dip between 0° and 5° to the northwest (i.e. obliquely inland). The sandstone units within the succession form prominent, sub-vertical cliffs, whilst the claystones form the intervening slopes. Figure 4 illustrates the relationship between the bedrock geology and these Slope Units.

Superficial deposits of colluvium derived mainly from debris flows and rock falls mantle the lower angled claystone slopes, and form fan-shaped deposits up to 40m thick in the two amphitheatres (GD2 and GD4).

The most prominent structural features in the area are two well-developed, vertical to sub-vertical joint sets, which strike 040° and 180°-190°. Other important structures are a series of normal faults that affect the stratigraphy.

3 SLOPE HAZARDS

The slope hazards are described by Hendrickx et al. (in prep.). The hazards are distributed over all parts of the escarpment from the crest (up to about 300 m above the existing road) to the coast (Figs 2-4). Most landslides from the cliffs consist mainly of rock (from single boulders to large masses), whereas most of the landslides from the intervening slopes consist of debris (mixtures of soil and rock).

Typical slope failure mechanisms from the intervening slopes include debris flows and slides. The steeper slopes are also vulnerable to erosion by running water while both cliffs and slopes are vulnerable to coastal erosion at sea level.

The main landslide hazards to road users are:

- *Rock falls/boulder rolls* from the Bulgo and Scarborough Sandstone cliff lines, landing on the road by rolling, directly by falling or subsequently by rolling and falling, when released from talus accumulations on the Stanwell Park Claystone slope. The boulders within the Hawkesbury Sandstone cliff can contribute boulders up to 20m wide to the hazard profile as well as provide boulders that rest on the steep slope above the Bulgo Sandstone cliff.
- *Debris or Boulder Flows* can be derived from the intervening slopes between the cliff-lines and represent remobilization of talus deposits

or failure of in situ material on the Stanwell Park Claystone slope, and also less frequently the Bulgo Slope. Boulder flows can also be derived from the Bulgo cliff where numerous boulders move down slope as a “river of boulders”.

- *Road embankment failure by toe erosion by the sea* and loading to embankment crown with man-made fills or through landslide debris accumulation.

Whilst most landslides are triggered by intense rainfall (annual rainfall about 1500mm), the slope processes are being accelerated by marine erosion that is over-steepening the slopes below the escarpment (Hendrickx et al., in prep.). In simple terms, marine erosion is removing the Bulli Coal Seam, which leads to toppling failures of the overlying Coalcliff Sandstone. This in turn leads to oversteepening of the overlying Wombarra Claystone that fails by landsliding. And so the process is repeated up the slope to the Hawkesbury Sandstone forming the cliffs at the crest of the escarpment. The processes are further driven by differential erosion and undercutting of the claystone intervals within the major sandstone units, and these lead to rock falls from the sandstone units. Excavation to form the road has both removed material from the Wombarra Claystone, and resulted in accelerated regression of the Wombarra Claystone, and subsequently the Otford and Scarborough Sandstones.

4 RISK ASSESSMENT FRAMEWORK

4.1 *Project slope risk to life criterion*

The LHD Link Alliance Agreement had a minimum risk to life assessment criterion relating to slope instability of ARL3 as defined in the RTA “Guide to Slope Risk Analysis Version 3.1” (Stewart, et al 2002). Furthermore, the ARL3 criterion applied to the entire project. That is, the sum total of all the slope risks to life on the site must be less than ARL3, not just the slope risks at individual locations. The Assessed Risk Level (ARL) rating for the road prior to remediation was judged to be ARL1.

The ARLs determined using the RTA Guide are derived from “rules” to rate qualitative descriptive phrases describing the likelihood and consequences of slope hazards, which are then combined using matrices to give the Assessed Risk Level. The RTA Guide is based on an underlying quantitative framework and this framework is reflected in the “rules” and the matrices used to assess the risk (Baynes, et al 2002).

There are five ARL levels ranging from ARL1 (highest risk level) to ARL5 (lowest risk level). The median quantitative probability of a fatality implied by the ARL levels have been judged to be roughly one order of magnitude apart with ARL1 roughly equating to an annual probability of death of $>10^{-3}$ and ARL5 roughly equating to an annual probability of death of $<10^{-6}$. ARL3 roughly equates to an annual loss of death of 10^{-5} . The Alliance agreement did not address the risk to property using the ARL criteria. Such risks were addressed as “whole of life costs”.

In order to define practical differences between the differing ARL levels, it was agreed at a project QRA Workshop that the ARLs would be defined for the project as shown in Table 1.

Table 1. Assessed risks levels

| Assessed Risk Level | Annual probability of death |
|---------------------|--|
| ARL3 | 3×10^{-5} to 3×10^{-6} |
| ARL4 | 3×10^{-6} to 3×10^{-7} |
| ARL5 | $< 3 \times 10^{-7}$ |

4.2 *Previous quantitative slope risk assessments*

Previously, two quantitative slope risk assessments had been conducted for the site (GHD-Longmac Pty Ltd, 2002 and URS Australia Pty Ltd, 2003).

The GHD-Longmac assessment used the RTA’s record of landslide events between March 1996 and November 2001, and selected events in 1988/1989, to conduct quantitative risk assessments of the site in mid-2003 in terms of total (societal) risk, and of individual risk to a bus commuter.

The URS report used the same record of landslide events with a slightly modified event-tree approach to verify the GHD-Longmac results. The URS report also provided separate analyses of the total risk for the individual domains for the site prior to the works in mid 2002 and the site in mid 2003.

The results of these analyses are summarised and discussed in Section 8 of this paper.

4.3 *Adopted risk assessment approach*

This study used a different approach from GHD-Longmac and URS when considering the likelihood of landslides impacting on the road. Specifically, this study used procedures discussed in Moon et al. (in prep.) to develop landslide size frequency models for each of the “slope units”.

These models were used to summarise and present judgements, knowledge and evidence on the type, size, frequency and volume of future landslides on site.

5 LANDSLIDES – HOW LIKELY

5.1 Adopted size frequency distribution of landslides

The size frequency distribution of landslides from a slope unit depends on the surface form of each slope unit and the underlying geological materials. Figure 5 shows size frequency curves that indicate the adopted number of events for each "order of magnitude" size distributions for hazards emanating from each Slope Unit (Moon et al, in prep.)

The curves have been normalized to show the size and frequency of landslide debris passing 100 m of road in the design life (100 years). The normalization was done to simplify the data handling in the risk assessment, but had the added advantage that the curves could be directly compared and differences noted. The normalization of the curves involved estimating the design life landslide yield of the slope unit as a proportion of the design life erosion yield, and using this volume to proportionally adjust the raw curve.

The process rate model adopted in this study assumes there is no net deposition on the site. That is, the material eroding from each slope unit will cross the road by landsliding or some other erosion process. But, the model does not assume that all debris from each and every landslide crosses the road each time there is a landslide.

5.2 Percentage of landslides reaching the road

The percentage of landslides (and percentage of debris from individual landslides) reaching the road depends (amongst other factors) on the size and nature of the landslide, the distance and travel angle to the road, and the presence of deposition areas along the flow path. Material that does not pass the road in the first instance locally accumulates on flatter slopes before eventually failing from these slopes.

For example, most landslides (i.e. rock falls) from the roadside cliffs will reach the road, and most of the debris of such landslides will also reach the road (as opposed to depositing on the cliffs). In contrast, many landslides from the other slope units do not directly impact on the road, and of those that do, not all debris reaches the road.

6 ELEMENTS AT RISK AND CONSEQUENCES

6.1 Who could be affected

The annual average daily traffic along LHD in the years from 1986 and 2000 (excluding periods when the road was closed for works) ranged between 2,200 and 3,400 vehicles (mostly cars) per day. This study adopted 4,000 vehicles per day, referred to in the calculations as 2,000 vehicles per lane per day.

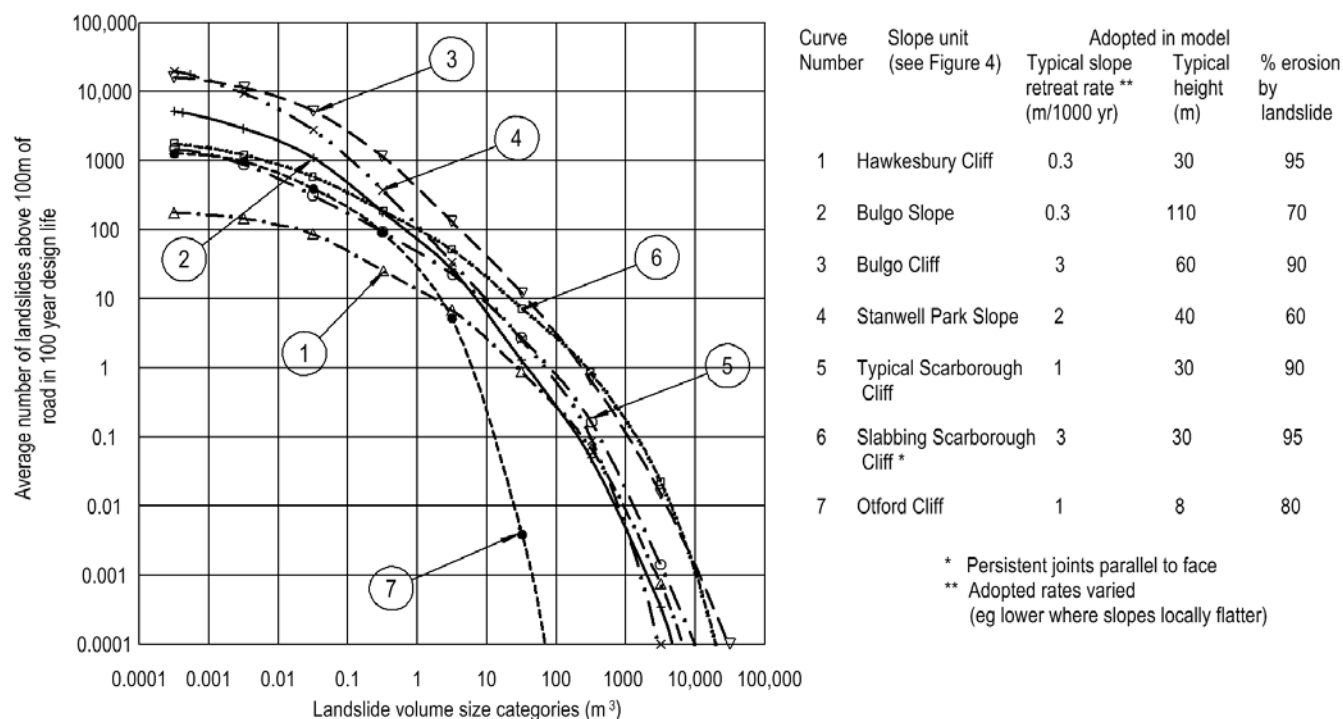


Figure 5. Adopted size frequency models for the various slope units.

Experience in Australia and elsewhere indicate that injuries or deaths could occur on the road as a result of

- Vehicles running into landslides; or
- Vehicles being hit by landslides; or
- Vehicles involved in collisions while swerving to avoid landslides; or
- Vehicles running into the voids created by landslides.

Other events, or combination of events for which it is difficult to predict the likelihood could occur which can result in accidents, injuries or damage. Examples include:

- Rockfall onto people sheltering near a cliff.
- A vehicle hitting a structure damaged by a landslide.
- A vehicle trapped by landslide debris, or otherwise stationary, getting hit by a subsequent landslide event.

Historical research (Hendrickx et al., in prep.) indicates that there has been one death probably attributable to a landslide in the project area. This death occurred when a car ran-off the road after probably hitting a developing embankment failure. There have been a number of close calls associated with vehicles being hit by quite large falling rocks, and RTA experience suggest many minor incidents did occur and these went unreported.

6.2 Vulnerability of persons

The vulnerability of road users to a landslide depends, amongst other matters, upon the type, speed and size of the landslide, the type and size of the landslide debris, whether the person is in the open or enclosed in a vehicle, and the speed and type of vehicle.

The vulnerabilities adopted for the project were based Stewart et al (2002) and AGS (2000), modified by the knowledge and experience of the geo-technical team in a workshop.

Two levels of vulnerability were considered, namely:

- 1) The vulnerability of persons in a car (or similar size vehicle) directly hit by a landslide, which is higher if the landslide debris falls vertically onto a car from the crest of a cliff compared to a landslide moving horizontally and hitting the side of a car.
- 2) The vulnerability of persons in a car that runs into a landslide.

The underlying assumption in these vulnerabilities is that the landslide reaches the road 40m or less in front of the car and the driver of the vehicle does not have time to avoid collision. The 40m dis-

tance is based on a 2 second response time at the posted road speed of 60 kph, plus an allowance for braking and avoidance (to avoid death but not necessarily car damage).

Some of the vulnerabilities adopted for this project are given in Table 2.

Table 2. Some adopted vulnerabilities for some landslide events

| Order of magnitude of landslide crossing road (m ³) ⁽¹⁾ | Rockfalls from Scarborough Cliff | | Debris flows from GD4 | |
|--|----------------------------------|--------------------|-----------------------|--------------------|
| | Landslide hits car | Car hits landslide | Landslide hits car | Car hits landslide |
| 0.03 | 0.05 | 0.0006 | - | - |
| 0.3 | 0.1 | 0.002 | - | - |
| 3 | 0.3 | 0.03 | 0.001 | - |
| 30 | 0.7 | 0.03 | 0.01 | 0.001 |
| 300 | 1 | 0.03 | 0.1 | 0.003 |
| 3,000 | 1 | 0.03 | 1 | 0.003 |

⁽¹⁾ Not all events sizes considered are shown in this table.

7 ASSESSMENT OF THE EFFECTIVENESS OF THE RISK MITIGATION MEASURES

In order to make quantitative judgments about the risk associated with the proposed works, it was necessary to make judgements about the effectiveness of engineering works that have been conducted on the site to date, as well as the effectiveness of those works that are proposed for the site.

7.1 Existing risk mitigation measures

There had been an extensive history of construction of risk mitigation measures along the road (Hendrickx et al., in prep.). The last series of works conducted prior to the road closure were conducted in late 2002 and cost about \$A3.5m. These works included substantial enlargement of the catch ditch in the southern half of GD2, the construction of a Geobruigg fence in the southern half of GD3, as well as scaling and the installation of rock bolts in GD1, GD3 and GD5.

Based on field observations of these works and some subsequent computer modelling using the commercially available packages “Rockfall” and “DAN-W”, it was judged that the effectiveness of the catch ditch and Geobruigg fence, in terms of the QRA, were as follows:

- The catch ditch in the southern half of GD2 trapped 99.9% of <0.3m³ events, 99% of 3m³ events, 95% of 30m³ events, 70% of larger events.
- In GD3 - Ch1000 to 1150 – The Geobruigg fence and associated works trapped 99% of

<0.3m³ events, 95% of 3m³ events; 90% of 30m³ events, 70% of larger events.

The impact of the scaling, the rock bolts and other pre-2002 works were included in judgements about retreat rates for particular slopes.

7.2 Proposed risk mitigation measures

In order to reduce the risk to road users to the required level, and to reduce construction risks, it was decided to bypass all of GD2 and GD3, and most of GD1 with two bridges. A 455m long balanced cantilever bridge will span the area between GD1 and GD3, and a 210m long incrementally launched bridge will bypass GD3. The bridges largely avoid hazards due to rock falls, debris flows and embankment failures in these zones.

The road returns to the current alignment with minor modification at the southern end of GD4 where slope stabilisation measures are being constructed. A debris containment bund is being built to address the debris flow and rock fall hazards in GD4. Slope stabilization measures including draped mesh, rock anchors and rock fall fences are being built to address rock falls in GD5 and part of GD1.

Where it was judged the slope stabilization measures would intercept almost all events, an effectiveness of 99.9% was adopted for analysis purposes. Also, the analyses assumed that the Armco barrier along the side of the road would be maintained.

The bridge piers are exposed to lesser hazard than the current road because of the differing exposed length (i.e. about 140m versus 600m), and their greater distance from the cliff.

The effective exposed length of the piers to each slope unit is greater where the landforms funnel landslide debris towards a pier, and the exposed length is less where the landforms direct debris away from the pier. In the analyses, the effective exposure lengths were estimated by using flow paths from each of the slope units.

The distance of the piers from the cliff have been taken into account by adopting lower percentages of both landslides and debris from each landslide reaching each pier. A conservative vulnerability of 0.1% was assigned for the purposes of estimating the risk of life associated with a large landslide impacting on a pier.

8 RISK ASSESSMENT

8.1 Mechanics of the risk assessment

In the study, the calculations were carried out using an Excel workbook composed of 59 linked spreadsheets. A separate worksheet was prepared for each hazard type in each part of each geotechnical domain and the results from each of these sheets presented on a linked summary spreadsheet. The layout of the worksheets is outlined in Figure 6.

In mathematical terms, the risks to road users were calculated in the spreadsheet models using the following three expressions (adapted from AGS, 2000, Reference 5):

$$R_D = P_s \times V_D \quad (1)$$

$$P_s = 1 - (1 - P_{S:H})^{NR} \quad (2)$$

$$P_{S:H} = (N_v \times L \times N_L) / (24 \times 1000 \times V_v) \quad (3)$$

Where:

- R_D = annual probability of death.
- P_s = probability of a car being hit by or hitting a landslide.
- V_D = vulnerability of the individual (probability of death) given the landslide impact on the car.
- $P_{S:H}$ = probability of spatial impact of the landslide on the road given the event.
- NR = annual number of landslides reaching the road.
- N_v = number of cars per day per lane.
- N_L = number of lanes affected by the landslide.
- L = length of the car (assumed to be 5 metres) or the reaction distance (as appropriate). A reaction distance is taken as 40 m allowing some slowing and swerving.
- V_v = velocity of the car in km/hr (assumed to be the posted speed limit of 60 km/hr).

The four cases considered in this study were:

- *CASE A* for the road prior to mid 2002 without any remedial measures.
- *CASE B* for the site in the period late 2002 to late 2003, including the effect of the Geobrigg fence and the catch ditches in GD2 and GD4.
- *CASE C* for the projected effects of the bridges, but without any other works.
- *CASE D* for the projected effects of the works including the proposed bridges and making assumptions about the effectiveness of the proposed geotechnical works elsewhere.

Those simplifications that have been directly included in the QRA are discussed in Sections 5, 6 and 7. Other simplifications that were not directly included in the QRA included:

- Falling rocks not landing on or staying on the road.
- Variations in the number of vehicles during the day.
- Adopted length of the vehicle and width of the landslide.
- Variations in how the persons in the vehicles are impacted.
- Buses.
- Heavy Vehicles.
- Sight distances.

Based on the results of the earlier QRAs and preliminary work conducted as part of this study it was judged that the effects of these items would produce second order variations in the outcomes of the QRAs for total risk if they were included. That is, individually they may result in variations of less than half an order of magnitude in the outcome of the risk analyses. Furthermore, because some of the effects are conservative and some are non-conservative, it was judged that not including these effects would not significantly alter the outcome of the QRA.

8.4 Road closures

The QRA workbooks were also used to assess the

number of days of unplanned closures for the road (as opposed to planned road closures for routine maintenance and programmed repairs).

This assessment was conducted by combining the number and size of landslides impacting upon the road from the risk portion of the workbooks with judgements on times the road could remain closed if the events happened.

9 DISCUSSION

9.1 Advantages of the adopted approach

The advantages of using the adopted approach included:

- The quantitative approach reflected the underlying basis of the RTA slope risk system.
- The large number and variety of landslides throughout the project could be addressed relatively easily.
- The “sum total of all the slope risks to life” project criterion could be simply addressed by summing the component risks.
- The component parts of the assessment were stated and hence could be more readily reviewed.
- The outcomes of the quantification could be interpreted in terms of the project ARL3 criterion (using Table 1), as well as other available risk assessment criterion.

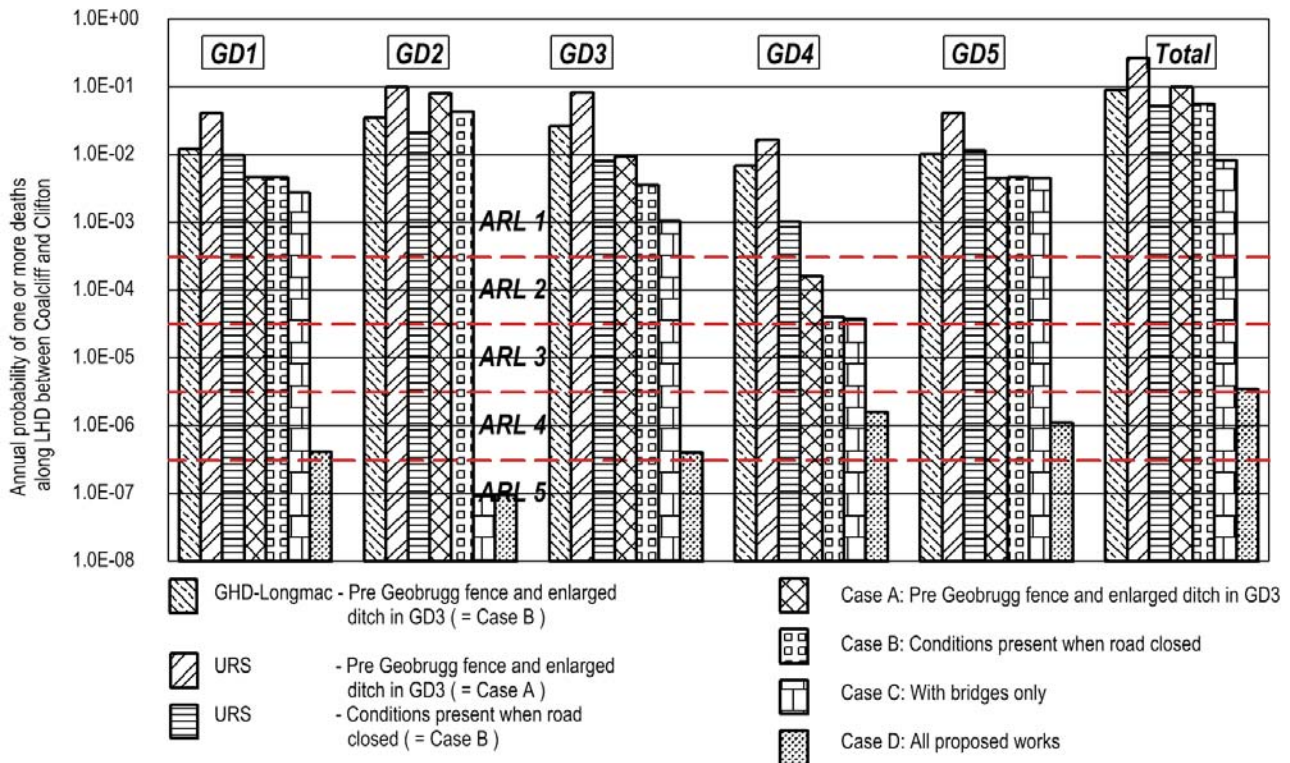


Figure 7. Summary of the results of the quantitative risk assessment calculations.

9.2 Are the results of the QRA credible?

This study judged that the annual probability of death along the road (Case B) immediately prior to closure was about 1 in 18, and this risk was dominated by the 1 in 23 risk associated with GD2. For this case, the annual probabilities of death for the other domains were less than 1 in 100.

These judged risks were comparable with the history of the site, which suggests only one death potentially attributable to landsliding and a number of close calls. These risks were also comparable with those assessed by GHD-Longmac and URS for the same road conditions, but using differing assumptions.

A further check on the credibility of the results was made by comparing the results for selected hazards across the site with results from a semi-quantitative risk assessment for the same hazards using the procedures described in Stewart, et al, (2002). The results of these checks showed comparable results.

10 WHAT WE LEARNED

1. Whilst the risk calculations were carried out numerically, significant judgments were required to provide many of the input parameters. As a consequence, the reproducibility of the QRAs are typically to an order of magnitude or more regardless of method (Stewart, in prep.).
2. QRAs should be used to facilitate risk decision-making by providing comparisons and those comparisons will always be approximate (Christian, 2004). Cut-off points for remediation and management plans have to reflect this reality (Stewart, in prep.) and, as always for ground engineering projects, robust engineering solutions need be adopted.
3. QRA is an indispensable tool to address multiple hazards and multiple consequences such as present on the LHD site because QRA provides a structured framework for collecting and presenting landslide information, and making risk decisions. QRA allows the large number and variety of landslide hazards to be addressed, and it allows the component parts of the QRA to be explicitly stated and reviewed.
4. QRA is a tool to use in conjunction with conventional slope analysis methods, which in the LHD study included rock fall, rock toppling, debris flow, and circular and planar sliding slope modelling and analyses.
5. It is difficult to assess the credibility or otherwise of a QRA because, as stated by Ho et al.

(2000), “*much judgement is involved which can be difficult to substantiate and there is considerable room for disagreement.*” Although, as also discussed by Ho et al., similar issues are often faced when using other slope assessment methods.

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