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The Rockfall of Huzzas Cliff, Gracetown, Western Australia

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Summary On the 27th of September 1996, four adults and five children died in a rockfall at Huzzas Beach, Gracetown. They were sheltering from rain under a large overhang at the base of a limestone cliff while watching a surfing carnival, when the cliff collapsed without warning. The rockfall was 10m high, 20m wide and about 4m thick and produced some 1,440 tonnes of rubble. The cliff consists of four bands of weakly lithified eolianite with interbedded paleosols and calcrete caprock layers overlying a rock platform of boulder conglomerate and marine limestone. The overhang was 3m deep and 3m high and was roofed with calcrete caprock. Widely separated calcrete infilled vertical 'joints' formed discontinuities. The limestones can absorb up to 40% moisture and driving rainfall provided the trigger for collapse. The rockfall has been analysed as the failure of a cantilevered beam. The maximum bending stress in the dry was 40kPa, and when wet, 48kPa. Failure occurred when the bending stress equaled the reduced tensile strength of the No. 3 caprock layer. The factor of safety when dry was about 1.4.

1. INTRODUCTION

Coastal limestones consisting of eolianites, beachrocks and marine beds are developed on the West Australian coast from Broome to the South Australian border over some 1200km. Eolianites consist of wind blown sand cemented by calcium carbonate under subaerial conditions. Beachrocks consist of sand and gravel lithified in place. On the Leeuwin-Naturaliste coast of WA (Figure 1) marine limestones and a boulder conglomerate are present at the base of the eolianites which range in age from Last Interglacial to Last Glacial (130,000 YBP to 17,000 YBP). These rocks on the westerly facing shores have been exposed to marine erosion for the last 7,000 years and now form some spectacular cliffs with overhangs and sea caves. Inland, karst weathering of older coastal limestones has produced notable caves and dolines. Limestone cliffs and karst are transient features of the landscape.

2. THE EVENT

On the afternoon of Friday the 27th of September 1996 a group of adults and children from Margaret River and Cowaramup Primary Schools were watching an inter-school surfing event in Cowaramup Bay, adjacent to the coastal settlement of Gracetown on the Leeuwin-Naturaliste coast of Western Australia (Figure 1). Because of heavy rainstorms a group of 12 people, including the judges took shelter at the base of a 14m high limestone cliff known as Huzzas where a prominent overhang provided cover.

About 2:45pm some of the young surfers and other spectators in the vicinity heard a loud crack and saw the spectator group disappear under a cloud of sand and rubble as the limestone cliff collapsed. The rockfall buried and killed nine people - four adults and five children - and one person was injured.

Rescue work was hazardous and was initially by hand digging with boulder removal by ropes, and when that became too dangerous a front end loader was brought in.

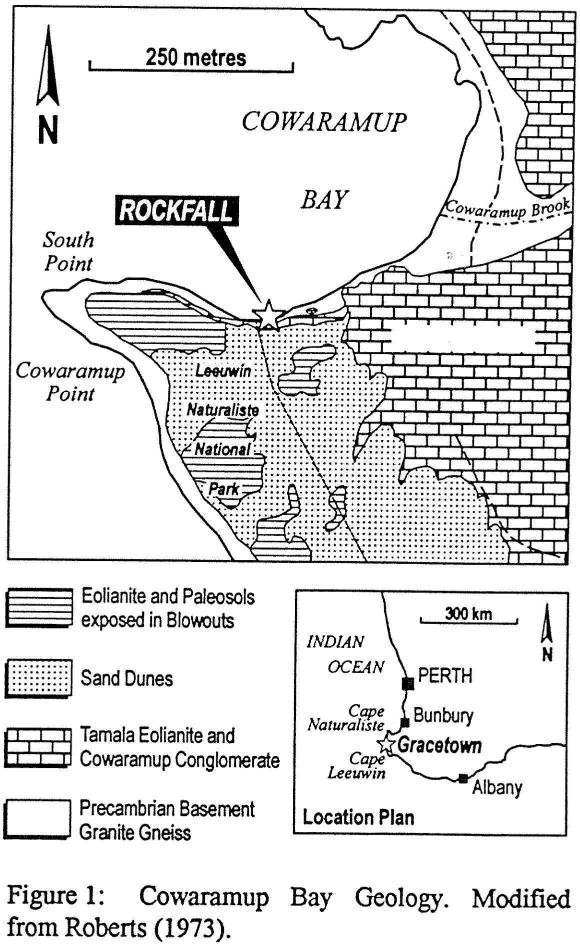

Figure 1: Cowaramup Bay Geology. Modified from Roberts (1973).

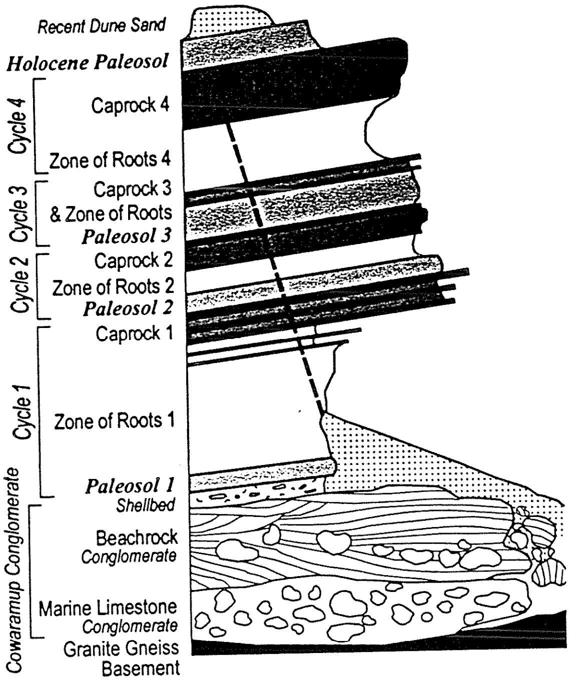

Figure 2. **Cowaramup Bay Rockfall** *Diagrammatic Cross Section before 2.45pm 27/9/1996*

One young girl, who was buried under a metre of sand and rock rubble for about 90 minutes, survived because of the presence of an air pocket, and was dug from the debris, virtually unhurt. Rescue work was completed late on the Friday night.

The rockfall included four cycles of eolianite and fossil soils which made up all of the cliff face except for the surface caprock layer (Figure 2). The rockfall was some 10m high and about 20m wide and was up to 6m deep, with an average depth of about 4m. The back scarp or plane of separation of the rockfall was planar (Figure 4). The rockfall contained about 720m^3 of rock and sand, or about 1,440 tonnes of rubble. The weaker layers broke down to sand during the rockfall movement.

A coronial inquiry took place in May 1997. The Coroner found the deaths were accidental. The driving rainfall which caused the people to seek shelter was the trigger for the collapse. (Gordon, 1997) The Coroner added riders that authorities responsible for cliff areas should monitor the potential hazards of rockfalls and should work together so that potential risks can be effectively managed. A minimum response to danger areas would be to erect warning signs and in some cases direct action would be required.

3. GEOLOGICAL SETTING

3.1 Cowaramup Bay

Cowaramup Bay is a rocky indentation into the Leeuwin-Naturaliste coastline (Figure 1). The Bay is floored with ancient (Archaean) basement rock of granite-gneiss which also forms cliffs and headlands on the north side of the bay.

3.2 Cowaramup Conglomerate

On the south side of the bay overlying the basement with a vast unconformity there is a basal conglomerate of Late Pleistocene age consisting of rounded granite-gneiss boulders up to 1m across cemented into a strong white marine limestone with pockets of shells. This is overlain by a 2.6m thick conglomeratic beachrock enclosing small rounded boulders of granite gneiss. Freshwater springs occur on top of the weathered basement rock surface.

A 0.4m thick bed of soft uncemented calcareous sand with abundant shells, lies on top of the strong beachrock and conglomerate bands. The overlying 0.3m thick fossil soil layer is also weak to very weak in strength.

The conglomerate, marine limestone, beachrock and shell bed make up the Cowaramup Conglomerate of Fairbridge and Teichert (1952) with an age of 100,000 years [Stage 5c]. The conglomerate and beachrock bands are exposed in a 2.8m high rock platform, some 4m deep. Rock platforms are horizontal, nearly level limestone features cut by bio-erosion of molluscs, limpets and chitons and by marine erosion and corrosion. This raised beach was left exposed when sea level fell 2.8m about 5,000 years before present. The rock platform forms a buttress at the base of the cliff and protects it from direct wave attack.

3.3 Tamala Eolianite and Fossil Soils

The eolianite and paleosol bands making up the upper and main part of Huzzas Cliff and the Cowaramup Conglomerate are members of the Tamala Limestone Formation which is better described as Tamala Eolianite. It is a medium to coarse grained, cross-bedded eolian calcarenite composed mostly of fragments of molluscs and foraminifera with some detrital quartz grains. The eolianite has formed in series of multiple dunes generally with the youngest on the present sea coast and aging inland. The seacoast limestone is not lithified to the extent that inland eolianites have reached, and intergrain space is higher and strength is lower compared with the more mature eolianites in the inland ridges.

Table 1 Coastal erosion of limestone

LIMESTONE IS A SOFT ROCK THAT WILL DISSOLVE IN WEAKLY ACIDIC WATER

- RAINFALL
- SEA SPRAY
- SEAWATER
- GROUNDWATER

IN ADDITION, THERE ARE THREE OTHER POWERFUL AGENTS FOR CHANGE:

1. MARINE EROSION

- Notching
- Undercuts – bioerosion
- Seacaves
- Spray impact and erosion
- Salt crystallisation
- Hydraulic impact
- Pneumatic effects
- Abrasion

2. SUBAERIAL EROSION

- Wind, rain and trees
- Soil slotting
- Sand blasting
- Rainfall solution
- Rainfall impact
- Rainfall weight
- Soil and root zone. CO_2
- Root wedging

3. HUMAN ACTIVITY

- Occupation and shelter use
- Dislodging rocks and sand
- Removing vegetation – blowouts
- Traffic exposing new faces
- Digging – sand and fossils
- Lighting fires under overhangs
- Quarrying

The Tamala Eolianite at Huzzas Cliff has a basal paleosol soil band overlain by four separate cycles of eolianite deposition, separated by thin fossil soil layers. These make up the 12m high main cliff face.

The eolianites consist of limesand cemented by calcium carbonate, and they show characteristic steeply dipping and cross-bedded and horizontal laminae of alternating fine and coarse grained bands. The top of each of the three eolianite bands shows weathering features as a consequence of sub-aerial exposure before the next wind blown layer was emplaced. Exposure has allowed the formation of fossil soils and has formed a calcrete enriched surface layer known as caprock or duricrust with an underlying carbonate depleted, layer. This is known as the 'zone of roots', because hard calcrete casts or molds of plant rootlets are left prominently displayed, as the leached limestone is very friable and weathers away under the strong caprock. At the cliff top the 1.4m thick, strong caprock zone shows some vertical solution tubes where tap roots of eucalypts have formerly been growing, indicating a relatively long period of exposure compared with the underlying caprock bands which are thinner and consist mainly of sheet calcrete.

The fossil soils (paleosols) are up to 1m thick and are pale brown coloured with a humic content of up to 2.5%, and have shells of land snails and calcified weevil cocoons. The paleosols are made up dominantly of fine grained carbonates, and are classified as rendzina soil types (Fairbridge and Teichert, 1952).

The cliff face was made up of 10 subhorizontal bands of calcareous rock (Figures 2 and 3) with widely differing strengths and porosities. The bands have a certain degree of coherence gained during diagenesis. The outer surface of the cliff showed grey coloured case hardening except where erosion is active (lower overhang) and the colour is yellow (Figure 3). Eolianite limestones have sparse natural joints which are vertical, and are usually parallel to the cliff face or less frequently, at right angles to it.

4. COASTAL PROCESSES OF EROSION

On a sea coast there are many agents of change and erosion. Nothing remains the same on a coastline, but for a limestone cliff the changes are dynamic because of its variability and particular vulnerability to solution. The forces for coastal change are summarised in Table 1.

5. RECENT GEOLOGICAL HISTORY

Huzzas cliff face with a notched marine undercut emerged some 5,000 years ago. Particular events since then include a blowout on South Point which was caused by the removal of vegetation during a hot bush fire and which has supplied loose sand for sand blasting. Human activity in using and trafficking the overhung basal shelter has accentuated the effects of wind and spray erosion. Severe winter storms of 1996 undoubtedly affected the cliff and increased the size of the overhangs.

In early 1996, a secondary school group examined the cliff and took several photographs including the bottom overhang (Figure 3). These photos show two vertical 6m long parallel joints at right angles to the cliff face located on the east side about the eastern margin of the rockfall. One of the joints was filled with calcrete. The other some 2m distant shows breakage of the calcrete infilling and some erosion has occurred, indicating initial settlement of the block to the west i.e. in the rockfall area.

6. ROCKFALL CLASSIFICATION AND MECHANISM

6.1 Rockfalls

In a rockfall the moving mass travels through the air by free fall. Movements are very rapid to extremely rapid, and may or may not be preceded by minor movements.

Figure 3: Rockfall area, overhang with sheet calcrete caprock, vertical joints LHS.

Distinctions have been made in the type of rockfall (Selby, 1993):

(i) rockmass falls,
(ii) rock slab and block falls,
(iii) rock particle falls.

6.2 Rockmass Falls

Rockmass falls are by definition failures of large bodies of material, likely to be internally jointed but which separate from the cliff on a single or stepped failure plane. For a fall, the inclination of the face is likely to be in excess of 80°. This is a rare situation and rockmass falls are commonly found on undercut sea cliffs or the walls of glacial cirques or on sites undercut by rivers. (Selby, 1993)

6.3 Slab and Block Failures

Slab and block failures are common on undercut rockfaces on sea cliffs or in valleys. The overhanging block remains stable until the tensile strength of the rock on a plane extending upwards from the back of the undercut is insufficient to support the overhanging mass. Tension cracks may form subvertically until the tensile strength of the last beam is exceeded.

Slab failures frequently leave overhanging roofs above the failure plane (Figure 4) and this may become a site for further slab failure (Selby, 1993). The Gracetown rockfall fits into the category of a slab failure with a well defined, planar separation face and a large overhanging roof left after the rockfall (Figure 3).

6.4 Mechanism and Timing

The overhanging block of a slab type failure can be analysed as though it was the cantilevered end of a beam protruding from the cliff face (Figure 4).

With such a cantilevered beam a bending stress acts as a tensile stress on the top half of the protrusion and as a compressive stress on the bottom half. (Maekado, 1990).

The maximum bending stress, $\sigma_{b,\max}$, is given by:

$$\sigma_{b\,\max} = M/Z, \qquad (1)$$

where M is the bending moment, and Z is the modulus of section;

$$M = {}^{1}/_{2}\, ybhl^{2} \qquad (2)$$

and

$$Z = {}^{1}/_{6}\, bh^{2}, \qquad (3)$$

where y is the unit weight of the overhang material, here about 15kN/m^3, (dry)
b is the horizontal dimension of the beam parallel to the cliff face, here 20m,
h is the height of the rockfall or beam thickness, (10m),
l is the overhang (distance the beam protrudes), (3m).

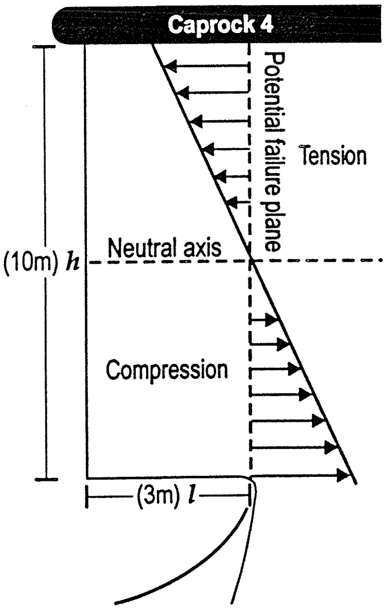

Figure 4. **Stresses acting due to self-weight on a protruding, rectangular, unjointed body of rock or soil.** *(after Selby 1993)*

$$M = \frac{15 \times 20 \times 10 \times 3^2}{2} = 13500\text{kNm}$$

and

$$Z = \frac{20 \times 10^2}{6} = 333\text{m}^3$$

$$\frac{M}{Z} = \frac{13500}{333} = 40\text{kPa}$$

The overhang is stable until the bending stress on the top surface becomes equal to the tensile strength σ_t: the critical value of the overhang distance is then given by:

$$l_{crit} = \sqrt{\frac{h\,\sigma_t}{3y}} \qquad (4)$$

[Matsukura (1988), Maekado (1990)]

The critical tensile strength of the saturated rock mass in the beam will be the tensile strength of the strongest band or layer in the rockfall. This will be that of Caprock 3. The top caprock (Caprock 4) is the strongest in the cliff and did not fail.

For the wet or saturated conditions that prevailed at the time of collapse when the unit weight was increased to 18kN/m^3 and the strength of the caprock was reduced from that of its dry state, then the bending moment M, is 16200kNm, and Z the modulus of section is the same as for dry conditions (333m^3) so the maximum bending stress is 48kPa. Failure then occurred.

The tensile strength of the Caprock 3 layer in the rockfall can also be determined by back analysis, as the critical overhang distance is known to be 3.0m; then from equation (4) σ_t = 48kPa (sat).

The strength of eolianites is intensely proportional to the porosity. Strength is also lowered by the presence of liquid in the pores. At a porosity of 8% which is realistic for the No. 3 Caprock the Unconfined Compressive Strength of dry samples is 40% higher than that of saturated samples. The point load index strength for the same porosity is 55% higher for dry samples as compared with saturated samples (Djakamihardja, 1992).

Unfortunately the test samples were dried back from the saturated state which would introduce case hardening which is the formation of carbonate cement. The dry tensile strength will be higher than that of the saturated rock from the back analysis of the cliff failure. The minimum factor of safety when dry is 1.8 / 1.5 = 1.2, i.e. the ratios of the wet and dry unit weights.

If the point load index figures at a comparable density are applied, less an allowance for case hardening, the factor of safety could be of the order of 1.4. As the rainfall increased the unit weight of the rock mass, the increasing moisture content was decreasing its strength.

Figure 5: Backscarp with top caprock overhang since removed, Paleosols are darker bands (Photo taken 28/09/96).

7. RAINFALL AND ROCKFALL

The role of rainfall in the Gracetown cliff collapse was that of the trigger, which accords with the concept that on a world wide basis most mass movements occur and most landslides are initiated during intense precipitation events (Crozier, 1986).

Discussion has occurred about the direct relationship of rainfall and landslides, and there has generally been an assumption that the landslide occurrence is related to the quantity of rainfall immediately prior to the event (short term) and possibly to the long term antecedent rainfall that occurs up to one month beforehand. Brand (1995) is of the opinion that for most landslides involving high permeability materials, short term intensity is the only rainfall parameter of importance. Other experts in the field disagree; Crozier (1986) reiterates both long and short term rainfall have to be taken into account for a landslide event and Fell (1995) says that antecedent rainfall was important in the Speers Point, Newcastle landslide.

The rainfall figures for 1996 have two deficiencies, (i) the nearest rainfall station is at Margaret River some 13km inland in a SE direction from Gracetown and (ii) the figures are for 24 hour periods so that hourly intensity figures are not available.

The rainfall on the day of the rockfall was 22mm which is unexceptional for a cold front, and there were similar fronts on the 23rd, (28mm), 16th (31mm), 10th (31mm), 9th (17mm), and 6th (20mm). This gives a total of 169.6mm for September, which is well above mean (102.7mm) but well below the highest (212mm) September figure which occurred in 1978.

The monthly rainfall figures for 1996 are only exceptional as far as July is concerned, (390.2mm) which is the second highest on record. June, July and August (859mm) together make up a period when the rockfall could possibly have occurred earlier in the year if rainfall alone was the only determinant.

The rockfall did not happen then because either:
(i) the overhang had not reached critical size, or (ii) strong bands in the caprock were still intact. The June, July, August period of turbulent weather was the occasion when damaging erosion occurred of the shorelines of the South West. The shoreline rock platform at the base of the cliffs was partially removed and the sub-aerial agents of change were at a maximum (see Table 1) and spray and salt attack were also accentuated. The heavy rainfall in June and July probably lead to surface runoff and erosion and solution of the lower overhanging caprock.

The effects of human trafficking erosion in the summer and winter of 1996 may also have been significant, drawing down the protective sand cover at the back of the overhang.

Conditions could have been close to equilibrium as the rains ceased and the separate perched water tables in the eolianite and paleosol layers drained away or evaporated. This process may also have completed dissolution of some harder bridges in the rock layers, and at the end of the slab, locally reducing its strength. The draining water may have opened or enlarged natural joints present in the rock mass such as seen in Figure 3, which allowed easy detachment on the sides of the rock slab fall and the rock strength decreased.

In September the rain fronts recommenced. Antecedent rainfall of 142mm thus preceded the rainfall on the 27th when the soil moisture was topped up with rock density approaching 18kN/m^3. The slab fall was initiated by the breakage of the No. 3 caprock and the remaining side bonds, which caused the cracking noise heard by the surfers in Cowaramup Bay and by some of those standing on the shore. Rainfall increased the unit weight of the rock mass and decreased its strength.

The initial tension joint presumably formed parallel to the cliff face near the top of the rockfall as lateral confining pressure was released through cliff erosion or there may have been a natural joint present, infilled with calcrete. The tension crack may have extended vertically and laterally until a set of natural joints (Figure 3) was intersected.

The top caprock layer that was removed after the rockfall was about 1.4m thick and had a UCS of 15MPa and thus an estimated tensile rock strength of about 1.5MPa.

Under these conditions the critical overhang would be about 5.6m before failure occurred. The overhang left in place after the rockfall was up to 5m. This was removed the next day.

8. SEISMICITY

Some residents of Gracetown reportedly felt seismic tremors on the 27th of September. The Leeuwin-Naturaliste area is a zone of known seismicity which presently is quiescent. The Mundaring Geophysical Observatory has confirmed that no small seismic events were recorded in the South West area on the day of the rockfall. It is concluded that the tremors felt were caused by the cliff decoupling. This is similar to small seismic events generated by rockfalls in the Kalgoorlie gold mines.

9. GROUNDWATER

The water table in the vicinity of the cliff face is perched on the weathered surface of the Precambrian basement rocks that slope down to the coast. The rockfall cliff section contains three calcreted or caprock zones which would inhibit vertical infiltration of rainfall, and the marine limestone and beach rock beds are quite dense; hence the groundwater table would not have been significantly raised by infiltration. It is not likely that a raised water table was a factor in the rockfall process. No water presence was seen in the excavations made following the rockfall. Subhorizontal movement of water is facilitated by the carbonate leached zone of roots layers and several local perched water tables may have been present.

10. CONCLUSIONS AND COMMENT

10.1 Rockfall Disaster

Nine people were killed in the cliff collapse. This was the biggest death toll for a rockfall or landslide in Australia at the time and equal to the number of lives lost in the Newcastle earthquake of 1989.

10.2 Best Shelter at Maximum Overhang

The fact that the rockfall occurred at the place where the spectators were sheltering is inter-related. At that place there was the maximum overhang of the lower layer providing the most protection, and therefore the maximum potential instability of the face was present there.

10.3 Shelter at Time of Maximum Risk

The fact that the rockfall occurred at a time when the people were congregated in one place is also inter-related. The driving rainfall which caused them to seek shelter was the trigger for the event as the weight of water in the cliff built up to breaking point and the rock strength decreased.

10.4 Cliff Collapse, Not Overhang Alone

The cliff face of five different rock types of five geological layers was involved in the rockfall. It was not just the collapse of an individual overhang during rainfall which is the usual mode of occurrence of rockfall in West Australian coastal limestones.

10.5 Geotechnical Advice Sought Late

It is an interesting commentary on the previous attitude and awareness of geological hazards that geotechnical advice was not brought to site until five days after the event (Ranasooriya, 1996). At that stage the top caprock overhang had been dropped and the cliff face regraded under the direction of the local Mines Inspector. Geotechnical advice could have been vital to the stability of the remaining cliff during the rescue efforts. The form of the rockfall and possible clues to its causes were covered up before any site investigations could be done.

10.6 Litigation

The families of the people killed in the rockfall have commenced legal proceedings and have issued a writ against (i) the Shire of Augusta-Margaret River, in whom the land was vested, (ii) the Department of Conservation and Land Management (CALM) who manage the adjacent National Park, (iii) the Education Department who conducted the surfing carnival and (iv) the WA Government. The action seeks unspecified damages, claiming negligence or breach of duty as the cause of the deaths. The trial will begin in March, 1998.

10.7 Mitigation of Rockfall Hazards

As a result of the Coroner's findings and the threat of legal action, limestone cliff management in Western Australia has undergone a revolution. Local authorities and government instrumentalities, especially CALM, have commissioned geotechnical studies of publicly accessed cliffs with caves and overhangs, and remedial and preventative works have been commissioned.

10.8 Need for a Geotechnical Model

The Huzzas Cliff Rockfall was a unique, tragic event but it provided some significant geological detail. The effort has been made to quantify the rockfall so that the findings can be applied elsewhere, especially to the adjacent cliff face. The engineering model used is not exact but the important parameters have been highlighted.

11. REFERENCES

Brand, E.W. (1995). Slope stability in tropical areas. *Landslides. Proceedings of the Sixth International Symposium, Volume 3.* pp 2031-2051. Balkema, Rotterdam.

Crozier, M.J. (1986). *Landslides, Causes, Consequences and Environment.* Publisher Croom Helm.

Djakamihardja, A.S. (1992). An evaluation of the engineering properties of coastal limestone from Rocky Bay, Perth Metro area. *Curtin University B.Sc (Hons) Project* (Unpublished).

Fairbridge, R.W. and Teichert, C. (1952). Soil Horizons and Marine Bands in the Coastal Limestones of Western Australia. *Journal Royal Society of N.S.W. vol. LXXXVI.*

Fell, R. (1995). Landslides in Australia. *Landslides, Proceedings of the Sixth International Symposium, Volume 3.* pp 2059-2100. Balkema, Rotterdam.

Gordon, F.R. (1997). Rockfall at Cowaramup Bay 27th September 1996. *Report to the Gracetown Coroner.* (Unpublished).

Maekado, A. (1990). Critical length of ledge developed on an artificially cut slope : an example. *Transactions Japanese Geomorphological Union 11.* pp 363-8.

Matsukura, Y. (1988). Cliff instability in pumice flow deposits due to notch formation on the Asana Mountain slope, Japan. *Zeitschrift für Geomorphologie 32.* pp129-41.

Ranasooriya, J. (1996). Geotechnical Assessment of the Gracetown Sea Cliff Failure. *Report of the Department of Minerals and Energy to the Police Department assisting the Gracetown Coroner.* (Unpublished).

Roberts, J.L. (1973). Quaternary Sedimentation of Cowaramup Bay, W.A. *BSc (Hons) Thesis U.W.A.* (Unpublished).

Selby, M.J. (1993). *Hillslope Materials and Processes. 2nd Ed.* Publisher Oxford University Press.