Rock-Falls into Water and Potential Wave Damage

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ABSTRACT

This paper presents the findings of experimental work undertaken to investigate the potential for wave damage caused by rock-falls into partially water-filled open pit mines. A particular mine geometry has been used to model the situation in a wave flume, with a modelled rock-fall of 10,000 tonnes. The main findings of interest to the mining industry are: a) transfer of energy efficiency from a rock-fall to the water ranges between 5 and 80% depending on slide impact velocity; b) maximum wave run-up distance up slope is about 40 meters; c) available evacuation times for personnel located at a pumping station within the maximum wave run-up distance is about 37 seconds, which is insufficient.

1 INTRODUCTION

History provides us with several cases where large landslides and rock-falls have occurred and impacted into water bodies. The waves generated by these have caused widespread devastation and loss of life. Examples of such events have been well documented, and include a massive landslide into Vaiont Dam, Italy in 1963 and another at Lituya Bay, Alaska in 1958. The Vaiont slide destroyed several villages downstream and killed over three thousand people when the wave generated by the landslide overtopped the dam, whereas the Lituya Bay failure produced the highest vertical wave run-up ever recorded of 524m. A similar situation, though potentially on a smaller scale, may occur in any of the open pit mines currently in operation in Western Australia. Recently, failures of waste dumps into accumulated water have generated waves that have led to deaths.

During an open pit mining operation, ground and mining water accumulate at the bottom of the pit. The depth of water may be significant - greater than 30m, particularly after heavy rains and during a period of cut back. Access to the bottom of the pit is limited during these situations so a pumping station is often installed to manage and monitor the water level. However, should a slope failure which impacts with the accumulated water occur, there is a potential for a water wave to be generated that propagates across the pit water and runs up an adjacent slope. If the failure is large and impacts with enough momentum, then the wave generated may cause severe damage to the pumping station or other infrastructure near the water. Furthermore, personnel who may be located at or close to the water, such as during periods of pump maintenance will also be under significant risk.

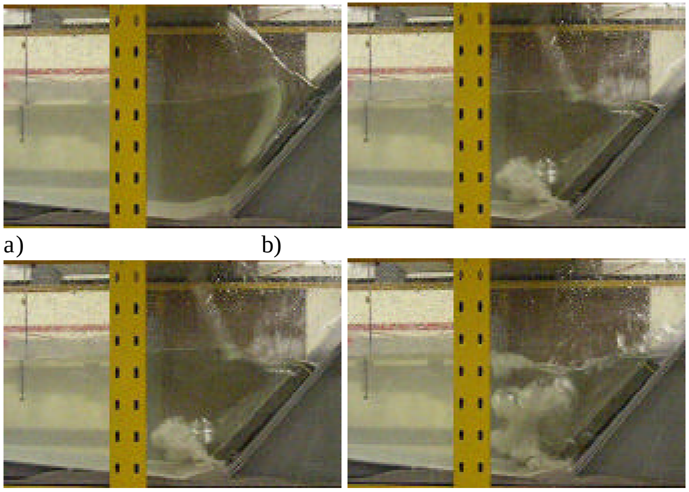

Figure 1 Model block entering water body

At the end of the mining life, such pits may be considered for use as a recreational facility for boating or fishing. However, de-watering of the pits ceases, possibly leading to build up of pore pressures in the slopes and an increase in slope failures. This raises significant risk concerns for the regulators of the land in terms of Health, Safety and the Environment (HSE) implications, of which will not be obvious to the general public who utilise the facilities at a later stage.

This paper attempts to simplify the problem of rock-falls into water while ensuring that parameters inherent to the problem are not trivialized. Experimental work demonstrated in Figure 1, attempts to quantify the severity of damage caused by rock-falls into water. These are presented with the aim of providing the mining industry with a greater understanding of likely outcomes.

2 AIMS AND METHOD

The disciplines of physics, geology, geomechanics, fluid mechanics and mining engineering are involved in this problem. The areas least understood are processes involved with transferring energy from a rock-fall via water body, to wave run-up height. The specific aims therefore focussed on:

1. Construction of a scale model to facilitate experimental work, thus providing comparisons with previous research and theoretical predictions; and
2. Providing suggestions on possible methods to warning personnel of dangerous situations such as a monitoring buoy in the water which measures wave heights.

Although both theoretical considerations and calculations from empirical approaches were investigated, this paper focuses on the experimental work undertaken.

3 EXPERIMENTAL MODEL

3.1 OBJECTIVES OF EXPERIMENTAL WORK

The main objectives of the experimental work were to:

1. Identify the modes of wave generation: particularly for first and second waves;
2. Determine the relationship between the impact velocity of a rock-slide with the water and initial wave amplitude of the first wave (maximum amplitude);
3. Determine an evacuation time for personnel located at a pumping station; and
4. Determine the relationship between the impact velocity of the rock-slide with the water and the wave run-up distance.

3.2 PARAMETERS

Rock-falls are generally complex mass movements of material, not easily modelled in the laboratory. Block, piston and granular models are three methods used to model rock-falls or landslides. Such methods have been utilized in studies of historic slides. For the purposes of this research (particularly with application to the mining industry), a simple block model was chosen. Experiments considered a real-life geometry with the parameters shown in Table 1.

Table 1 Parameters considered in current research

Density of intact slide material (ρ_s)	2.8	tonnes/m^3
Still-water depth of water (h)	30	M
Maximum length of water body (x)	300	M
Failure slope angle (α)	50	Degrees
Run-up slope gradient (β)	1:10	-
Slide velocity range (v_s)	0.5 - 20	m/s
Slide tonnage	10000	Tonnes

3.3 SCALING LAWS AND PARAMETERS

A simplified model of the problem was created at a scale of 1:100 to enable a slide of about 10,000 tonnes to be modelled in the wave flume shown in Figure 2. The two major dimensionless parameters considered for scaling in open channel or free-surface flows are Froude (F) and Reynolds' (Re) numbers. With a model length scale of 1:100, the kinematic viscosity scale ratio would be 1/1000 which could not be satisfied. Therefore a 'distorted' model similar to an open channel or free-surface flow is needed, Young *et al.* (1).

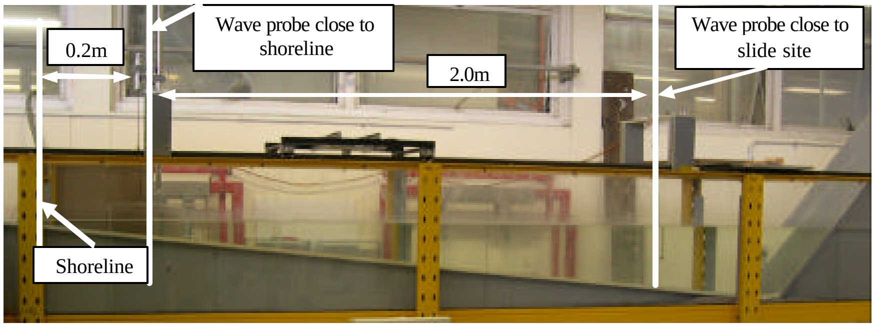

Figure 2 Wave flume used in experimental work

3.4 METHODS OF MEASUREMENT

The impact velocity was measured using a simple 'ticker-tape' measuring device which allowed measurement of velocity at 40Hz. This was a relatively quick, efficient and low-cost method, adequate for current requirements. The wave amplitude was determined both near the impact site and 0.2m from the model shoreline using wave probes. These provided information on variance in wave form and height, as well as the ability to measure the wave period and velocity.

4 RESULTS

Over 200 individual tests were undertaken in this research, to allow a reasonably complete and cohesive set of data to be generated.

4.1 RELATIONSHIP BETWEEN IMPACT VELOCITY AND INITIAL WAVE AMPLITUDE

The experimental results for wave amplitude at impact for 1st and 2nd waves are shown in Figure 3. The main observations that may be drawn are:

- Increase in impact velocity corresponds to an increase in amplitude of the first wave close to the impact site, with wave heights ranging from 1 to 2m; and
- Amplitude of the second wave close to the impact site is larger than the first wave, although there is significant scatter.

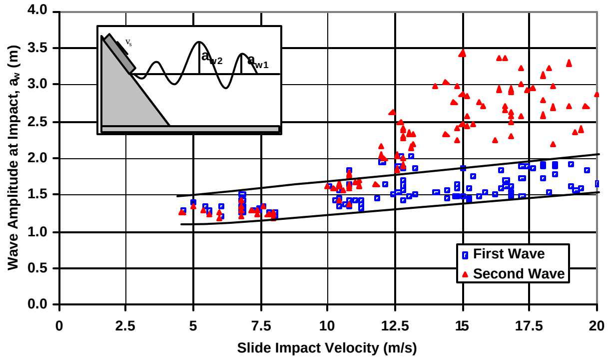

Figure 3 Initial wave amplitude vs. impact velocity

4.2 RELATIONSHIP BETWEEN SLIDE IMPACT VELOCITY AND WAVE PERIOD

Figure 4 shows the relationship between the slide impact velocity and the wave period, by considering the change in ratio of the first wave amplitudes. The main points of interest are:

- No noticeable change in the wave period for increasing slide impact velocities;
- Wave period of waves increase as they approach the shoreline, compared with near the impact site; and
- Wave period close to the shoreline decrease slightly in length with increasing impact velocity.

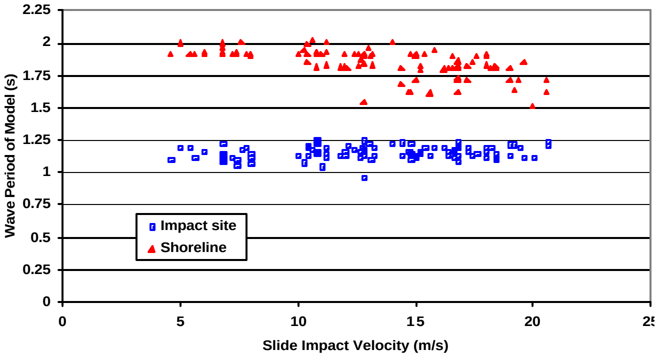

Figure 4 Wave period at impact site and shoreline

4.3 RELATIONSHIP BETWEEN SLIDE IMPACT VELOCITY AND WAVE RUN-UP HEIGHT

The relationship between the slide impact velocity and wave run-up height up the slope can be seen in Figure 5. Three key observations are made:

- Increasing impact velocity generally corresponds to an increase in wave run-up height up slope;
- For the range of velocities investigated, depending on the slide impact velocity, the wave run-up distance ranges between 30 and 40m; and
- There appears to be a plateau in the wave run-up height up slope for impact velocities greater than 14.5 m/s.

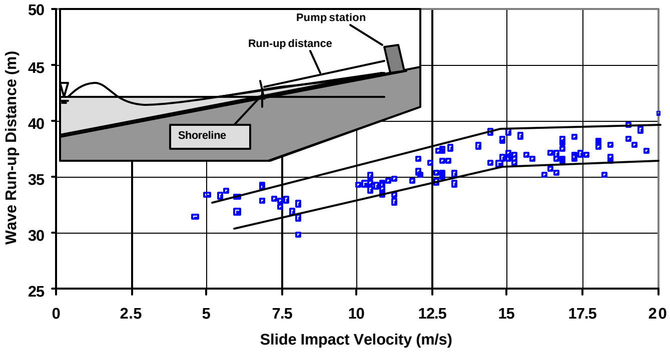

Figure 5 Experimental wave run-up height up slope

5 DISCUSSION OF RESULTS

The trend in results presented in Figure 3 are comparable to those from previous research, such as Davidson and McCartney (2). Fritz (3) considered a slide impact velocity range of 27 to 82m/s, and therefore it is suggested the current research may extend the understanding of slower slide impacts. The conclusions of Chaudhry *et al.* (4) were that "the heights of the generated waves were independent of the slide velocity". This discrepancy may be attributed to different wave generation techniques. Chaudhry *et al.* (4) considered generation of waves by very low 'impact force' with the water, implying only slow impact velocities. Figure 1 clearly demonstrates the significant force of block impacting the water observed in the current investigation.

5.1 INVESTIGATION OF ENERGY TRANSFER

The principle result in Figure 3 is the relatively small increase in initial wave amplitude of the first wave for a relatively large increase in slide impact velocity. To investigate this observation further, a comparison between the energy of the slide and the first wave was undertaken. To determine the energy of the slide, it was assumed that at the impact of slide with water, all energy was kinetic, given by Equation 1:

$$E_k = \frac{1}{2} m v_s \qquad \textit{Equation 1}$$

where E_k is the average kinetic energy of slide material and v_s is the slide impact velocity. To determine the energy of the wave, it was assumed that the first wave may be approximated by a solitary wave. Monaghan and Kos (5) and Fritz (3) also considered this as a reasonable assumption. The energy of a solitary wave may therefore be estimated using Equation 2:

$$E_{sol} = \frac{8}{3\sqrt{3}} ?_w g \left(\frac{a}{h}\right)^{3/2} h^3 \qquad \textit{Equation 2}$$

where E_{sol} is the total average energy per unit length of wave crest and 'a' is the amplitude of the wave. Table 1 provides definitions for the other variables used. It should be noted that the generally accepted relationship given in Equation 2 does not include the slide width, b, and therefore has units of Joules per metre. To make comparisons with the energy of the slide at impact, the total kinetic energy given by Equation 2 is multiplied by the slide width to allow consistent units. Figure 6 demonstrates the efficiency of transfer of energy from the slide to the first wave for increasing impact velocities, with efficiency ranging from about 5 to 80%.

The energies of the slide and first wave were generated assuming that the energy of the first wave as approximately equivalent to that of a solitary wave. Figure 6 demonstrates the counter intuitive result that with increasing slide impact velocity, the efficiency of transfer of energy decreases. One possible explanation is that the energy is dissipated through turbulence and spray as illustrated in Figure 1. With higher impact velocities, the displacement of water in the form of an impact crater (as suggested by Fritz (3)) increases dramatically. By considering the efficiency of energy transfer from slide to water, it may be possible to explain why a relatively low increase in initial wave amplitude of the first wave for increasing slide impact velocity is observed. Furthermore, the efficiencies demonstrated in Figure 6 endorse the findings of Kamphuis and Bowering (6) and Monaghan and Kos (5) who suggest energy conversion from slide to water wave during impact ranging from 10 to 50%. Monaghan and Kos (5) propose that the energy transfer of 10% may present a lower bound. Figure 6 demonstrates that lower efficiencies are possible, suggesting the need for more detailed work in this area.

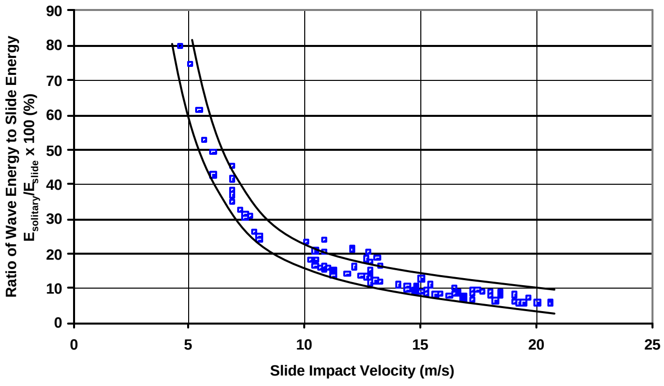

Figure 6 Efficiency of transfer of energy from slide to 1st wave

5.2 RELATIONSHIP BETWEEN SLIDE IMPACT VELOCITY AND WAVE PERIOD

From Figure 4, it can be seen that the wave period is independent of the slide impact velocity, demonstrated by the constant wave period. This follows the observations of Fritz (3) who concluded that there was a very poor correlation between the slide impact velocity and wave period. This has implications for the estimated time for evacuation of personnel. An approximation for the time taken by the wave to reach the shoreline is determined by calculating the velocity of the wave from the period. Figure 4 also demonstrates that the wave period increases close to the shoreline. Theoretically, this implies an increase in the wave velocity as the wave approaches the shoreline. However, current wave theories require the wave period to remain constant as the wave enters shallow water. By assuming conservation of energy, the wave length would decrease and the wave height increase due to the shallowing of the water depth.

An explanation of this discrepancy may be that the waves travel as a 'packet' (as shown by Figure 7), and thus the period of the first wave (measured in the current research) is not representative of the whole group. Further research is recommended to consider the waves as a 'packet', combined with Fourier transforms to better analyse the wave forms .

Figure 7: Representation of group velocity and 'packet' of waves (modified after Dean and Dalyrmple (7)

5.3 CALCULATION OF EVACUATION TIME

To calculate evacuation times, the period of the wave close to the impact site was used to determine the initial velocity of the first wave. Assuming shoaling occurs, the group velocity can be predicted. The change in wave velocity with distance to the pumping station can be plotted, as demonstrated in Figure 8. This figure also shows the theoretical breaking depth for this wave, based on McCowan (8). Conservatively, the wave velocity after breaking was assumed to be equal to the breaking velocity, leading to an estimate of the time taken to travel the distance from the slide impact site to the shoreline of 37 seconds.

This is comparable to the results based on Fritz (3) which were also calculated, but not reported here. These can be considered a lower bound (conservative) result as the velocity of a broken wave is assumed to be constant from the point of breaking. In reality, the velocity of the breaking wave would decrease during run-up, therefore increasing the evacuation time. However, this lower bound indicates insufficient time for personnel to evacuate to safety. The use of wave buoys to provide warning signals is inadequate. It is therefore suggested that other methods, such as the construction of a windrow on the run-up slope, may be more appropriate. Further testing is needed to validate its effectiveness for wave energy dissipation.

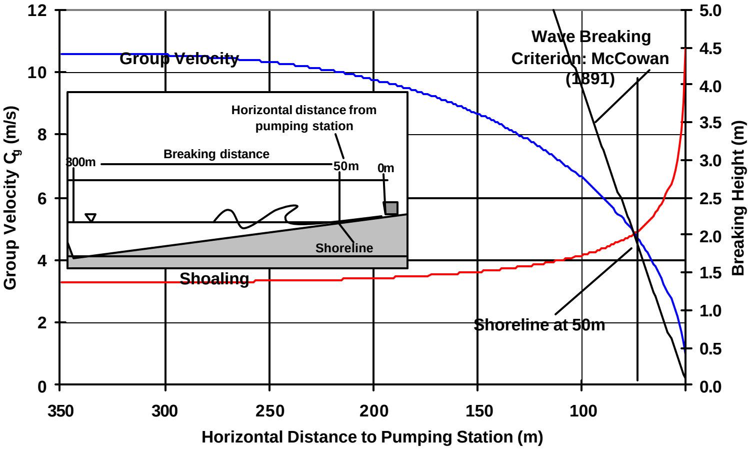

Figure 8 Shoaling, breaking and variation of group velocities

5.4 RELATIONSHIP BETWEEN SLIDE IMPACT VELOCITY AND WAVE RUN-UP DISTANCE

The observation that an increase in impact velocity corresponds to an increase in the wave run-up height up slope shown in Figure 5 was expected, and follows the findings of previous research. The plateau in the results may be an outcome of wave breaking that was observed for higher slide impact velocities during experimental work, and shown in Figure 9. Comparison with empirical wave run-up equations given by previous researchers (not presented here), show that the wave run-up of a nonbreaking wave is significantly higher than that of a breaking wave. This would be due to the amount of energy that remains within the wave, and which would be lost during the breaking process.

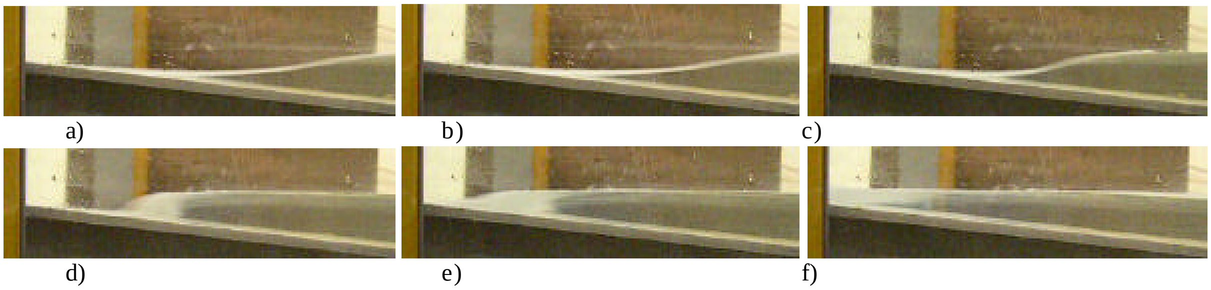
a) b) c)
d) e) f)

Figure 9 Photos from current experimental work showing wave breaking for high impact velocities (17m/s)

By considering the breaker type, it is of great interest to note that the plateau corresponds with the theoretical transition between a surging and breaking (plunging) wave (shown in Figure 10). Thus the change in wave run-up heights at a slide impact velocity of around 14.5 m/s (shown in Figure 5) may correspond to a change in wave breaker type. The relevance to the mining industry is that if a non-breaking wave is generated by a small rock-fall, then the resulting damage may be as significant as that caused by a larger rock-fall which breaks. Further work is required in this area to determine the magnitude of rock-fall that will generate waves that produce non-breaking waves.

In terms of providing information that is of use to the mining industry, it is demonstrated that a 10,000 tonne slide travelling at slide impact velocities of greater than 5 m/s are capable of generating waves that have a run-up distance of over 30 m for this slope angle.

This can be used in risk analyses to determining the location of structures such as a pumping station. If the example of a pumping station with maximum suction capacity of 50 m is used, then it is concluded that wave damage is probable if the pump's initial location is below 40 m, as demonstrated by Figure 5. However, as the water level decreases during the pumping process, the risks involved will decrease as well. This is based on the current assumption that a slide travelling at higher impact velocities is less likely than one impacting at slower velocities. This assumption needs further consideration before application in the mining industry.

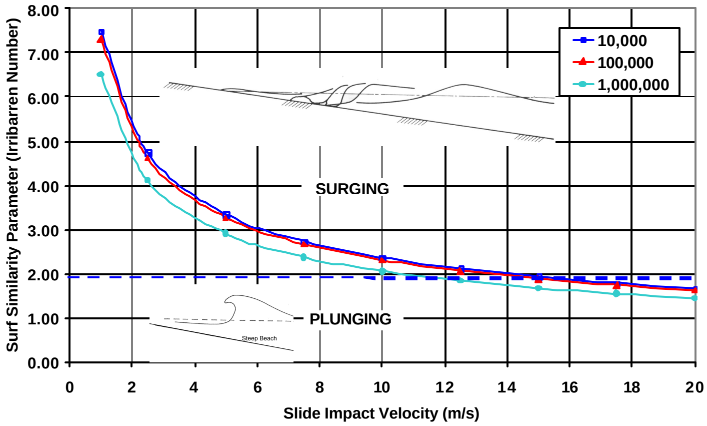

Figure 10 Breaking-type regions for waves of various slide tonnages

6 CONCLUSIONS

The potential for wave damage caused by the impact of rock-falls into water has been considered. The implications for open pit mines include:

- Transfer of energy efficiency from rock-fall to the water body ranges between 5 and 80% for high and low slide impact velocities respectively.
- Maximum wave run-up distance up-slope for a 10,000 tonne rock-fall is about 40m, corresponding with slide impact velocities between 14.5 and 20m/s;
- For a 10,000 tonne slide, the risk of structural damage and injury to personnel may be as significant for slower impact velocities, as for higher impact velocities based on wave breaker type; and
- The evacuation time for personnel located within 40m of the shoreline is inadequate. Devices such as a warning buoy do no give sufficient warning, and research into devices such as windrows to dissipate wave energy during wave run-up is proposed.

Although some solutions to the vast question of rock-falls into open pit mines containing water have been proposed, a great amount of research is still needed. The problem is multi disciplinary, and calls for collaboration between traditionally unconnected areas of research.

7 ACKNOWLEDGEMENTS

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