Calibrating a 2D rockfall model using video footage to reevaluate rockfall hazard in post earthquake Christchurch

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Abstract

2-Dimensional rockfall modeling can help reshape earthquake prone areas for safe redevelopment by simulating rockfall patterns for future shaking events. Since rockfall is nearly unpredictable, 2D programs like RocFall use statistical analysis to model hypothetical run out distances, bounce heights, and velocities of falling boulders for different seismic scenarios. In this study, we looked at rockfall hazard in the Port Hills of Christchurch, New Zealand, and found that these 2D models can be effectively calibrated using video footage to compare the model with real rockfall to ensure accurate model parameters. We also deduced that even the most accurate 2D model has limited capability to model seismically induced rockfall because in only using two dimensions, it cannot fully model the dynamic process of these types of rockfall events. That being said, this calibration technique produces the most effective 2D model possible.

1. Introduction

For as long as people have been drawn to mountains, rockfall has jeopardized the safety of communities around the world. Rockfall is the process of rocks loosening from a cliff face and falling down a slope. It is a hazard of utmost concern due to the large areas of the world it effects, and because it is a nearly unpredictable event (Chen et al. 2012; Masuya et al. 2009; Stevens, 1998; Singh et al. 2013; Volkwein et al. 2011). The list of factors that can cause rockfall is extensive: geometry of slope, rock type, fracturing, weathering, soil properties, freezing and thawing, water infiltration, atmosphere, permeability of rock, gravity, seismicity, as well as others (Volkwein et al. 2011). Seismicity is of utmost concern in Christchurch and its surrounding suburbs after the 2010-2011 Canterbury Earthquake Sequence and the concern for future seismic events.

Between September 2010 and June 2011, the greater Christchurch area experienced the devastating Canterbury Earthquake Sequence. On September 4, 2010 the Greendale fault ruptured 35 km west of Christchurch, which caused the M_w 7.1 Darfield earthquake. On February 22, 2011, there was a M_w 6.3 earthquake approximately 10 km southeast from downtown Christchurch in the Port Hills. An aftershock of this earthquake was felt on June 13, 2011 and had a M_w of 6.1, also in the Port Hills. During the February Christchurch earthquake and subsequent aftershocks Christchurch was heavily damaged by shaking, liquefaction, cliff collapse, and rockfall. 181 people died in the Christchurch Earthquake, three from cliff collapse, two from rockfall, and the rest of the fatalities were due to building collapse (Bell et al., 2013).

After the Canterbury Earthquake Sequence, Christchurch began a period of rebuilding that it continues today. It is a major undertaking for the city and the estimated cost to rebuild is in the range of $40 billion (Key, 2013). The shape of the city has been changing in the past three years as risk assessment has deemed previously populated areas of the city no longer fit to inhabit.

The Port Hills surround the city of Christchurch from the south and are comprised of Miocene andesitic lava flows overlain with loess and colluvium deposits. During shaking events, rocks break away from outcrops along planes of weakness, and previously loosened boulders from the hill run down the slope, creating rockfall hazard. The boulders are ellipsoids so they both roll and bounce down the hill in irregular patterns.

Since rockfall is unpredictable, various models are used to explore all possible ways this process might behave. These models provide information that informs zoning or remedial decisions. In order to make realistic decisions, a well-calibrated model is required that actually reflects the geology of the area and the interaction of the falling boulders with the topography. Using data collected from video analysis, 2D rockfall models can be created and properly calibrated to analyze this risk in similar geological environments for future shaking events.

2. Geological Setting

The Port Hills are part of the extinct Lyttelton Volcanic complex, a Miocene aged, basaltic volcano (Massey, 2014). The bedrock is comprised of layers of weathered basalt lava flows, scoria, agglomerate, ash, and palaeosols (Massey, 2014). On top of the volcanic deposits is a layer of quaternary aged loess, wind blown sand and silt, which is 1 to 5 m thick (Bell and Trangmar, 1987). On top of that is talus that comes from the weathered and cracked volcanic rocks that have fallen down the slope (Massey et al. 2012). For this study, three slopes in the Port Hills are being analyzed: Godley's Head, Boulder Bay, and Evan's Pass. The source area of the rockfalls are outcrops of volcanic rock that have a slope angle greater than 37 degrees (Massey et al. 2012). These areas of made up of weathered lava flows and scoria, which are very blocky due to irregular cooling joints (Massey, 2014).

3. Methods

Due to the difficulty of modeling rockfall, many different types of models exist. To create our model we used the statistical analysis program RocFall, which creates a 2D rockfall model. This program was created to address the major difficulties of rockfall analysis: variable or unknown slope materials, unknown starting location of the rocks, variable slope geometry, and the fact that the calculations utilized in numerical rockfall modeling were extremely sensitive to minute deviations in different parameters (Stevens, 1998). To create the RocFall model and run the subsequent simulations, slope, feeder zone, mass of rocks, and their velocity must be known (Stevens, 1998). We acquired this information from the scaling videos.

3.1 Creating the slope

To get accurate slopes for all three sites and decrease user error, we used a DEM (digital elevation model) of the Port Hills, found the locations from the scaling videos, and extracted the slope using the spatial analyst tool in ArcMap. Figure 1 shows the DEM overlain with an aerial photo of the area to ensure that we identified the correct slope locations. The slope is extracted from ArcMap as X,Y coordinates in Excel. This is then entered into RocFall.

The next step is to determine the correct materials along the slope. We did this by estimating the location and extent of each material from the video footage. Each slope material has its own unique properties which affects the boulder's behavior when they make contact.

The main property that affects boulder trajectory is the materials Coefficient of Restitution (R). R represents the change in velocity of the boulder once it encounters the slope material, expressed as the ratio of outgoing velocity to incoming velocity (Massey et al. 2012). The value of R can be from 0 to 1. This value reflects the elasticity of the material, so a material with a high R value means that the values of incoming and outgoing velocity are very similar, which in turn means that the material is very elastic (Massey et al. 2012). An R value closer to 0 means that the material is less elastic and will slow down or stop the boulder (Massey et al. 2012). These values can be determined by either field or lab tests.

For this work, we used R values from Baishan Peng's Masters of Engineering Geology thesis at the University of Canterbury entitled "Rockfall Trajectory Analysis – Parameter Determination and Application." In this work Peng performs various experimental field and lab tests to determined coefficient of restitution for the slope materials in the Port Hills. These values are listed in Table 1.

3.2 Initial Seeder Conditions

Finally, a seeder area must be determined. This is the source area of the rocks in the model. The initial conditions of the seeder zone were selected by reviewing previous work on rockfall in the Port Hills. Rockfall can either be triggered by dynamic or static initial conditions (Brehaut , 2012). Dynamic conditions refer to earthquake shaking, and static conditions are any other process, such as weathering, that can cause rockfall (Brehaut, 2012). In our model we used initial horizontal and vertical velocity values calculated from Peak Ground Accelerations during the Canterbury Earthquake Sequence (Brehaut, 2012). For boulder size we selected a size similar to ones released during the February and June 2011 earthquakes. These values are listed under Table 2.

3.3 Running the model

Once all of the initial parameters are entered, the user runs the model, (which calculates the statistical distribution of the results). 50 boulders were released from the feeder zone in each simulation. The output is a slope profile overlain with the boulder trajectories, as well of graphs of the various values of runout distance, bounce height, and velocity.

3.4 Video analysis

Once the simulation is run, it is necessary to analyze the video footage to see if the model is behaving the same as in actuality. To do this we used Kinovea, a video analysis program to extrapolate the overall trajectory pattern, bounce heights, runout distances, and velocities of boulders falling down the slope. If these values do not match the models, then the model is not properly calibrated and we must adjust the slope properties. To determine bounce heights we used the following relationship between bounce distance and height for shallow jumps [Volkwein et al., 2011]:

$$f/s = 1/12$$

Velocity is calculated using an estimate for parabolic distance over time:

$$d = \left[\frac{\sqrt{s^2 + 16(f^2)}}{2}\right] + s^2 \left[\frac{ln\left[4f + \sqrt{s^2 + 16(f^2)}\right]}{8f}\right]$$

$$v = d/t$$

f = bounce height; s = bounce distance; t = time; d = parabolic distance; v = velocity. Values for bounce distance and time were taken from the video.

Once these values are determined, we compared them to the values produced in our simulations. If the values were not within an acceptable range of those observed in the video, then parameters were adjusted and the process of running the model and comparing the results to those from the video was repeated.

4. Results

Results of this calibration technique are listed in the appendix. They show the velocities, runout distances, and bounce heights of the calibrated model (Figures 2, 3, 4, 5, 6, 7, 8, 9, 10, 11) compared to those values extract from the videos (Table 3).

5. Discussion

The values calculated and observed for bounce height, velocity, and runout distance in the models all are within the ranges produced by the RocFall model. This indicates that using video footage is an effective way to create an accurate 2D model. The action of scaling, which is captured in the videos, mirrors the dynamic motion of seismically induced rockfall. Being able to watch the behavior of the rock falls in the footage mirror those produced by the model assure a degree of confidence that the parameters chosen for the model are correct. This process also brought to light many issues with RocFall's method of 2D modeling. This, as well as limitations of using video footage, are addressed below.

5.1 Limitations of using footage

This work has shown that video footage is an extremely useful tool in creating an accurate model. This technique's principal disadvantages are that this process relies on the quality of the video footage. The major challenges of video footage include the camera's extent, and the action of the boulders. The Boulder Bay footage was very difficult to analyze because every time the boulder fell down the slope it created a massive cloud of debris and dust. This obscured the boulders movements for most of the initial slope, and by the time the boulder exited the dusty cloud, it was so far down the slope that its movements could no longer by clearly seen or analyzed. If a simple meter scale stick were placed within the video frame, this process would be more precise. Although it is possible for the user to infer scale markers, there will always be a certain amount of uncertainty and human error with that technique.

5.2 Limitations of 2D Modeling

While this work has shown that 2D models can be properly calibrated, it also points out many weaknesses in the technique. The accuracy of the 2D models depends heavily on correct values for coefficient of restitution. Slight changes in these values completely alter the rock falls trajectory because of varying material elasticity. Unfortunately, coefficient of restitution is not constant throughout the slope material in actuality (Peng, 2000). This means that while accurate coefficient of restitution values help create a realistic model, the overall assumption of uniform coefficient of resistivity through a slope material is not correct. Even if that assumption were correct, coefficient of restitution is an extremely difficult value to get (Peng, 2000) (Massey, 2012).

Using only two dimensions also presents limitations. RocFall and other similar programs cannot predict how falling rocks will move laterally, which would impact their run out distances and area. This also does not take into account for the slopes the rocks may run down if they move laterally since the model only takes place on one fragment of a slope. With those things in mind, perhaps a more in depth modeling technique, such as 3D, should be looked into in the future for this type of work.

Perhaps RocFall's greatest weakness is its treatment of the size of the falling rocks. It is a hybrid model, which means it is both a lumped mass model, which considers the rock to be simultaneously a weightless particle traveling down the slope, and a rigid body model, which incorporates the mass of the rock. In RocFall's case, each rock is represented as an immeasurably small particle in the model that are so miniscule they never interact with once another (Brehaut, 2012). They have no size and their mass is not used to calculate their motion as they fall, but only to determine their kinetic energy (Brehaut, 2012). Their mass remains constant throughout the simulation, and therefore the rocks never fragment. These assumptions make the 2D model easier and quicker to use because it skims over these inputs, but these assumptions are contrary to the behavior of falling rocks. In all of the videos we analyzed for this calibration, the rocks fragmented as they fell down the slope. For example, in the Boulder Bay footage, all of the boulders released fragments as they travel down the slope. These fragments generally stopped at a patch of colluvium towards the bottom of the slope, and the main boulder that all of the fragments broke off of all fall into the water and the bottom of the slope. In the model, every rock made it into the water. Because the model does not account for the fragments, it does not have the ability to predict their runout distances separate from the principle rock or consider this change in mass of the principle boulder.

5.3 Future work

Even though this technique produced a model that mirrored the reality as captured in the video, it must be questioned if this simulation can really be used for seismically induced rockfall. During the Canterbury Earthquake Sequence, over 5,000 boulders were released in the Christchurch City area (Kaiser, et al., 2012). These boulders did not fall down the slope solitarily, as our boulders in the scaling videos and RocFall model did. So while this calibration technique can create an accurate model that is able to mirror the behavior of boulders in a scaling video, it is unclear how well this process can be translated to seismically induced rockfall.

With that being said, calibrating a 2D model in this manner is probably the most accurate 2D technique available at this time and the parameters we have determined in this study can be used on other slopes in the Port Hills as well as Bank's Peninsula for the time being. Future simulations run using these correct parameters can be used to assess hazard risk in the area with a high degree of confidence that the results are as accurate as possible using a 2D modeling technique. The model can be run using various peak ground accelerations to simulate the slope's behavior in earthquakes of various sizes. These results can be combined to see what remedial techniques, if any, can be used to the ensure safety.

The bounce heights, runout distance, and velocities produced by these 2D simulations can help to inform engineers on the most cost effective and safe remediation techniques. For example, as the rocks fall down the slope their bounce height decreases. The Canterbury Earthquake Recovery Authority mandates that all catchments areas be three times as tall as the maximum bounce height. By modeling the bounce heights along the slope, engineers can build catchment areas further down the slope that are affective, and don't need to be as tall and are therefore less expensive. The same goes for velocity, and as the rocks change they travel down the slope, different and more economical materials can be used to construct the catchment areas.

While it is clear that 2D modeling has many limitations, it is also apparent that the technique of calibrating the model using video footage increases the accuracy of these models. This study is just a primary synthesis of this technique, and should be further studied in the future to reiterate or refute these findings.

6. Conclusion

After the Canterbury Earthquake Sequence, the Canterbury Earthquake Recovery Authority began zoning properties in the Port Hills to designate the amount of risk they pose to their owners and those living around them. As of December 2013, 714 properties in the Port Hills have been designated as in the red zone, which means that the risk to life is unacceptable (greater than 1 in 10,000) and cannot be economically and logically stabilized (Canterbury Earthquake Recovery Authority, 2013).

In order to make the most practical zoning decisions, there needs to be an accurate assessment of rockfall hazard in the area. This assessment, factored in with the recurrence interval for seismic events in the greater Christchurch area, can inform decisions on future land development, remediation, or abandonment. 2D models are an often-used technique to assess this hazard in Christchurch. While they are easy to operate, they trade off simplicity with accuracy. Using video footage to calibrate these models and ensure that the parameters used are correct is a good option to increase model accuracy. While future work should be done to examine the ability of even the most accurate 2D model to simulate seismically induced rockfall, we hope that in the time being engineers who continue to work in two dimensions will adopt this technique of video calibration. Scaling work is extensively done all over Christchurch and provides an untapped goldmine of footage that is extremely beneficial to creating accurate models.

7. Acknowledgements

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References

Admassu, Y. and A. Shakoor (2013), Computer simulation-based evaluation of rock fall roll-out distances for catchment ditch design in Ohio, USA, Georisk, 7(3), 198-208.

Bell, D.H., and Trangmar, B.B., 1987. Regolith materials and erosion processes on the Port Hills, Christchurch, New Zealand. Fifth International Symposium and Field Workshop on Landslides. Lusanne, A.A. Balkema., 1, 77-83.

Berger, F. and L. Dorren (2005), Objective Comparison of Rockfall Models using Real Size Experimental Data, Disaster Mitigation of Debris Flows, Slope Failures and Landslides, 345-252.

Brehaut, J. C. (2012), 2D-Modelling of Earthquake-Induced Rockfall from Basaltic Ignimbrite Cliffs at Redcliffs, Christchurch, New Zealand, Master of Science in Engineering Geology, University of Canterbury, .

Chen, G., L. Zheng, Y. Zhang, and J. Wu (2013), Numerical simulation in rockfall analysis: A close comparison of 2-D and 3-D DDA, Rock Mech Rock Eng, 46(3), 527-541.

Cubrinovski, M., B. Bradley, L. Wotherspoon, R. Green, J. Bray, C. Wood, M. Pender, J. Allen, A. Bradshaw, G. Rix, M. Taylor, K. Robinson, D. Henderson, S. Giorgini, K. Ma, A. Winkley, J. Zupan, T. O'Rourke, G. DePascale, and D. Wells (2011), Geotechnical aspects of the 22 February 2011 Christchurch earthquake, Bulletin of the New Zealand Society for Earthquake Engineering, 44(4), 205-226.

Kaiser, A. et al., 2012. The M w 6.2 Christchurch earthquake of February 2011: preliminary report. *New Zealand Journal of Geology and Geophysics*, 55(1), pp.67–90.

Khajavi, N., M. Quigley, S. T. McColl, and A. Rezanejad (2012), Seismically induced boulder displacement in the Port Hills, New Zealand during the 2010 Darfield (Canterbury) earthquake, N. Z. J. Geol. Geophys., 55(3), 271-278.

Koleini, M. and J. L. van Rooy (2011), Falling rock hazard index: A case study from the Marun Dam and power plant, south-western Iran, Bull. Eng. Geol. Env., 70(2), 279-290.

Massey, C., Gertenberger, M., et al., 2012. Canterbury earthquakes 2010/11 Port Hills slope stability: additional assessment of the life-safety risk from rockfalls (boulder rolls) report a.

Massey, C.I., McSaveney, M.J., Heron, D., Lukovic, B. 2012. Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Pilot study for assessing life-safety risk from rockfalls (boulder rolls), GNS Science Consultancy Report 2011/311.

Massey, C.I., McSaveney, M.J., Taig, T., Richards, L., Litchfield, N.J., Rhoades, D.A., McVerry, G.H., Lukovic, B., Heron, D.W., Ries, W., and Russ J. Van Dissen (2014) Determining Rockfall Risk in Christchurch Using Rockfalls Triggered by the 2010–2011 Canterbury Earthquake Sequence. Earthquake Spectra, 30(1), 155-181.

Masuya, H., K. Amanuma, Y. Nishikawa, and T. Tsuji (2009), Basic rockfall simulation with consideration of vegetation and application to protection measure, Natural Hazards and Earth System Science, 9(6), 1835-1843.

Peng, Baishan. 2000. Rockfall trajectory analysis : Parameter determination and application, Master of Science in Engineering Geology, University of Canterbury, .

Sadagah, B. H. and S. I. El-Shanooty (2012), Modeling and remedial measures of rock slope stability and rockfalls problems along Werka descent road West of Saudi Arabia, paper presented at 46th US Rock Mechanics / Geomechanics Symposium 2012.

Singh, P. K., A. B. Wasnik, A. Kainthola, M. Sazid, and T. N. Singh (2013), The stability of road cut cliff face along SH-121: A case study, Nat. Hazards, 68(2), 497-507.

Stevens, W. D. (1998), RocFall: A tool for probabilistic analysis, design of remedial measures, and prediction of rockfalls, Masters of Applied Science, University of Toronto, Canada.

Tagliavini, F., P. Reichenbach, D. Maragna, F. Guzzetti, and A. Pasuto (2009), Comparison of 2-D and 3-D computer models for the M. Salta rock fall, Vajont Valley, northern Italy, GeoInformatica, 13(3), 323-337.

Vijayakumar, S., T. Yacoub, M. Ranjram, and J. H. Curran (2012), Effect of rockfall shape on normal coefficient of restitution, paper presented at 46th US Rock Mechanics / Geomechanics Symposium 2012.

Volkwein, A., K. Schellenberg, V. Labiouse, F. Agliardi, F. Berger, F. Bourrier, L. K. A. Dorren, W. Gerber, and M. Jaboyedoff (2011), Rockfall characterization and structural protection - A review, Natural Hazards and Earth System Science, 11(9), 2617-2651.

Wang, Y., F. Tonon, and R. Guardia (2011), 2D Rock-fall simulations taking into account rock fragmentation, 45th US Rock Mechanics / Geomechanics Symposium.

6. Appendix

Figure 1: DEM of the port Hills with aerial photographs superimposed showing boulder trails of the three sites.

	Coefficient of normal restitution (R_n)	Coefficient of tangential restitution (R_t)
Weathered basalt	0.85	--
Loess	0.17	0.35
Colluvium	0.17	0.33

All materials have a friction angel of 20 degrees with a standard deviation of 5.

Table 1: Coefficient of restitution for slope materials.

	Mean	Standard Deviation
Horizontal Velocity (m/s)	1.5	0.0
Vertical Velocity (m/s)	1.0	0.0
Mass (kg)	2700	1000
Angular Velocity	3.0	1.0

Table 2: Initial seeder conditions

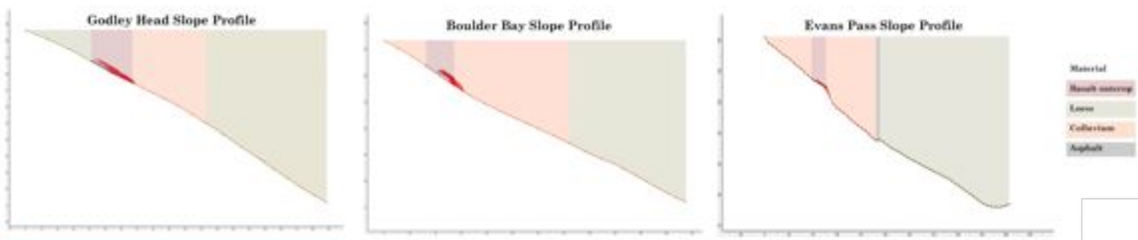

Figure 2: RocFall produced slope profiles with boulder trajectories in red

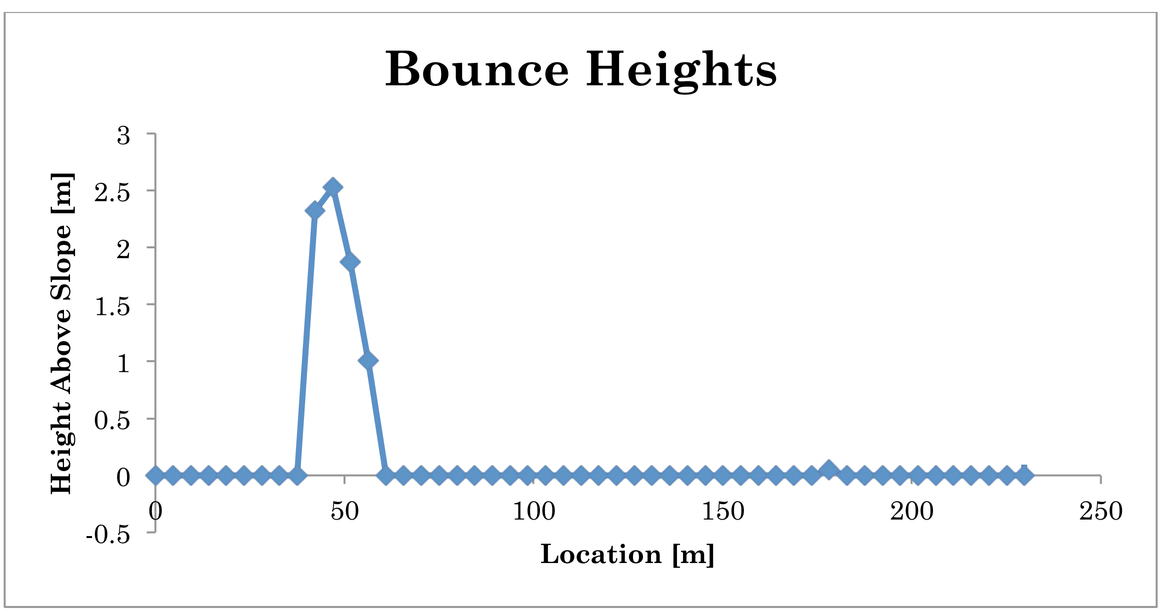

Figure 3: Boulder Bay bounce heights

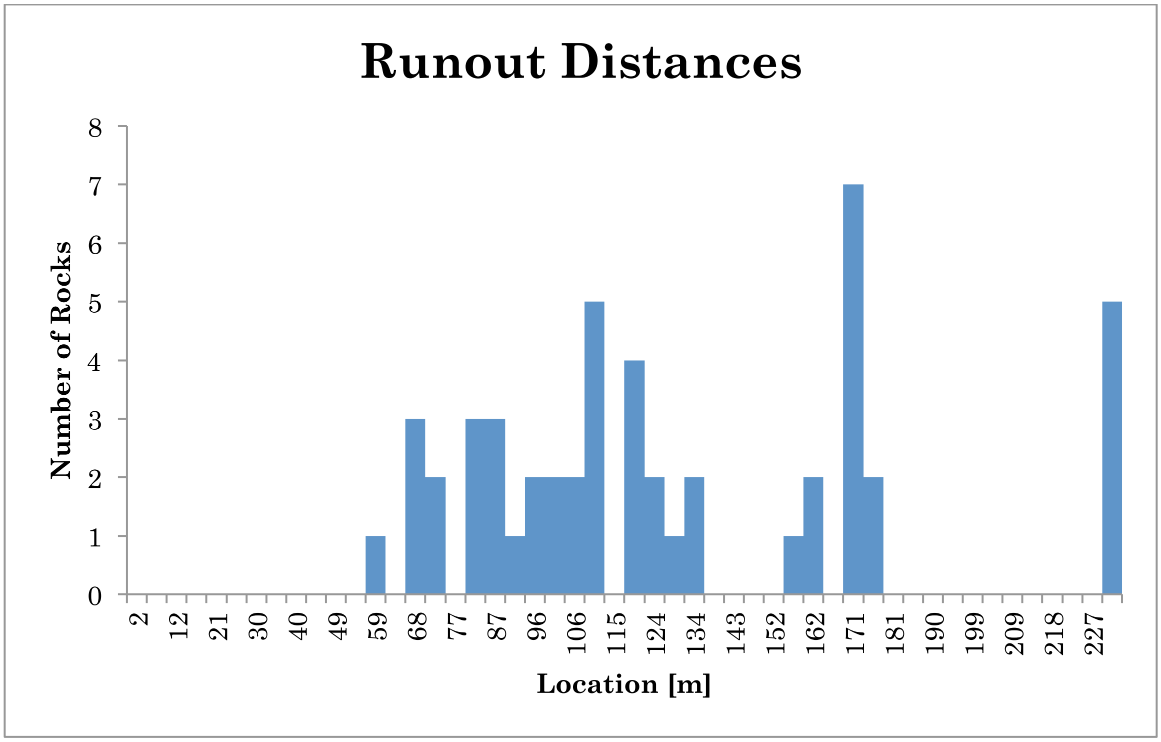

Figure 4: Boulder Bay runout distances

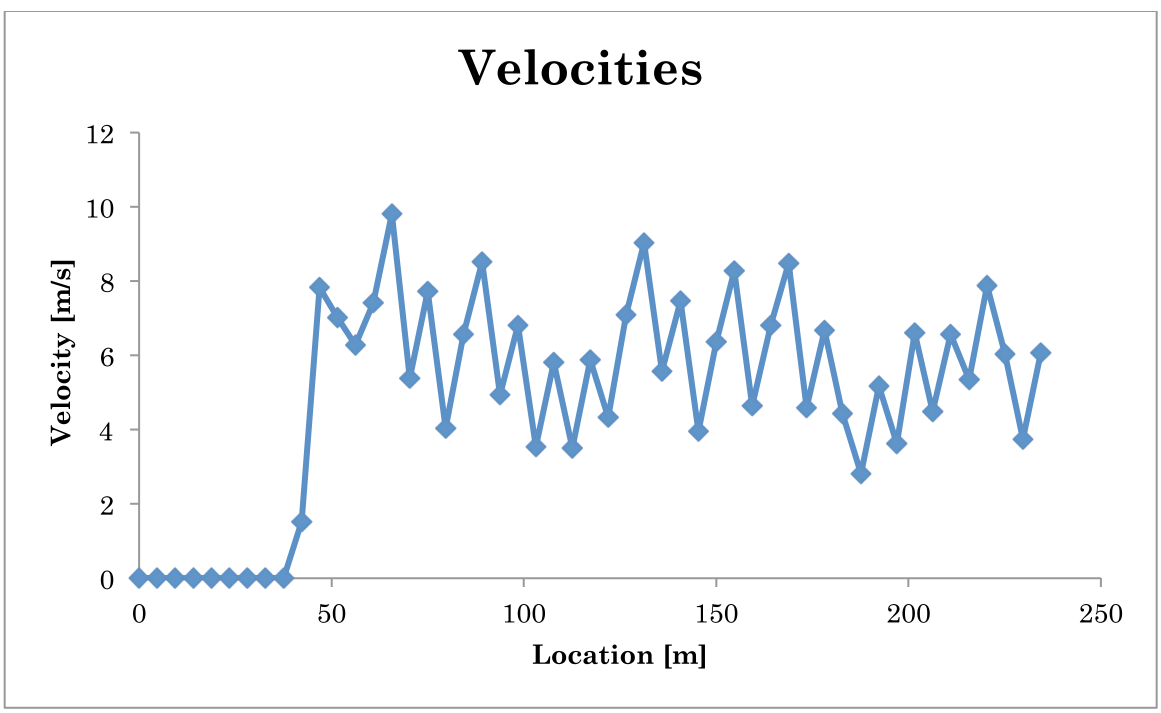

Figure 5: Boulder Bay velocities

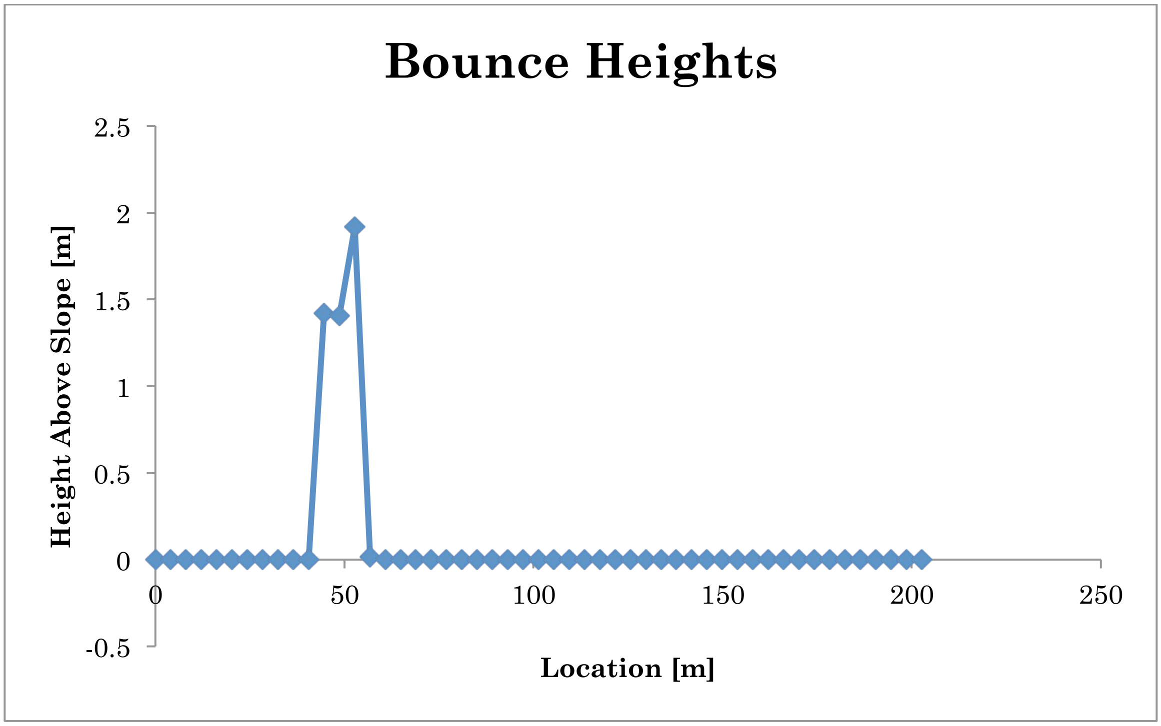

Figure 6: Evan's Pass bounce heights

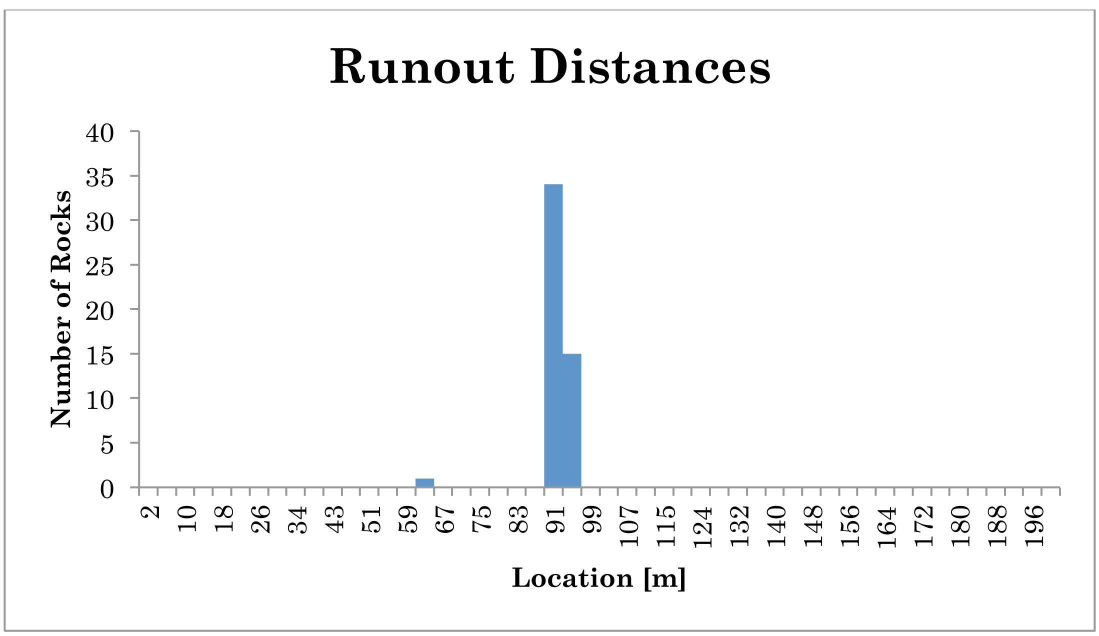

Figure 7: Evan's Pass runout distances

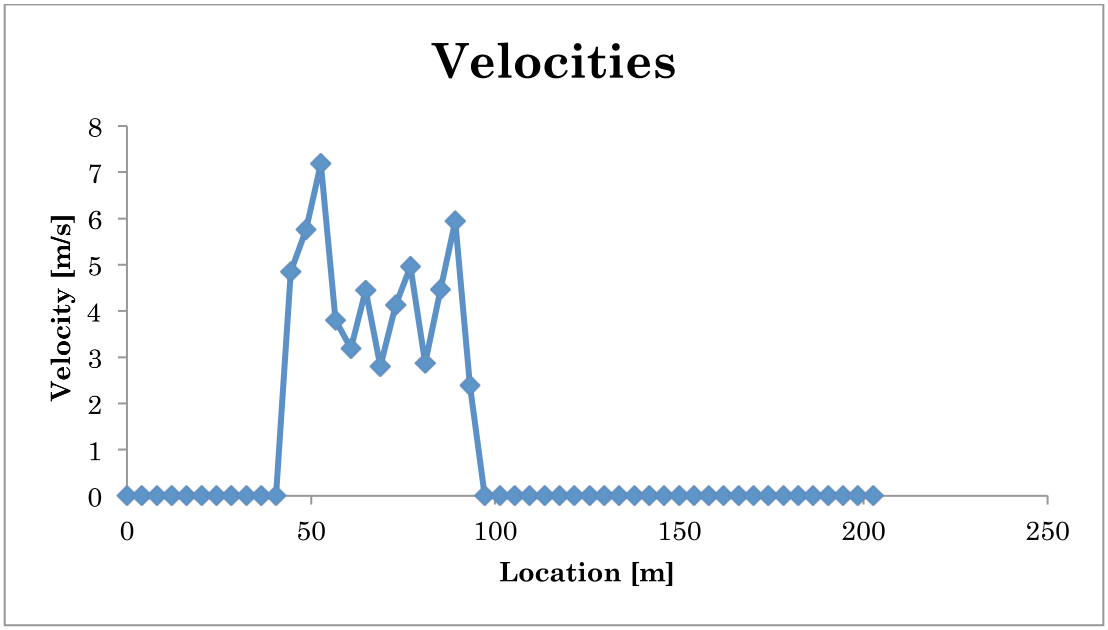

Figure 8: Evan's Pass velocities

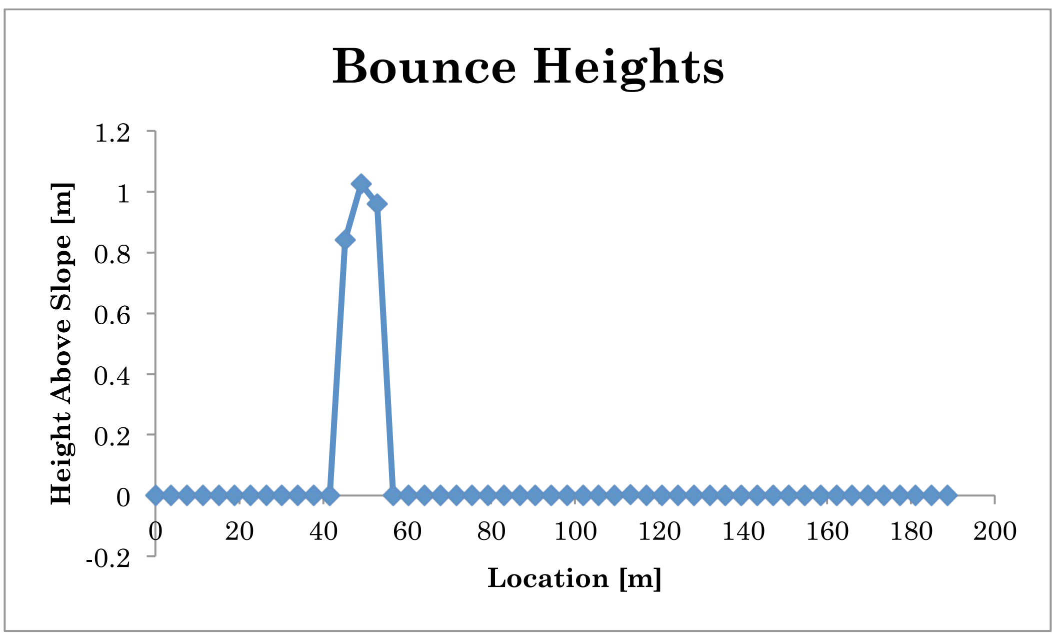

Figure 9: Godley's Head bounce heights

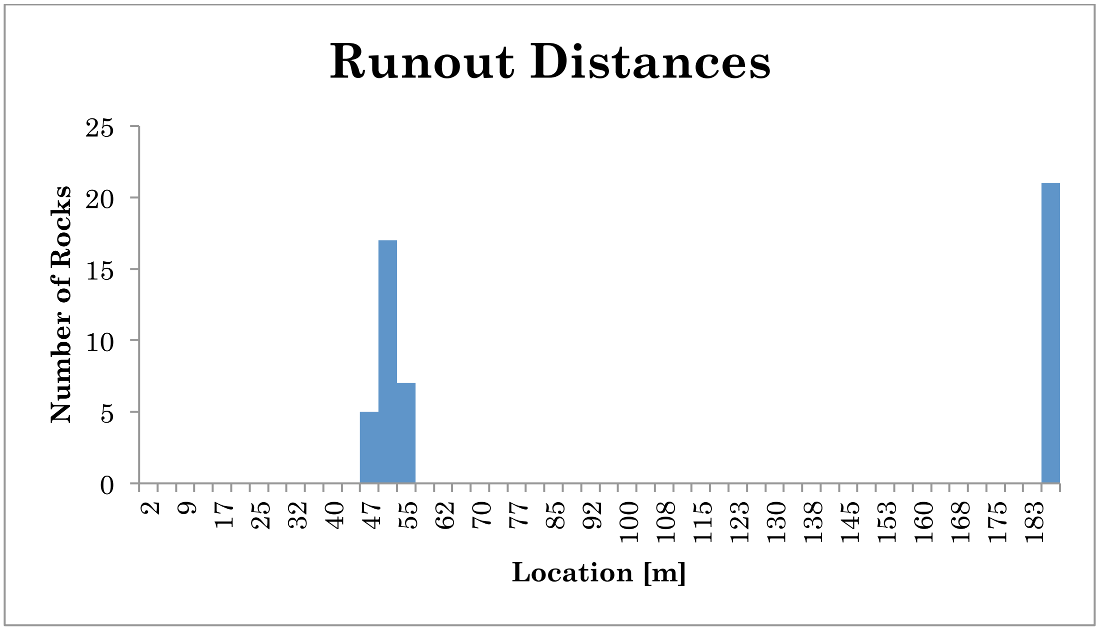

Figure 10: Godley's Head runout distances

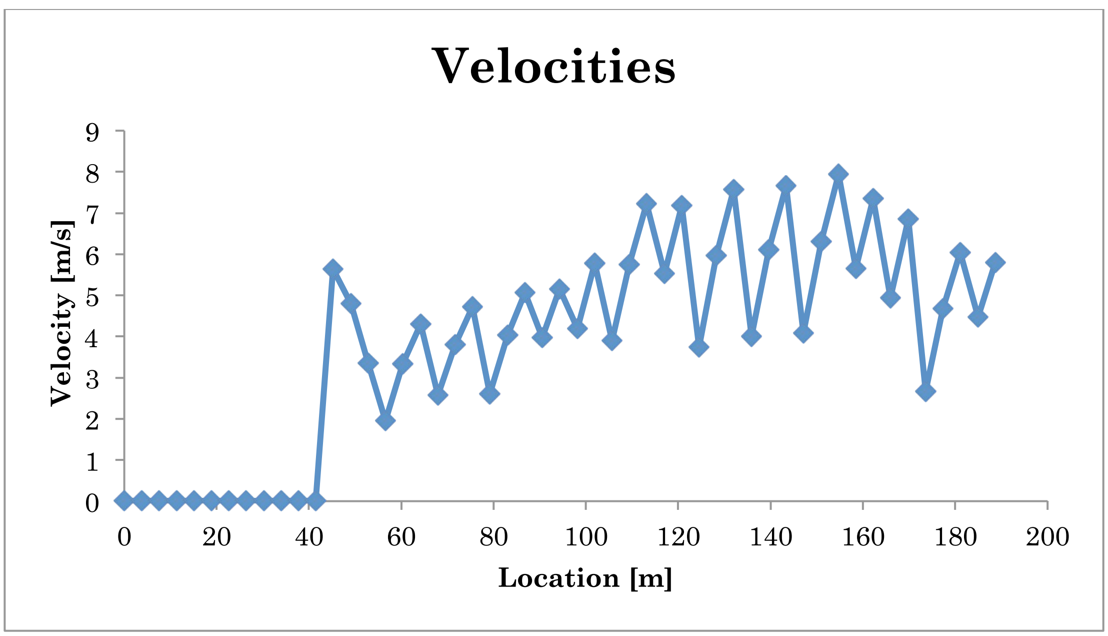

Figure 11: Godley's Head velocities

	Bounce Height (m)	Runout Distance (m)	Velocity (m/s)
Evan's Pass 1	.11	94	2.90
Evan's Pass 2	.10	96	2.77
Evan's Pass 3	.21	96	4.64
Godley Head 1	.17	190	10.20
Godley Head 2	.21	190	8.51
Godley Head 3	.27	190	8.77
Godley Head 4	.21	190	8.51
Boulder Bay	.33	--	11.66

Table 3: Values of bounce height, runout distance, and velocity as calculated from scaling video footage